DAMAGE PATTERNS CAUSED BY THE BURNING OF LIQUIDS ON WOOD SURFACES

by

D. Robinson.

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1 SUMMARY

Knowledge of the damage caused to timber floors by the burning of liquids is of importance in the investigation of fires where the use of accelerants is suspected. This project has examined the damage caused to a piece of wood by a pool burning on its surface. Actual sections of floors were also constructed and their behaviour in fires, following the use of an accelerant, studied.
2 INTRODUCTION

The choice of this dissertation topic was born out of a desire to do an experimental project related to fire investigation, and from a statement in a book\(^1\) which caught the attention of one of the staff of this department. The passage read: ".... an isolated, or indeed, several isolated holes in a timber floor with charring from above and in particular where the other general levels of fire damage in the vicinity are less may well indicate that a liquid accelerant has been used." However Kirk in his more authoritative book on fire investigation\(^2\) states that ".... holes are burned in floors by liquid flammables only when the liquid itself can penetrate below the floor surface.... Lacking such conditions flammable liquids can never carry fire downwards. The floor surface which holds them cannot be heated above the boiling point of the liquid applied as long as the liquid is present. This temperature is far to cold to ignite the floor. However if the liquid itself can penetrate to a lower level by way of cracks or holes the fire can be generated below the surface and will burn holes in the floor."

Clearly there is some confusion as to how damage to flooring can be caused by flammable liquids, one author claiming it is by attack from above the floor and the other that it is by attack from below. Neither produce any experimental evidence to back up their claims.

The professional fire investigator is normally called to the scene of a fire if something suspicious or unusual is thought to have occurred. Among the signs that may alert him to the possibility that a flammable liquid has been used to deliberately start or accelerate a fire are:

i. burn marks on, or charring of, floors in a distinctive 'pool pattern'.

ii. a trail of small burn marks along a floor (see Plate 1)

iii. holes along cracks in a floor eg along the tongued and grooved or plain edged joints between floorboards (see Plates 2 and 3)

iv. large holes in a floor

v. deep charring of a floor with crocodiling of the char surface.

Samples of the debris taken from the scene can be subjected
Plate 1: A trail of burn marks (some arrowed) on a bituminous floor where flammable liquid is believed to have been splashed and subsequently ignited.

Plate 2: Holes burned through a timber floor along the joints between the boards. A flammable liquid is believed to have been used.

Plate 3: Charring of an area of flooring in a pool pattern. The boards have been penetrated in one place along the joints. A flammable liquid is believed to have been used.
to standard analytical tests to detect the presence of fire accelerants. Where commercial fuels have been used there will normally have been a preferential loss of the more volatile hydrocarbons. Motor gasoline and kerosine are the two most commonly used accelerants, being encountered by the Metropolitan Police Laboratory in approximately equal frequencies. Other easily available flammable liquids that have been used by arsonists include paint thinners, white spirits and methylated spirits.

The type and extent of damage to a timber floor may depend on many factors including:

i. the type and quantity of liquid used

ii. the type of flooring eg tongued and grooved or plain edged boards, or large sheets

iii. the species of timber

iv. the thickness of the flooring

v. the size of gaps between boards or the presence of holes

vi. whether any holes or gaps are filled with dirt

vii. the age of the floor

viii. the moisture and resin content of the wood

ix. whether the floor has been varnished, painted or polished

x. the presence of carpets, linoleum etc

xi. the size of the sub-floor space; it will be deeper beneath a ground floor than beneath an upper floor

xii. the quantity of combustible material eg timber joists in the sub-floor space

xiii. the growth of the fire in the rest of the room and the consequent increased levels of environmental radiation onto the flooring.

Obviously the effects of altering all these parameters could not be investigated during the short time available. Firstly it was decided to try to determine the heat transfer and damage to a piece of wood from a liquid burning on its surface. However, on pouring small quantities of liquid onto wood and igniting the pool it was found that the liquid pool quickly receded in area as it burned. Whilst this might represent what would happen in a real fire it made the heat transfer
from the pool fire to the wood difficult to analyse. Therefore in the first series of experiments, various methods were tried to keep the pool stationary on the wood by supplying liquid fuel to the pool at the same rate as it was being burned. In the second series of experiments actual sections of floors were constructed and their behaviour in flammable liquid fires investigated.
3 STATIONARY POOL EXPERIMENTS

3.1 Experimental

3.1.1 Wood used in the experiments.
The wood used was 2 cm thick, planed spruce boarding conditioned for several weeks in the laboratory. Its moisture content was measured before each experiment with a 'Protimeter' moisture meter. This instrument measures the electrical resistance between two points in a piece of timber and the moisture content can be read off a scale for the species tested. Values lay in the range 11.7 - 13.0 % H₂O with a mean of 12.4 % and a standard deviation of 0.4 %. The density of the wood was 0.40 g/cm². The specimens were bunded on three sides with 45 x 12 mm red pine stripping nailed and glued ('Evostik Resin W' - a water based adhesive). Since burning of these bund walls was found to be a problem they were painted with 'Parfire' intumescent paint as were the exposed ends of the boards (see Plate 4). Originally boards 13.5 cm square were used. Later these were replaced with boards 27 cm long x 13.5 cm wide.

3.1.2 Flammable liquids used in the experiments.
Kerosine was used in most of the experiments since it represented less of a hazard in handling than petrol. The kerosine, of density 0.77 g/ml, was stained with waxoline red dye (hence the commonly used name of pink paraffin). Since the effect of radiation from the pool fire to the wood was to be studied some tests were also conducted with methanol to provide a comparison between luminous and non-luminous flames. The methanol was of density 0.79 g/ml.

3.1.3 Liquid fuel systems.
Two methods were tried to keep the pools stationary during the burns. The first method is illustrated in Figure 1. The liquid fuel was supplied from a 6 litre open-top brass feed vessel of large cross-section, covered with aluminium foil to reduce evaporation. A flexible tube led from the feed vessel to a short length of copper tubing pushed through a hole drilled in the piece of bunded board on which the pool was to be formed. The bunded board was rested on a cantilever platform kept at an angle of 5° by means of a wedge (see Plate 5). The board was raised above the level of the liquid in the feed
Figure 1: Initial liquid feed system adopted.

Plate 4: The boards were banded on 3 sides with pine stripping painted with intumescent paint.
Plate 5: The bunded board was rested on a cantilever platform which was kept at an angle of 5°.
vessel by means of the cantilever platform and the feed vessel tap opened. The platform was then lowered until liquid fuel started to flow onto the board, forming a shallow rectangular pool bounded on the two sides and rear by the bund walls. The front of the pool formed a distinct liquid/wood interface a predetermined distance from, and parallel to, the rear bund wall. Slight vertical movements of the cantilever platform caused the front edge of the pool to advance or recede relative to the rear bund. When the liquid was ignited the platform was slowly lowered in an attempt to keep the front edge of the pool stationary ie to match the recession rate of the liquid in the feed vessel. This was found to be impracticable and a second method had to be devised.

In this modified arrangement the bunded board was kept on the cantilever platform at an angle of 50° but the liquid fuel was supplied from a constant head device as shown in Figure 2 and Plate 6. This was made from a 3 litre tin can. An 8 mm diameter copper overflow pipe ran via flexible tubing to a winchester bottle and another copper pipe led from below the overflow via flexible tubing to the bunded board. The liquid was kept at the level of the overflow by letting fuel drain from a 1 litre separating flask, acting as feed vessel, into the constant head device at a rate greater than it was being burned on the board. During long burns the feed vessel had to be refilled several times. A pump from the winchester bottle to the feed vessel would have made the procedure much simpler but one of a suitable capacity was not available. The open tops of the feed vessel and the constant head device were covered with aluminium foil to reduce evaporation.

Adjusting the height of the cantilever platform again caused the front edge of the pool to advance or recede relative to the rear bund wall. Hence the length and surface area of the pool could be adjusted before the test.

3.1.4 Experimental procedure.
The weight of liquid fuel was measured before and after each experiment enabling the quantity burned to be determined. The level of the front edge of the pool was adjusted to a predetermined position and the apparatus left for 5 - 10 minutes to settle down. Any changes in the position of the pool during this time were compensated for and the pool
Figure 2: Final liquid feed system adopted.

Plate 6: The constant head device.
was ignited with a wax taper. The kerosene pools were first primed with 1 ml of n-heptane.

One of the initial fires was conducted in an open-bottomed asbestos enclosure, resting on bricks to provide a gap for ventilation, smoke being exhausted via a chimney to an extract duct. Observations were made through a wired-glass window. This procedure was abandoned however since the enclosure started to crack and distort. All future tests were conducted in the open air of the laboratory, beneath a hood connected to the extract duct. The results of the enclosed fire were disregarded since heat feedback to the pool from the hot gas layer which built up in the enclosure caused a significantly higher liquid fuel burning rate than for those fires conducted in the open.

During each fire observations were made of the behaviour of the wooden board and of the liquid pool and flames. Estimates of maximum flame height were made by means of a scale marked on a panel behind the fire.

The duration of each fire was measured with a stopwatch and when it was decided to terminate a test, the flames were smothered with a piece of aluminium foil shaped to closely fit over the bunded board. Where problems in quickly extinguishing a particular fire occurred a BCF aerosol extinguisher was used. This knocked the flames down in less than one second. The pool of liquid fuel was then drained back into the constant head device and liquid nitrogen poured over the board to extinguish any residual smouldering.

3.1.5 Measurement of depth of charring.
After each test the board was cut in half with a vertical band-saw along a line parallel to the bund sides i.e. perpendicular to the front edge of the pool. The char was brushed away with a soft brass-wire brush and the depth of charring measured with a travelling microscope at regular intervals along the board. The depth of charring at a point was calculated by subtracting the depth of residual wood at the point from the original depth of the board. However, this method of measuring the depth of residual wood was found to be very time consuming. The use of a micrometer or vernier calipers was considered and rejected. Since the surface of the
residual wood after the char had been brushed away was not parallel to the base of the board the parallel facing jaws of the micrometer could not be used. The vernier calipers were unsuitable since they did not incorporate a ratchet to ensure a constant pressure on the jaws when measurements were being taken. The method finally adopted for about half the boards measured, involved the use of an overhead projector. A thin section was cut from the bisected board, the char brushed away as before and the silhouette of the section projected onto a screen. A magnification of approximately ten times was achieved. The depth of residual wood was measured by comparing the projected image with a projected image of known size. Accuracies of approximately 0.1 mm were obtained. The depth of charring was then calculated as before.
3.2 Results and observations

3.2.1 Tests on 13.5 cm square boards.
As previously mentioned the original experiments were conducted on boards approximately 13.5 x 13.5 x 2.0 cm thick. The level of the cantilever platform was adjusted until liquid from the constant head device formed a pool, the front edge of which was 3 - 4 cm from the front edge of the board. Since I expected the greatest damage to occur near to the pool edge this seemed an adequate amount of dry board in front of the pool.

Tests were conducted using kerosine and methanol on boards with the grain of the wood running either parallel or perpendicular to the front of the pool.

3.2.1.1 Kerosine fires.
The kerosine pool fires burned with a bright yellow flame 40 - 50 cm high (see Plate 7) causing immediate charring of the board a few mm in front of the pool (ie there was a narrow band of uncharred 'dry' wood between the apparent edge of the pool and the beginning of the char). Flames spread along the dry part of the boards in front of the pools, charring the surface black as they did so. By four or five minutes the flames had reached the far end of the boards ie a flame spread velocity along the wood of \( \frac{1}{2} - 1 \) cm/minute. Meanwhile the liquid pools had receded towards the back bund wall by up to 2 cm; this recession then ceased. The kerosine within a few cm of the front edge of the pool was boiling vigorously by now. The wood beneath the pool was not charring. Cross grain cracks started appearing in the charred parts of the boards and by 20 minutes those flames over the char were mostly emanating from these cracks (see Plate 8). These flames were not uniform, intermittently moving from crack to crack and to the unbundled edge of the boards.

Some tests had to be abandoned because of leaks or because the level of kerosine in the constant head device fell below the overflow, altering the length of the pool on the board. However, satisfactory tests were completed for fires of 15, 40 and 60 minutes duration with the grain of the wood running parallel to the front edge of the pool, and of 20, 33 and 40 minutes duration with the grain of the wood running
Plate 7: Pool of kerosine 13.6 cm x 7.7 cm burning on board 13.6 cm x 13.4 cm. The black markers on the wall are 20 cm apart.

Plate 8: Kerosine pool fire at 14 minutes. The main body of flames is above the pool. Less uniform flaming above charred wood in front of the pool.
perpendicular to the front edge of the pool.

Average burning rates were calculated for the kerosine pools. Unfortunately the pool areas were not the same for each test. The burning rates of kerosine expressed in terms of the surface areas of the pools varied from 0.15 g/cm²/min for a pool of 88 cm² to 0.098 g/cm²/min for a pool of 141 cm².

Plate 9 shows the typical appearance of a board after a test. In this case the fire was of 40 minutes duration. The area which was beneath the pool is uncharred although there is a light brown discolouration or scorching to the surface for a few cm behind the front edge of the pool. There is a distinct line between the charred and the uncharred wood. The surface of the char within 2 cm of the pool edge has a smooth shiny appearance, the grain of the wood is still visible and there are only a few very fine cross grain cracks. Beyond this area the surface of the char is rougher, less shiny and has deep cross grain cracks up to 2 mm wide.

Plate 10 shows the cross-section of the same board after it has been cut in half. The depth of charring is zero at the pool edge and increases in a uniform manner with distance from the pool. Beneath the char there is a band of brown discolouration, about 6 mm deep. Figures 3 and 4 show the appearance (full size) of the sectioned boards for the six tests here reported. The dotted areas indicate char. On brushing the char away it was found that there was a distinct transition between the soft char and hard uncharred wood beneath. However the surface of this freshly exposed uncharred wood was in a series of ridges and troughs corresponding to the annual rings of the wood. The ridges occurred along the narrow late or summer-wood part of the rings and the troughs along the wider early or spring-wood part (see Figure 3). The depths of charring were measured with the travelling microscope (to the base of the troughs) and are shown in Figures 5 and 6.

3.2.1.2 Methanol fires.
The methanol fires burned with a blue flame, almost invisible in the artificial light of the laboratory (see Plate 11). On darkening the laboratory the flames were seen to be 20 - 25 cm high and hugging the the surface of the liquid around the periphery of the pool. There was no immediate damage to the
Plate 9: Appearance of board after 40 minute kerosine fire. Uncharred area was beneath the pool.

Plate 10: Cross-section through the board shown in Plate 9. Char depth increases with distance from the area which was covered by the pool.
Figure 3: Sections through boards after kerosine fires of increasing duration. Grain of wood parallel to front of pool.

Figure 4: Sections through boards after kerosine fires of increasing duration. Grain of wood perpendicular to front of pool.
Figure 5: Char depths from kerosine pool fires on 13.5 cm square boards. Grain of wood parallel to front of pool.
Figure 6: Char depths from kerosine pool fires on 13.5 cm square boards. Grain of wood perpendicular to front of pool.
Plate 11: Methanol pool fires on 13.5 cm square boards. The blue flames are almost invisible.

Plate 12: Methanol pool fire at 14 minutes. The flame is invisible but the bubbling of the milky exudate indicates the front edge of the pool. Only half the board has a band of char.
boards in front of the pools. Within about 30 seconds a light yellow stain formed in a narrow band across the boards in front of the pool fires. This staining was accompanied by hissing noises. By about two minutes a milky fluid was bubbling out of the wood in places along these yellow bands. There were yellow/orange streaks in the methanol flame where the bubbling was occurring. Meanwhile the liquid pools had receded by \( \frac{1}{2} - 1 \) cm; the recession then ceased. The methanol did not boil. By five minutes there was still no charring of the boards. The yellow staining started to turn brown soon afterwards and by seven minutes small areas of char started to form beneath the frothing milky exudate just in front of the pools. This char formation was not regular across the boards. In one case, by 14 minutes, a band of char approximately 1 cm wide had formed across half the board whilst the other half was uncharred (see Plate 12).

Again, some tests had to be abandoned because of leaks but successful burns of 15, 30 and 60 minutes duration were achieved, all with the grain of the boards running parallel to the front of the pool.

Average burning rates were calculated for the methanol pools and values between 0.070 and 0.079 g/cm²/min were obtained.

Plates 13, 14 and 15 show the appearance of the boards after the tests. Those areas which were beneath the pools are completely undamaged and the bands of charring in front of the pools are irregular in appearance. There are some fine cracks, mostly across the grain, in the surface of the char. On cutting the boards in half it was found that the charring was only superficial. Figure 7 shows the appearance (full size) of a sectioned board after a 60 minute methanol fire. In this case the maximum depth of charring was only 0.23 cm. On brushing the char away a distinct transition was found between the char and the uncharred wood beneath. Again this freshly exposed uncharred wood was in a series of ridges and troughs. There was no brown discolouration beneath the char as had been found with the kerosine fires.

3.2.2 Tests on 27.0 x 13.5 cm boards.
Since, contrary to my initial expectations, the depth of charring in front of the kerosine fires increased with distance from the front edge of the pool right up to the end of the
Plate 13:
Damage to board after 15 minute methanol pool fire.

Plate 14:
Damage to board after 30 minute methanol pool fire.

Plate 15:
Damage to board after 60 minute methanol pool fire.
Pool

60 mins burning.

Figure 7: Section through a board after a methanol fire of 60 minutes duration.
boards, it was decided to repeat the tests with double length boards. The pools were to be kept approximately the same size as before.

3.2.2.1 Kerosine fires.
Bright yellow flames from the kerosine pool fires were 50 - 60 cm high and caused immediate charring of the boards just in front of the pools. Flames then spread along the dry surface of the boards at 1\(\frac{1}{2}\) - 2 cm/min until they reached within at least 2 cm of the end. They charred the boards as they spread. Meanwhile the kerosine pools which were originally 11.6 - 12.8 cm long again receded by 1 - 2 cm. Once the flames had reached their furthest extent along the boards they dropped back until they covered about half the dry area of the boards. These flames merged with, and were indistinguishable from, the flames of the pool fire. Over the other half of the dry board flames a few cm high emanated from cross grain cracks in the char layer. This flaming was not uniform, flames jumping from crack to crack. The top surface of this deeply cracked char layer became concave and a grey ash formed (see Plate 16).

Satisfactory tests were completed for kerosine fires of 15, 30 and 60 minutes duration with the grain of the boards running parallel and perpendicular to the front of the pool. The burning rates of kerosine varied from 0.096 g/cm\(^2\)/min for a pool of 163 cm\(^2\) to 0.134 g/cm\(^2\)/min for a pool of 131 cm\(^2\).

Plate 17 shows the typical appearance of a board after a test. In this case the fire was of 60 minutes duration. The area under the pool (a) is uncharred although there is some brown discolouration (b) near the front edge. There is a distinct line (c) between the charred and uncharred wood. The original position of the pool before it receded a couple of centimetres is marked by a slight ridge (d) on the char. The surface of the char for the first 5 - 6 cm (e) is continuous with the surface of the unburned wood. It is black and shiny with a few very fine cracks present. Lines corresponding to grain of the original wood are visible. Beyond this, the char is less shiny and is dished inwards towards the base of the board. This char (f) has deep cross grain cracks up to 3 mm wide and 1 - 3 cm apart. Finally there is a small area of char (g) at the end of the board, similar in appearance
Plate 16: Kerosine pool fire on larger board at 38 minutes. Much of the charring is occurring in front of the main body of flame. Smaller flames were seen emanating from the deeply cracked area of char.

Plate 17: Appearance of the board shown in Plate 16 after a 60 minute kerosine fire. See text for explanation of symbols.
to (e).

Figures 8 and 9 show the appearance (full size) of the boards after they were cut in half. The depth of charring (i.e., the distance from the original top surface of the board to the base of the char layer) increases with distance from the edge of the pool reaching a maximum some 9 - 10 cm from the edge. However, the depth of the char layer itself over much of the board is not so great as the depth of charring, resulting in a dished appearance to the section. As with the smaller boards there was a distinct transition between the char layer and the unburned wood below, the latter also exhibiting a series of ridges and troughs corresponding to the annual rings of the wood. The depths of charring were measured by the projection method described earlier and are shown in Figures 10 and 11.

3.2.2.2 Methanol fires.

Only one methanol fire was conducted on the larger sized boards and was of 60 minutes duration. The grain of the board was parallel to the front of the pool. Observations proved to be similar to those with the smaller boards. The pool was originally 14.3 cm long and receded during the first few minutes by 0.8 cm. The almost invisible blue flames were 20 - 25 cm high and again a milky fluid bubbled out of the wood just in front of the burning pool. Char first appeared at 11 minutes as an incomplete thin black line in front of the pool. This band of char was not complete until 30 minutes after ignition of the pool. There was a dry uncharred area approximately 1 cm wide across the board, between the front of the pool and the beginning of the char. Orange streaks were visible in the methanol flame where the milky fluid was bubbling out of the wood.

Plate 18 shows the appearance of the board after the test. That part of the board that was under the pool is completely undamaged. In front of this there is a band of char 1.2 cm wide running across the whole width of the board. There are no cracks in the char. The milky fluid has solidified into a soft yellow springy substance on top of the char. The wood in front of the char is also undamaged.

The average burning rate of the methanol pool was 0.077 g/cm²/min.
Figure 8: Sections through boards after kerosine fires of increasing duration.

- 60 mins Burntime
- 30 mins Burntime
- 15 mins Burntime
Figure 10: Char depths from kerosine pool fires on 27.0 cm x 13.5 cm boards. Grain of wood parallel to front of pool.
Figure 11: Char depths from kerosine pool fires on 27.0 cm x 13.5 cm boards. Grain of wood perpendicular to front of pool.
Plate 18: Appearance of a board after a 60 minute methanol fire.
On cutting the board in half it was found that the charring was only superficial. The appearance of the sectioned board is shown in Figure 12. The maximum depth of charring was 0.8 mm.
Figure 12: Section through board after methanol fire of 60 minutes duration.
3.3 Discussion of results and observations
3.3.1 Experimental limitations.
One of the principle limitations encountered was that the pools receded by up to 2 cm horizontally within a few minutes of ignition. The variability of this recession meant that the surface area of the pools was not the same in each test. A horizontal recession of 2 cm on the boards angled at 5° to the horizontal is equivalent to a loss in head of 1.7 mm. This pressure loss was due to friction in the pipes, tubes and tape between the constant head device and the bunded boards. The burning rate of a liquid fuel varies with the dimensions of the pool. Therefore, since the radiation falling onto the dry board in front of a pool fire is proportional to the flame height, and since the height of the flames above a pool are proportional to the burning rate of the fuel, then the variation of pool area in different tests will have caused a variation in the heat flux onto the boards.

The visual measurement of maximum flame height introduced another inaccuracy since what we are really interested in is the time averaged height of the flame. This would best have been obtained by taking a cine film of the tests.

Other problems encountered included leaks and spills from the bunded boards.
3.3.2 Damage to boards beneath the pools.
With neither the kerosine nor the methanol fires was there any charring of the boards beneath the pools although, with the kerosine, there was some slight scorching of the boards at the shallow end. Heat transfer from the flame to the liquid fuel raises the sensible heat of the liquid in the pool and provides latent heat for vaporization. This heat transfer will be mainly radiative with the kerosine fires and convective with the methanol fires. Heat transfer to the wood will be by conduction from the hot liquid, and with the kerosine fires also by radiation passing through the liquid onto the board. Since the absorption of radiation by a liquid increases with the depth of the liquid, more radiant heat transfer to the wood will occur at the shallow end of the pool than at the deep end. If \( I_0 \) is the intensity of radiation onto the liquid fuel surface, then the intensity of transmitted radiation I
at depth $x$ is given by Lambert's law:

$$I = I_0 e^{-kx}$$  \hspace{1cm} (1)$$

where $k$ is the absorption coefficient for the liquid. Although $I$ was unable to obtain a value for the absorption coefficient of kerosine, Burgess and Hertzberg\textsuperscript{8} report an experiment which allows $k$ to be determined for hexane. They found that 71% of flame radiation passing through 3 mm of liquid hexane in a cell with CaF\textsubscript{2} windows (which are transparent to infra-red radiation) was absorbed. Substituting these values into equation (1) gives an absorption coefficient for hexane equal to 0.41 /mm. If we make the reasonable assumption that the absorption coefficient of liquid kerosine is similar to that for hexane, then we find that radiant heat transfer from the flame, through the kerosine, to the wood, is only likely to be significant for very shallow depths of liquid. Whilst for a pool 1 mm deep 66% of the radiation incident onto the pool reaches the wood, for a pool 5 mm deep only 12% is transmitted and for a pool 1 cm deep only 1.6% is transmitted. Since in the tests described with a typical pool of 10 cm length, the depth increased from zero at the edge to 9 mm at the deep end, the percentage of radiation onto the liquid surface that was transmitted to the board below will have varied from almost 100% at the shallow end to only 2% at the deep end. The emissivity and, assuming Kirchoff's law holds, also the absorptivity of wood have the value\textsuperscript{9} of approximately 0.91 (planed oak at 38°0) and so most of the radiation that reached the boards will have been absorbed. In the 60 minute kerosine test shown in Plates 16 and 17 the slight scorching to the wood beneath the pool extends for approximately 3 cm from the pool edge. Because of the radiant heat transfer the wood surface in this area may have been at a temperature greater than that of the boiling liquid immediately above. Elsewhere on the boards, where no scorching occurred, the main mode of heat transfer will have been conductive, the temperature of the board gradually approaching that of the liquid above. The methanol never boiled and we may assume that the surface of the board beneath the pool never exceeded its boiling point of 65°0. The kerosine did boil over about
half the pool, but not violently so and we may assume that the
temperature of the wood beneath the deeper parts of the pool
did not exceed the boiling point of kerosine. This ranges
from 160°C (initial boiling point) to 285°C (final boiling
point) over its distillation range\(^\text{10}\). Fresh fuel from the
constant head device will have reduced the temperature of the
liquid in the pool near the inlet.

To sum up, the damage to the plane surface of a piece of
timber whilst beneath a burning kerosine or methanol pool is
not going to exceed slight scorching even for extremely
shallow pool depths.

3.3.3 Damage to boards in front of the pools.
From the observations described earlier in this report it is
clear that with the kerosine pool fires on 13.5 cm square
boards the full extent of possible damage to the dry wood in
front of the pools was not being realised. By doubling the
length of the board it was possible to observe the full range
of damage with distance from the pool. These latter results
made those from the tests with the smaller boards somewhat
superfluous.

Obviously, radiant heat transfer from the liquid fuel
flames to the part of the board in front of the pool has played
an important role in the spread of flames along the boards.
With the highly luminous kerosine flames there was immediate
charring of the boards in front of the pool and flames spread
along the surface at 1½ - 2 cm/min. However, with the almost
invisible methanol flames there was no immediate charring of
the boards and virtually no spread across the surface.

Convective heat transfer from the flame to the timber
surface is unlikely to have been important in the spread of
flame across the boards since the temperature of the methanol
flames, which did not cause spread, was considerably higher
than the temperature of the kerosine flames which did.
Rasbash et al\(^\text{7}\) determined temperatures of 990°C and 1218°C
respectively for kerosine and methanol flames.

To quantify the radiative heat transfer from the pool
flames to the 'dry' board it is necessary to know the flame
temperature T, the flame emissivity \(\varepsilon\) and the configuration
factor \(\varnothing\). The latter is a function of the size of the

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flames, the distance of the receiving element along the board from the flames and the relative orientation of the board to the flames. The radiant heat flux \( \dot{q}'' \) onto the surface is given by:

\[
\dot{q}'' = \sigma \varepsilon T^4
\]

where \( \sigma \) equals Stefan's constant \((5.67 \times 10^{-12}\text{ W/cm}^2/\text{K}^4)\)

The radiant heat flux onto the board at increasing distances from the pool fire, along a line drawn down the centre of the board, has been calculated for one kerosine fire and one methanol fire (both 60 minute tests on the long boards). The dimensions of the pools and flame heights were:

<table>
<thead>
<tr>
<th></th>
<th>Kerosine</th>
<th>Methanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pool width</td>
<td>13.6 cm</td>
<td>13.9 cm</td>
</tr>
<tr>
<td>Pool length</td>
<td>9.6 cm</td>
<td>13.5 cm</td>
</tr>
<tr>
<td>Flame height</td>
<td>55 cm</td>
<td>30 cm</td>
</tr>
</tbody>
</table>

The emissivities of the kerosine and methanol flames can be calculated using the equation:

\[
e = 1 - \exp(-\alpha L)
\]

where \( \alpha \) is the emission coefficient and \( L \) is the thickness of the flame. Rasbash et al.\(^7\) estimate \( \alpha \) to be 0.026 and 0.0037 for kerosine and methanol respectively. Equating the thickness of the flame with the length of the pool (an approximation) gives emissivities of 0.22 and 0.049 for kerosine and methanol respectively.

Configuration factors \( \varnothing \) can be estimated by modelling the flame with an isoseles triangular radiator, having the same height as the flame and sitting in the pool thus:
The maximum configuration factor for this triangular radiator and a perpendicular receiver at a given distance, is for the receiver opposite the centre of the base of the triangle.

Law\textsuperscript{11} gives the following formula for the configuration factor:

\[
\phi = \frac{1}{n} \left[ \tan^{-1} \left( \frac{D}{b} \right) - \frac{1}{(1+f^2(D^2+4))^{\frac{1}{2}}} \left( \tan^{-1} \frac{0.5D}{(1+f^2(D^2+4))^{\frac{1}{2}}} + \tan^{-1} \frac{2f^2D}{(1+f^2(D^2+4))^{\frac{1}{2}}} \right) \right]
\]

\[\text{where } \frac{d}{c} = D, \quad \frac{h}{d} = f\]

\[\text{ie } h \text{ is the flame height, } d \text{ the pool width and } c \text{ the distance from the centre of the pool to the elemental area of board under consideration. Values of } \phi, \text{ for various distances } c, \text{ were calculated for both the kerosine and methanol fires. These values were then substituted into equation (2) allowing the radiant heat flux at increasing distances from the pool edge to be calculated. The previously quoted temperatures of kerosine and methanol flames were assumed. The calculated heat fluxes } q'' \text{ W/cm}^2 \text{ are shown in Figure 13 for different distances L cm from the edge of the pool. The heat flux onto the board in front of the kerosine pool fire is approximately five times greater than the flux from the methanol fire at equal distances.}

Simms and Hird\textsuperscript{12} have shown that if a pilot flame is in contact with the surface of a piece of wood then the amount of heat required to cause ignition is much less than for normal pilot ignition. The critical intensity for this surface ignition of columbia pine is 0.41 W/cm\(^2\) whilst that for normal
Figure 17. Radiant heat fluxes at various distances in front of kerosene and methanol pool fires. Gas loss rate
pilot ignition is 1.46 W/cm$^2$. Similar results were obtained for oak and fibre insulating board. The front edge of the pool fires may be considered as a pilot flame in contact with the board. Thus radiant heat transfer may account for the ignition of the board in front of the kerosine pool fires since the radiant heat flux just in front of the pool was greater than 0.41 W/cm$^2$. If we think of flame spread as a continuing series of surface ignitions, then the radiant heat flux accounts for much of the flame spread as well.

However, with the methanol pool fire, the radiant heat flux onto the board was less than 0.41 W/cm$^2$ near to the pool edge and further along the board. The wood was very slow to char, did not ignite in the conventional sense i.e. did not support the luminous yellow flame characteristic of wood burning, and flame did not spread across the surface.

The milky white fluid observed bubbling out of the wood just in front of the burning methanol pools was thought to be the result of resins etc. being driven out of the wood by heat and dissolving in the hot methanol. To see if this was likely, 5 g of fresh spruce sawdust was mixed with 50 ml of methanol and left for one hour. The liquid was then filtered into a petri dish and allowed to evaporate. As the evaporation proceeded the liquid changed from clear to milky and when all the liquid had evaporated a few tiny pieces of a soft white material were left. When a piece of wood-resin was dissolved in methanol and the resulting cloudy liquid evaporated a similar soft pinkish-white material was left.

The possibility of kerosine soaking through the unburned wood ahead of the flame and so assisting fire spread was also considered. To see whether this was possible small pieces of spruce 1 x 1 x 5 cm high were supported vertically with one end just submerged in a dish of kerosine, the grain of the wood running vertically up the specimen. The kerosine was stained a deep red with an oil-soluble dye ('Magic Marker' ink). The specimens were removed after varying periods and split down the middle. The dyed kerosine did not spread evenly up the specimens but the maximum rate of spread was no more than 3 mm/hour. This is much too slow to have assisted fire spread in the tests conducted.
Spread of liquid kerosine through the char layer once burning was established is also unlikely since a gap a few mm wide was often observed between the edge of the pool and the beginning of the char.

One of the most surprising results of the tests was that the depth of charring increased with distance from the kerosine pools reaching a maximum some 8 - 12 cm from the pool edge. Intuitively one would expect charring to be greatest near to the front edge of the pool where incident radiation from the kerosine flame was also greatest. However, the flame from the burning wood near to the front edge of the pool merged with, and was indistinguishable from, the flame above the kerosine pool and it is possible that kerosine volatiles were mixing with volatiles driven out of the wood in this region. If sufficient oxygen were unable to diffuse to the surface of the wood against this upward moving flow of volatiles then the charring rate of the wood would be less than in the regions further away from the pool. In fact, in the central area of the boards, the top surface of the char became concave in appearance as some of the char layer itself underwent surface oxidation to a white ash implying more efficient combustion in a more adequate oxygen supply.

The rate of charring of the boards in front of the kerosine pools gradually decreased with time (see Figures 10 and 11). With the grain of the wood parallel to the front of the pool the maximum rates of charring averaged over 15, 30 and 60 minutes burning were 0.53, 0.47 and 0.30 mm/minute respectively. With the grain of the wood perpendicular to the front of the pool the maximum rates of charring were 0.43, 0.33 and 0.32 mm/minute averaged over the same time intervals. These maximum rates of charring are less than the often quoted 1/40 inch per minute observed in timber beams and columns in the standard fire resistance test (BS 476: part 8).

To see whether the radiant heat flux from the pool flame was necessary to sustain these charring rates, the average rates of mass loss of wood at different points on the board exposed to a 60 minute kerosine fire were calculated. If \( X \) (cm) is the depth of charring at a particular point on the board after time \( t \) (seconds) and \( Y \) (cm) is the depth of the char
then the average rate of mass loss $\dot{m}'$ (g/cm$^2$/s) at the point is given by:

$$\dot{m}' = \frac{x \rho_w - y \rho_c}{t}$$  \hspace{1cm} \text{(5)}

where $\rho_w$ = density of the wood = 0.40 g/cm$^3$

$\rho_c$ = density of the char = 0.13 g/cm$^3$

The density of char was measured for one area of the board and was assumed to be constant over the whole sample. The calculated rates of mass loss are shown in Figure 13. Tewarson et al.\textsuperscript{13} give the critical mass loss rate for the pilot ignition of wood (red oak) as $2.5 \times 10^{-4}$ g/cm$^2$/s. However, this is greater than the rate of mass loss at all points on the boards. Therefore, we may conclude that without the continuous radiant heat flux onto the boards from the kerosine flame, the flaming over the boards in front of the pool would not have been sustained.

As previously noted, when the char was brushed away, the unburned wood below was not smooth but rather exhibited a series of ridges and troughs. The narrow, late or summer-wood part of each annual ring is denser than the wider, early or spring-wood part\textsuperscript{14} and would be expected to char at a lower rate. This accounts for the appearance of this unburned wood, the ridges corresponding to the summer growths.

3.3.4 Relevance of the results to actual fires involving the use of kerosine.

The tests have shown that damage to a plain timber surface below a kerosine pool will not exceed slight scorching even after prolonged exposure. They have also shown that radiant heat transfer from the pool fire may cause flames to spread away from the pool onto the unwetted parts of the timber.
However, this radiant heat transfer must be sustained if significant damage is going to occur. If the liquid has just been poured or spilled onto the floor it will form a very shallow pool which will burn off in a few minutes or less. As the burning pool recedes, the timber previously protected by the liquid will become exposed and may ignite. The recession of the liquid pool will also cause the flames above the pool to get smaller and the radiant heat transfer to decrease. Without an external radiant heat flux the damage to a plain timber board will cease as the kerosine pool fire exhausts its fuel and goes out. However, if the general level of radiation onto the timber from burning elsewhere in the room exceeds 0.41 W/cm², the timber may continue to burn. Such levels of radiation would occur in the vicinity of even quite small fires and would be greatly exceeded if full room involvement occurred. In such situations a hole, or holes, could conceivably be burned through a plain timber board.

If kerosine was constantly flowing onto a timber surface, say from a leaking fuel drum, the pool, if ignited, would quickly assume an area for which the burning rate matched the rate of fuel supply. Charring beyond the edge of the pool could then be sustained without an external source of radiation. Such situations are not often likely to be encountered.

All the tests described above were conducted on plain timber surfaces i.e. without the tongued and grooved or plain edged joints common in traditional floors. The results cannot therefore be applied to predict the damage which would occur at such sites. The large scale tests described in the next section go some way to overcoming this restriction.
4 LARGE SCALE TESTS

4.1 Experimental

In this series of tests it was decided to simulate as closely as possible the behaviour of actual floors in real flammable liquid fires. Sections of both ground and upper floors were constructed with either relatively liquid-tight tongued and grooved boards or with leaky plain edged boarding.

Figure 14 shows details of a typical ground floor complying with the Building Regulations 1972. The tongued and grooved boards lie on 125 x 50 mm rough sawn timber joists at 40 cm centres. These joists rest on 100 x 75 mm rough sawn timber wall plates which in turn lie on half-brick honeycomb sleeper walls. The whole rests on a layer of concrete not less than 100 mm thick. Building Regulations require that with 125 mm joists the sub-floor space must be at least 250 mm deep.

Plate 19 shows one of the ground floor constructions used in Tests 1, 2 and 5. Five tongued and grooved spruce boards each 77 cm x 11.2 cm x 19 mm thick forming a floor section 77 cm long x 56 cm wide were nailed to three 125 x 50 mm rough sawn joists at 36 cm centres. These joists were nailed onto two 62 x 50 mm rough sawn wall plates at 51 cm centres. The whole was supported on four bricks resting on concrete. The underside of the floorboards was 29 cm above the surface of the concrete. 45 x 12 mm pine stripping was nailed to the exposed edges of the floorboards to prevent unrealistic free burning at these locations i.e. the stripping simulated a skirting.

In Test 3 a leaky ground floor was simulated with four
Figure 14: Details of a typical ground floor.

Plate 19: A simulated ground floor construction just prior to the commencement of a test. The liquid fuel was poured onto the centre of the top surface of the boards.
plain edged spruce boards each 74.5 cm x 13.2 cm x 20 mm thick nailed to three joists (same dimensions as the other joists) at 34.7 cm centres. They formed a floor 74.5 cm long x 53.4 cm wide with gaps 1 - 3 mm wide between the boards. The joists were nailed to wall plates (same dimensions as before) at 48.4 cm centres, the whole resting on four bricks on the concrete. The underside of the floorboards was 29 cm above the surface of the concrete. The exposed edges of the boards also had a skirting.

In Test 4 a tongued and grooved upper floor was simulated. The construction was identical to that in Tests 1, 2 and 5 with the omission of the wall plates. The joists were laid directly on a sheet of plasterboard which represented a ceiling. The underside of the floorboards was only 12.5 cm above the surface of the plasterboard.

The moisture content of the floorboards just before the tests was 11% H₂O and that of the joists and wall plates 12%.

The tests were conducted in a large room with a concrete floor, made available to me by the Edinburgh Airport Fire Brigade.

Before the tests were carried out it was necessary to consider whether in a real flammable liquid fire, the air supply to any burning which took place beneath the floor (eg due to burning liquid flowing through gaps between boards) would be adequate to prevent a restriction of the burning rate. If such a restriction were likely, it would be necessary to partly enclose the sides of the simulated floor to reproduce these conditions. It was proposed to use 500 ml of kerosine in each test. If such a volume of kerosine were to flow beneath a real floor it would require 4.4 m³ of air to burn
completely. If we assume that the floorspace was 29 cm deep (as in four of the tests) then the area of unobstructed floorspace would need to be 15 m$^2$ i.e. approximately 4 metres square to contain an adequate air supply. In modern buildings the floorspace often extends beneath the whole plan area of the building. In older buildings the floorspace may be subdivided beneath the walls of individual rooms. In either case the available volume of air would be adequate to burn 500 ml of kerosine. Air-bricks in the external walls would further increase the air supply to a sub-floor fire. The sides of the simulated floors were therefore left unenclosed in the tests.

A spirit level was used before each test to ensure that the top surface of the boards was truly horizontal. 500 ml of the liquid fuel were poured onto the centre of the boards (see Plate 19) and sufficient time allowed for it to flow across the surface and down between any gaps or joints. The pool which formed on top of the boards was then ignited.
4.2 Results and observations

4.2.1 Test 1.

The simulated ground floor comprised tongued and grooved boards on joists, wall plates and bricks on a concrete base. 500 ml of kerosine were poured onto the floor and covered most of the boards. Some flowed into the sub-floor space via the sides of the floor and the skirting, through knots, and, to a lesser extent, through the tongued and grooved joints between the boards. Ignition was by means of a burning strip of fabric 30 cm long x 4 cm wide which had been previously soaked in kerosine. The following observations were made:

0 min. The burning fabric was dropped onto the centre of the pool of kerosine which had formed on top of the boards. There was no immediate spread of flame away from the cloth.

1 min. Flames a few inches high began to spread lazily across the surface of the boards away from the burning fabric, leaving a dry area behind them where the kerosine had been consumed. They caused virtually no damage to the wood.

2 min. The main flaming had died down. There were only small flames, about 3 cm high, at three locations: along a tongued and grooved joint, at a knot further along the joint and at the piece of fabric. It appeared to be mainly kerosine, which had accumulated at these locations, that was burning although the wood in these places was being charred black. Plate 20 shows the test at 2½ minutes.

3½ min. Only the flame at the knot was still burning.

8 min. All flames out. Not all the kerosine on the top
Plate 20: Test 1 at $2\frac{3}{4}$ minutes. Small flames about $2\frac{1}{2}$ cm high are limited to the tongued and grooved joint between two boards and to the remains of the piece of fabric used to ignite the pool. Much kerosine remains unburned on the boards and some has run through to the joists, wallplates, bricks and concrete base of the sub-floor space.

Plate 21: Appearance of the floor section after Test 1. Most of the surface of the boards is undamaged.
surface of the boards had been burned off. None of the kerosine that had run into the sub-floor space had ignited.

Plate 21 shows the damage to the floor at the end of the test (the remains of the piece of fabric have been removed). Most of the surface of the boards was undamaged. The outline of the piece of fabric was superficially charred onto the boards. Elsewhere, charring was limited to the tongued and grooved joint between two boards, being greatest at the knot mentioned above. Even here it was only about 1 mm deep. Since so little damage had occurred it was decided to use the floor section again for Test 2.
4.2.2 Test 2.

In Test 1 the ignition source was too small to raise more than a fraction of the kerosine to its firepoint and consequently little damage was caused to the floor section. Since it was the damage patterns caused by the burning, rather than the mode of burning itself that was of principle interest, it was decided to ensure the involvement of a greater proportion of the kerosine in this and future tests. Either a larger ignition source eg a screwed up newspaper could be used, or the kerosine could be primed with another liquid fuel of a much lower flashpoint. The latter course was decided upon and in this test the kerosine was primed with 2% petrol. 500 ml of the kerosine/petrol mixture were poured onto the boards. As in Test 1, a proportion of the liquid flowed into the sub-floor space which was still contaminated with kerosine from the previous test. Large parts of the joists and wall plates were soaked with fuel and a pool formed on the concrete below. Since the flashpoint of the kerosine/petrol mixture was still above ambient temperature a piece of burning fabric was again used as an ignition source. The following observations were made:

0 min. Ignition. Flames 30 cm high immediately began to spread across the top surface of the boards.

½ min. One quarter of the wetted surface was now involved in fire.

1 min. The initial flaming died down and went out. Only about half of the liquid fuel on the surface had been consumed. There was virtually no damage to the wood and fire had not spread to the sub-floor space. Small flames, only a few cm high were
burning in a few places along the tongued and grooved joints between some of the boards, especially where these coincided with knots. Flaming, again only a few centimetres high, was also occurring at nail heads, at the piece of fabric used as an ignition source and at the skirting along one end of the floor section. The wood was slowly charring at these locations.

8 min. One small flame was moving slowly along a tongued and grooved joint towards an undamaged piece of skirting.

10 min. This flame had now reached, and was spreading along the skirting.

14 min. Flaming at the skirting, more substantial than elsewhere, was greatest where three of the tongued and grooved joints abutted.

15 min. Flames began to spread lazily from this burning skirting to an adjacent pool of the kerosine/petrol mixture on the surface of the boards. Only superficial scorching of the boards occurred.

17½ min. Flames at that skirting which was ignited at 1 minute were now out.

23 min. A flame was held over a knot in one of the boards.

27 min. Slight flaming at a nail head.

30 min. All flames out.

Plate 22 shows the damage to the floor section at the end of the test. Most of the floor surface was completely undamaged. There was light brown scorching to the wood in places, mainly on knots or rough parts of the surface. This tended to accentuate the natural wood-grain patterns on the boards. The
underside of the floorboards and the joists and wall plates in the sub-floor space were completely undamaged. The deepest charring along the tongued and grooved joints occurred at knots where it was up to 3 mm deep. Elsewhere, bands of charring had occurred on either side of the tongued and grooved joints having a maximum depth of 1 mm at the joint itself and decreasing away from the joint. There were small areas of charring, up to 1 mm deep, centred on nail heads. Narrow bands of char approximately 1 cm wide occurred at the ends of the boards where they abutted the skirtings that had been burning. This charring was greatest at the tongued and grooved joints where it was up to 5½ mm deep. The adjacent skirting was charred over its whole height in these areas, the charring being up to 3 mm deep. Only those skirtings which abutted the ends of the boards were charred ie only those to which liquid fuel and flames could spread along the joints. Those skirtings which abutted the sides of the floor section were completely undamaged. When the char on the boards and skirting was brushed away, the surface beneath showed similar patterns to those observed in the small scale tests ie hard wood, stained or scorched brown and exhibiting a series of ridges and troughs corresponding to the annual rings of the wood.
Plate 22: Appearance of the floor section after Test 2. Again, most of the surface of the boards is undamaged. Note charring of skirtings where they abut the ends of the floor section.

Plate 23: Test 3 at 5 seconds. Flames up to 2 metres high completely engulf the top of the floor boards. A pool of kerosine is also burning beneath the floor.
4.2.3 Test 3.

In this test the ground floor section with plain edged boards was used. As previously noted, there were gaps of 1 - 3 mm between the boards. 500 ml of a 90% kerosine/10% petrol mixture with a flashpoint below ambient temperature were poured onto the top surface of the boards. Much of the liquid flowed into the sub-floor space through gaps between adjacent boards, and through gaps between boards and adjacent skirtings. The pool formed on top of the boards was ignited with a wax taper. The following observations were made:

0 min. Ignition. Flames were 1.8 - 2.0 metres high almost immediately and completely engulfed the top surface of the floor section. The pool of liquid fuel which had formed on the concrete base beneath the floor was also burning. Plate 23 shows the test at 5 seconds.

45 sec. Plate 24 shows the test at this time. Most of the flames on top of the boards died down and went out as the pool of liquid fuel was burned off. About two-thirds of the top surface of the boards were scorched brown or charred black in this initial burn-off, the rest was completely undamaged. Flames on top of the floor were now limited to the gaps between adjacent boards or between the boards and the skirting. However, in the sub-floor space, flames were still burning quite vigorously and in Plate 24 one of the wall plates can be seen burning.

2 min. Plate 25 shows the test at this time. The liquid pool on the concrete had almost burned off and burning on the timber in the sub-floor space was limited
Plate 24: Test 3 at 45 seconds. Most of the flames on top of the boards have died down but those in the sub-floor space are still burning quite vigorously.

Plate 25: Test 3 at 2 minutes. Burning in the sub-floor space is limited to the intersection between a joist and the boards above.
to the intersection between a joist and the boards above. There were flames up to 15 cm high above the widest gap between the boards, and along the adjacent skirting.

5½ min. Plate 26 shows the floor section at this time. Most of the flaming was occurring at the skirting. Elsewhere, flaming was limited to a small part of the gap between two boards where the wood was charring and glowing. The gap between these boards was widening as the exposed surface of the char was being oxidized to a white ash.

7 min. Non-flaming combustion ie smouldering was visible in several places between boards.

10 min. The skirting was burned through in one place. There was a smouldering gap over 1 cm wide between parts of two adjacent boards.

13 min. Plate 27 shows the floor section at this time. There was only a little smouldering at this stage. When a piece of glowing skirting was pulled gently away from the glowing end of an adjacent board, the glowing ceased showing the importance of cross radiation in the maintenance of such smouldering combustion.

17 min. Smouldering ceased and test terminated.

The appearance of the floor section at the end of the test did not differ significantly from that shown in Plate 27. About 30% of the top surface of the boards was completely undamaged. The rest was either scorched dark brown or charred black. Away from the plain edged joints between the boards this surface charring was no deeper than 1 mm and was covered
Plate 26: Test 3 at 5½ minutes. Flaming is limited to part of the gap between two boards and to the adjacent skirting.

Plate 27: Test 3 at 13 minutes. All flaming has ceased but a little smouldering continues.
in tiny cross-grain cracks. When brushed away it again revealed a series of ridges and troughs on the underlying wood. Deep charring only occurred at the gaps between boards (ie at the plain edged joints). The boards on either side of part of a 3 mm wide gap had burned away to form a hole up to 15 mm wide (including residual char) when measured from above and up to 22 mm wide when measured from below. When the char was brushed away the hole was up to 30 mm wide both top and bottom. Other boards on either side of smaller gaps had also burned away in places, but to a lesser extent. The holes thus formed were all wider at the underside of the boards than at the top surface even when the char was brushed away and were all adjacent to joists, which had also charred. The skirting was completely burned through in places at one end of the floor section. Most of the underside of the boards was charred or scorched. The char was typically 2 - 3 mm deep and when brushed away revealed the by now familiar series of ridges and troughs on the underlying wood. The sides and bottoms of the joists were burned in places, charring being greatest, up to 8 mm deep, at the sides where they abutted the boards. Typically, charring was only 1 mm deep elsewhere on the joists. The tops and sides of the wall plates were also charred in places.
4.2.4 Test 4.

In this test, the upper floor section, with relatively liquid tight tongued and grooved boarding was used. 500 ml of the 90% kerosine/10% petrol mixture with a flashpoint below ambient temperature were poured onto the top surface of the boards. Some liquid leaked into the sub-floor space via slight gaps between the skirting and the boards. It formed pools on the plasterboard making up the underside of the cavity. The pool on top of the floorboards was ignited with a wax taper.

The following observations were made:

0 min. Ignition. Flames were 1.4 metres high within 10 seconds and completely engulfed the top surface of the boards. Plate 28 shows the state of the fire at this time. The pools of liquid fuel on the plasterboard were also burning.

½ min. Most of the flames on top of the boards had died out as the pool of liquid fuel burned off. A large proportion of the surface of the boards was undamaged in this initial burn off. Flames on top of the floor were then limited to the tongued and grooved joints between boards, to knots and nail heads and to the skirting (see Plate 29).

1 min. Much more substantial flaming was occurring beneath the boards where pools of liquid were still burning (see Plate 30). Some of the joists were also burning.

3 min. On the top surface of the floor section flames approximately 3 cm high were limited to parts of the tongued and grooved joints between some of the boards, and to parts of the skirting. Beneath the
Plate 28: Test 4 at 10 seconds. Flames up to 1.4 metres high have completely engulfed the top surface of the floor section.

Plate 29: Test 4 at 30 seconds. Most of the flames on top of the boards have died out.
Plate 30: Test 4 at 1 minute. There is quite substantial flaming from the pools of liquid on the plasterboard and on the joists.

Plate 31: Test 4 at 4 minutes. Only the joists are burning in the sub-floor space. Some of the flames are impinging onto the adjacent floorboards.
floor the flames were much smaller than before and the paper face of parts of the plasterboard had been burned black.

4 min. Flaming ceased on the top surface of the floor section except along one part of a skirting board. The liquid fuel on the plasterboard had burned off and flames in the sub-floor space were limited to the joists, some of these flames impinging onto adjacent areas of floorboards (see Plate 31).

7 min. There was still some flaming in the sub-floor space along a junction of the central joist and the floorboards above.

10 min. Flaming continued along the joist/floorboard junction mentioned above.

12 min. There was still a very weak flame at one of the skirtings (see Plate 32). The flame on the central joist in the sub-floor space was also very weak.

14 min. All flames out. Test terminated.

The appearance of the floor section after the test was identical to that shown in Plate 32. About 70% of the top surface of the boards was undamaged, the rest being either scorched brown or charred black. The charring was centred on the tongued and grooved joints between boards, on nail heads and on knots and cracks in the wood. It was up to 2 mm deep at the joints. Bands of charring on either side of the joints became progressively less deep away from the joints. The skirting along one end of the floor section was charred through its whole thickness in places. Charring to the ends of the boards and to an underlying joist in this area was up to 12 mm deep. Plate 33 shows the appearance of the underside of the
Plate 32: Test 4 at 12 minutes. A very weak flame is visible at one of the skirtings. The appearance of the floor boards is identical to that 2 minutes later when the final flame went out.

Plate 33: Appearance of the underside of the floor-section after Test 4.
floor section at the end of the test. The underside of the boards was charred over half the floor and smoke blackened over the other half. The charring was up to 2½ mm deep and its surface was covered with numerous cross-grain cracks. The sides of the joists were also charred, typically to a depth of 1 mm. The paper was burned off parts of the plasterboard.
4.2.5 Test 5.
In this test a ground floor section with tongued and grooved boards was used. It was carpeted with squares from a sample book. The squares, although of different colours, were identical in composition. They consisted of a 100% nylon pile looped through a polypropylene backing on an integral latex foam underlay. 500 ml of the 90% kerosine/10% petrol mixture were poured onto the centre of the carpeted floor. This soaked into the carpet, apparently wetting about half its area. No liquid penetrated to the underside of the floor section. The wetted area was ignited with a wax taper and the following observations were made:

0 min. Ignition. The wetted area was immediately involved in flame (see Plate 34).

30 sec. The flames were now 80 cm high.

45 sec. The flames reached a height of 1.4 m and copious black smoke was being evolved.

1 min. The flames reached their maximum height of 1.8 m (see Plate 35).

1½ min. The flames were now 1.4 m high. Some of the carpet squares were beginning to curl up at their edges thus exposing parts of the underlying boards.

3 min. Flames 1.2 m high covered most of the carpet. There was still no penetration to the underside of the boards by either liquid or flame.

4 min. Most of the carpet was still burning and flames were up to 60 cm high. As some of the carpet squares curled up at the edges, or were partly destroyed, the wood exposed was charred but these charred areas did not support any substantial flaming.
Plate 34: Test 5 at 10 seconds. Flames are established on the wetted part of the carpet.

Plate 35: Test 5 at 1 minute. Flames have now reached their maximum height of 1.8 metres.
7½ min. Flames were now only about 10 cm high and were burning in discrete areas across the floor (see Plate 36).

13½ min. There was only one small area still burning, the flame being about 3 cm high (see Plate 37).

14 min. All flames out. Test terminated.

The appearance of the floor section at the end of the test was identical to that shown in Plate 37. Some parts of the carpet were completely reduced to a soft ash; other parts had all the nylon pile and polypropylene backing burnt off but the latex foam underlay beneath largely undamaged. One small area of carpet was intact. The appearance of the floorboards after the remains of the carpet were removed is shown in Plate 38. About 20% of the floor was completely undamaged including that part under the intact area of carpet. The heaviest charring, up to 4 mm deep, occurred on the areas of boarding beneath the edges of adjacent carpet squares. This char was covered in cross-grain cracks and when brushed away revealed the familiar series of ridges and troughs on the wood below. The 12 mm skirting was burned through in two places and heavily charred in others. There was no damage to the underside of the boards or to the joists and wallplates.
Plate 36: Test 5 at 7 1/2 minutes. Small flames are burning in discrete areas across the floor.

Plate 37: Test 5 at 13 1/2 minutes just prior to the last flame dying out. Note area of carpet still undamaged.

Plate 38: Test 5. Appearance of the floor boards after the remains of the carpet have been removed (photograph taken from the opposite side to that shown in Plate 37).
4.3 Discussion of results and observations

As mentioned in the introduction there are very many different factors, each of which may have an effect on the type and extent of damage to a timber floor in a flammable liquid fire. Obviously, in just five tests, it has only been possible to study the effects of a fraction of these factors and limitations in the interpretation of the results must be recognized. In particular, since there was no external radiant heat flux onto the boards in the tests, the modes of burning and damage patterns observed will only be representative of those in fires which have not spread to involve other combustible materials which would otherwise provide such a heat flux. The tests only model situations where isolated areas of flooring have burned.

When the liquid fuels were poured onto tongued and grooved boards, a pool formed on the surface. Some liquid also ran into the sub-floor space, mainly through slight gaps between the skirtings and the floorboards but also, and to a much lesser extent, through the tongued and grooved joints themselves and through knots and cracks. With plain edged boards, a pool also formed on the surface but more liquid ran into the sub-floor space. Obviously, the larger was the gap between adjacent boards, the larger was the leakage of liquid through the gap. It seems reasonable to conclude that if a flammable liquid were to be poured onto a real tongued and grooved floor, leakage to the sub-floor space would probably only be significant if the spillage occurred near to a skirting or other discontinuity. With a real plain edged floor, leakage to the sub-floor space would be much more likely even if the spillage occurred away from the skirting. The proportion
of the spilt liquid which ran into the sub-floor space would depend upon the size of the gaps between adjacent boards and upon whether the gaps were blocked with dust or dirt. Large gaps would be most likely in old floors where shrinkage or movement of the boards had occurred.

If pure kerosine was used as an accelerant on uncovered timber boards and was ignited with a small ignition source, small flames would only spread lazily across the pool causing very little damage to the boards. If a larger ignition source was used, which quickly raised a substantial proportion of the pool to its firepoint, or if a liquid with a flashpoint below ambient (such as primed kerosine or petrol) was used instead of pure kerosine, then the flaming on top of the boards would be much more substantial. Even so, without an external radiant heat flux, charring to the surface of the boards away from the tongued and grooved or plain edged joints would be limited to the areas around nail heads, knots, cracks and other rough or damaged parts of the surface. Such charring would probably be only 1mm or less deep.

The tests have shown that the most significant damage to floorboards is likely to occur at the joints between adjacent boards, and at skirtings. With tongued and grooved boards some of the flammable liquid is retained in the joint and flames continue to burn long after the rest of the liquid fuel on the surface has burned off. Even so, the greatest depth of charring observed at these joints away from the skirtings, was only 3 mm where the joint coincided with a knot, and 1 mm elsewhere.

Small flames were observed travelling along the tongued and grooved joints to the skirting boards which then ignited
and burned much more vigorously. 12 mm thick skirtings were sometimes burned through in less than 15 minutes, a charring rate of more than 0.8 mm/min (1/30 inch per minute). This higher rate of burning may be accounted for by the vertical orientation of the skirtings. There was also heavy charring, up to 12 mm deep, to the ends of boards where they abutted the skirtings. However, in a real room the skirting would also abut a wall, and fire behaviour at the skirting/floor-board junctions may be somewhat different.

With one of the tongued and grooved floor sections (Test 4) and with the plain edged floor (Test 3) enough of the flammable liquid entered the sub-floor space to allow quite substantial flaming beneath the boards. The liquids used were both 90% kerosine/10% petrol mixtures with a flashpoint below ambient temperature. However, had the liquids been pure kerosine, it is unlikely that any such flaming would have occurred. This is because the liquids in the sub-floor space would have been unlikely to come into contact with an ignition source large enough to raise them to their firepoint. Such considerations would also apply in real fires.

In Test 4 some of the flammable liquid that entered the sub-floor space soaked into the rough sawn sides of the joists and the rest formed pools on the plasterboard below. This liquid below the floorboards ignited very soon after the pool on top of the tongued and grooved boards was set alight but it was not possible to determine exactly how this ignition occurred. Flammable vapours from beneath the floor may have reached the burning fuel on top of the boards in which case a flame would have flashed back into the sub-floor space. Alternatively, drops of burning liquid may have run through gaps at the
skirting. Both the fuel soaked joists and the pools on the plasterboard burned quite vigorously (see Plate 30) but the charring caused to the underside of the floorboards was still no more than 2\(\frac{3}{4}\) mm deep. Although greater than the depth of charring to the top surface of the boards there was no chance of holes being burned through the solid timber of the boards.

The greatest damage observed in the five tests occurred in Test 3. The liquid which entered the sub-floor space soaked into joists and wall plates and formed a pool on the concrete below. After the vigorous pool-fire in the floorspace had died down flaming beneath the floor was limited to the intersection between a joist and the boards above. The edges of two adjacent plain edged boards, initially 3 mm apart, were supporting small flames (see Plate 26) causing the wood to char and glow. This flaming was occurring to the side of the burning joist. A hole began to form as the surface of the char was oxidized to a soft white ash, and continued to grow even when the flaming combustion was superceded by smouldering. Smaller holes were also forming between the edges of other, closer boards. These holes were all near to joists. When the char was brushed away, all but the largest hole were wider at the bottom surface of the boards than at the top. Each of the boards making up either side of the largest hole had been charred to a depth of 14 mm in 17 minutes, a charring rate of approximately 0.8 mm/min (1/30 inch per minute).

With the tongued and grooved boards, the joints between the boards tended to retain some of the liquid fuel and act as reservoirs, supplying this fuel to the small flames above the joints, which themselves were only charred very slowly. With the plain edged boards separated by gaps of the order 1 - 3 mm
this reservoir effect would have been greatly diminished, if it existed at all. In this case, fire attack from above and below during the initial burn-off of the liquid fuel would have raised the wood in the gaps to a temperature high enough to sustain flaming or smouldering combustion when the liquid was exhausted. Heat losses in the gaps would be much less than on the exposed horizontal surface of a board and an external heat flux unnecessary for combustion to continue. Cross radiation between the adjacent glowing faces is probably important in such cases and will impose a limit on the size of hole formed. As the hole increases in size the faces get further apart, the radiant heat transfer decreases and heat losses increase.

Certain of the damage patterns to the uncarpeted floor sections in Tests 1-4 would not be expected in a real fire unless a flammable liquid (or molten plastic) had been burning. These distinctive features could be looked for when trying to decide if an accelerant has been used.

Plate 39 shows a quite heavily charred skirting board adjacent to the ends of relatively undamaged tongued and grooved floorboards. Without the use of an accelerant one would not expect a skirting to be charred right down to the floor unless the adjacent boards had also been ignited, perhaps by falling debris. However, the tests described above have shown that if an accelerant has been poured onto a tongued and grooved floor near to a skirting, such damage would be expected if the skirting ran along the ends of the boards, since liquid fuel and flames could spread along the tongued and grooved joints to the skirting. Such damage would be less likely at a skirting alongside a floorboard.
Plate 39: A quite heavily charred skirting board adjacent to relatively undamaged floorboards.

Plate 40: Holes burned between adjacent boards of a plain edged floor.
Plate 41: As Plate 40 but viewed from beneath the floor. Note charring to joists and to underside of floorboards.

Plate 42: Charring around a nailhead caused by the burning of a flammable liquid (several times magnification).
5 CONCLUSIONS

i. In a real fire, a pool of low flashpoint flammable liquid on top of a timber floor is likely to burn off quickly, causing only superficial damage to the boards as it recedes. However, flames may then continue to burn at skirtings, at the joints between boards, at knots, nail heads and other surface irregularities. In the absence of an external radiant heat flux, smooth parts of the boards are unlikely to similarly support flaming.

ii. Holes are most likely to be burned in a timber floor if a substantial quantity of low flashpoint liquid can penetrate into the sub-floor space. Such penetration is likely if the boards are plain edged with slight gaps between them. The holes formed may then be centred on these gaps.

iii. Some of the findings of this report suggest that a different mode of burning may occur if the general level of radiation onto a timber floor from burning elsewhere in the room exceeds a certain value. In this case flames might continue to burn on both the smooth and irregular parts of the surface of a floor after the liquid fuel has burned off. This could lead to fire penetration of a liquid-tight floor. Further experimental research is necessary to test this hypothesis.

iv. Flammable liquids cause certain distinctive burning patterns on the boards, skirtings and joists of floor constructions. These patterns can be looked for when trying to decide if an accelerant has been used in a fire.
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7 REFERENCES

1) RICHARDS N. How did it start? The Institution of Fire Engineers. 1980.


6) THOMAS PH. The size of flames from natural fires. 9th Combustion Symposium. 1963. 844-859.


9) FISHERDEN M and SAUNDERS OA. Calculation of heat transmission. HMSO. 1932.


13) TEWARSON A, JAMES LL and RUSSELL FP. Fuel parameters for evaluation of the fire hazard of red oak. FMRC JI.006M2.RC. Massachusetts.1979.