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Behaviour of Light Timber-Framed Floors Subjected to Fire Attack From Above

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Preface

This report on a project carried out at the Building Research Association of New Zealand describes a full-scale experiment to investigate the potential for fire to spread in a downward direction through timber floors. The full-scale experimental work verifies earlier reduced-scale furnace-based experiments. The purpose of the project was to further the knowledge gained previously and to report the findings.

Note

This report is intended for fire engineers, architects, designers, manufacturers, codewriters and other researchers into fire spread between firecells.

BEHAVIOUR OF LIGHT TIMBER-FRAMED FLOORS SUBJECTED TO FIRE ATTACK FROM ABOVE

BRANZ Study Report SR 117 (2003) **P. N. Whiting**

REFERENCE

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ABSTRACT

Traditional test methods for fire-resistance of floors evaluate the performance of floor/ceiling assemblies when exposed to a fire from below. This is accepted as being the most severe orientation, with little or no research having been carried out with respect to fire from above. Light timber-framed floor/ceilings in New Zealand are typically of asymmetric construction with sheets of 20 mm thick reconstituted wood particleboard on the top surface of timber joists with a paper-faced gypsum plasterboard ceiling on the underside of the joists; the thickness of the plasterboard depending on the fire-resistance rating required. The fire-resistance of a floor is expected to be quite different depending on the direction of fire exposure. With exposure from the downward direction, it is the thickness of reconstituted wood floor panels which determines the time at which the floor joists become significantly affected by fire. However, the thickness of the reconstituted wood is unchanged (at 20 mm) for floors with fire ratings ranging from 30-120 minutes.

Previous experiments reported on by the author were carried out using a fire-resistance wall furnace adapted to enable this type of floor/ceiling construction to be exposed, from above, to a standard time-temperature curve (AS 1530 Part 4). This determined that the fire-resistance achieved by the floor in this configuration was significantly lower than when exposed from below, for periods of exposure greater than about 30 minutes.

The experiment reported in this paper is a continuation of the earlier series of experiments, and here uses an ISO 9705 standard "room" with timber crib fuel load, rather than the furnace driven to the AS 1530.4 time-temperature curve. The use of an ISO room represents a conventional, universal approach to testing at "full-scale". Here the behaviour of the floor was observed together with that of the room as a whole. The ISO room configuration permitted the performance of the floor to be directly compared to the performance of the room's ceiling (both assemblies being essentially of identical construction). Again, the fire-resistance achieved by the floor

in this configuration was significantly lower than it was when exposed from below, for periods of exposure greater than about 30 minutes.

In this experiment, wall, floor and ceiling finishes were not added. This would have added an unnecessary extra layer of complexity to the room fire.

This research was intended to investigate the validity of specific requirements in the New Zealand Building Code Acceptable Solution for Spread of Fire (issued 1 December 1995) which required the use of a non-combustible overlay on some fire-rated floors constructed of reconstituted wood products.

The subsequent revision of the New Zealand Building Code Acceptable Solution for Control of Internal Fire and Smoke Spread (effective from 1 June 2001) has removed this requirement. It states that floors need to be rated only on the underside, and floors constructed of reconstituted wood products are satisfactory provided they meet minimum thickness requirements.

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1. INTRODUCTION

This paper describes a research project carried out to investigate the behaviour of light timber-framed floors when exposed to a fire from above.

The New Zealand Building Code (NZBC) Acceptable Solution C3/AS1 (1995) [1], addressed the possibility that fire can spread downwards into a lower firecell through a timber floor by requiring non-combustible floor overlays to be used where the fire resistance rating is required to be 60 minutes or more. It is important to note that no performance requirements or verification methods existed to determine compliance with this requirement.

It was previously concluded by the author [2], that the purpose of the overlay provision is for the protection of occupants in the firecell immediately below the firecell of fire origin.

The revised New Zealand Building Code (NZBC) Acceptable Solution C/AS1 (2001) [3], has modified the requirements relating to wood and wood products in floors, stating that in any firecell which has a firecell below, the flooring may be of wood products provided the product used is no less than 20 mm thick.

The aim of this study was therefore to better understand the phenomenon of downward fire spread and its potential hazard in a real fire environment. The configuration of the experiment had a two fold purpose, to enable a correlation of the results to the previous fire tests, and to maintain relevance in terms of the fire resistance rating of the construction systems used.

It is important to note that in considering the performance of the floor exposed to fire, the experiment was not configured to assess the potential effects of furniture, wall and ceiling linings, or floor coverings on the fire development.

The fire load consisted of 500 kgs of untreated Radiata Pine cribs. This was calculated using M. Law's correlation (refer Appendix 1), to attain flashover and to achieve a fire resistance equivalent time of one hour. This equates to approximately 752 MJ/m² using a calorific value of 13.0 MJ/m² reported as adjusted by Thomas [4].

In terms of the Fire Load Energy Density (FLED), the BIA Acceptable Solutions [1 and 3] to the NZBC uses the following basic data for calculation.

Table 1: FLED data for basic calculations, abridged from BIA Fire Safety Annex Appendix A

Fire hazard category (purpose group is as given in Table A1)	Range of FLED (MJ/m²) (MJ fire load/ m² floor area)	Design value of FLED (MJ/m²) (80 percentile)
1	0 - 500	400
2	501 - 1000	800
3	1001 - 1500	1200
4	>1500	

The crib fire load as calculated falls neatly within the FLED range for a fire hazard category 2 building, and slightly below the 80 percentile design value.

Typical fire hazard category 2 buildings include:

- schools
- libraries
- nightclubs
- restaurants
- retail outlets
- banks
- medical offices
- radio stations.

2. TYPICAL TIMBER FLOOR/CEILING CONSTRUCTION

A typical timber floor construction in New Zealand consists of 20 mm thick sheets of reconstituted wood products (particleboard) over timber joists of dimensions and spacing determined by the span. Ceiling linings are typically sheets of fire rated paper-faced gypsum plasterboard secured directly to the underside of the joists.

The construction of the floor used in this research followed the plasterboard manufacturer Winstone Wallboards Ltd, GBFC 60 [5] documentation for the specification and installation of a 60-minute fire-resistant rated floor/ceiling assembly, and was built in accordance with NZS 3604 [6]. The floor/ceiling assembly consisted of 200 x 50 mm joists at 600 mm centres with solid strutting at 1800 mm centres and intermediate nogs fixed on flat at 600 mm centres. The 20 mm timber particleboard sheet flooring was nailed directly to the tops of the joists and a ceiling lining of 16 mm fire-resistance rated paper-faced gypsum plasterboard was screw-fastened directly to the underside of the joists.

3. CONSTRUCTION OF THE TEST ROOM

The room was built to comply with the dimensions of the ISO 9705 (1993) Standard Room Test [7]. The internal dimensions of the floor measured 3600 mm x 2400 mm, with a wall height of 2400 mm. A clear door opening in one of the short walls measured 800 mm wide x 2000 mm high. The door opening provided the only ventilation for the room. Construction of the test room complied fully with NZS 3604, 1990 [6], for light timber-framed construction. The floor, ceiling and walls were framed using standard number one grade framing timber as specified by NZS 3631, 1988 [8].

The floor and ceiling assemblies were essentially the same, 60 minute fire resistance rated systems described above. The floor varied only in that half of the gypsum ceiling lining below was removed for observation purposes. By making the construction of the floor and ceiling essentially the same, a direct comparison of their respective performance was possible.

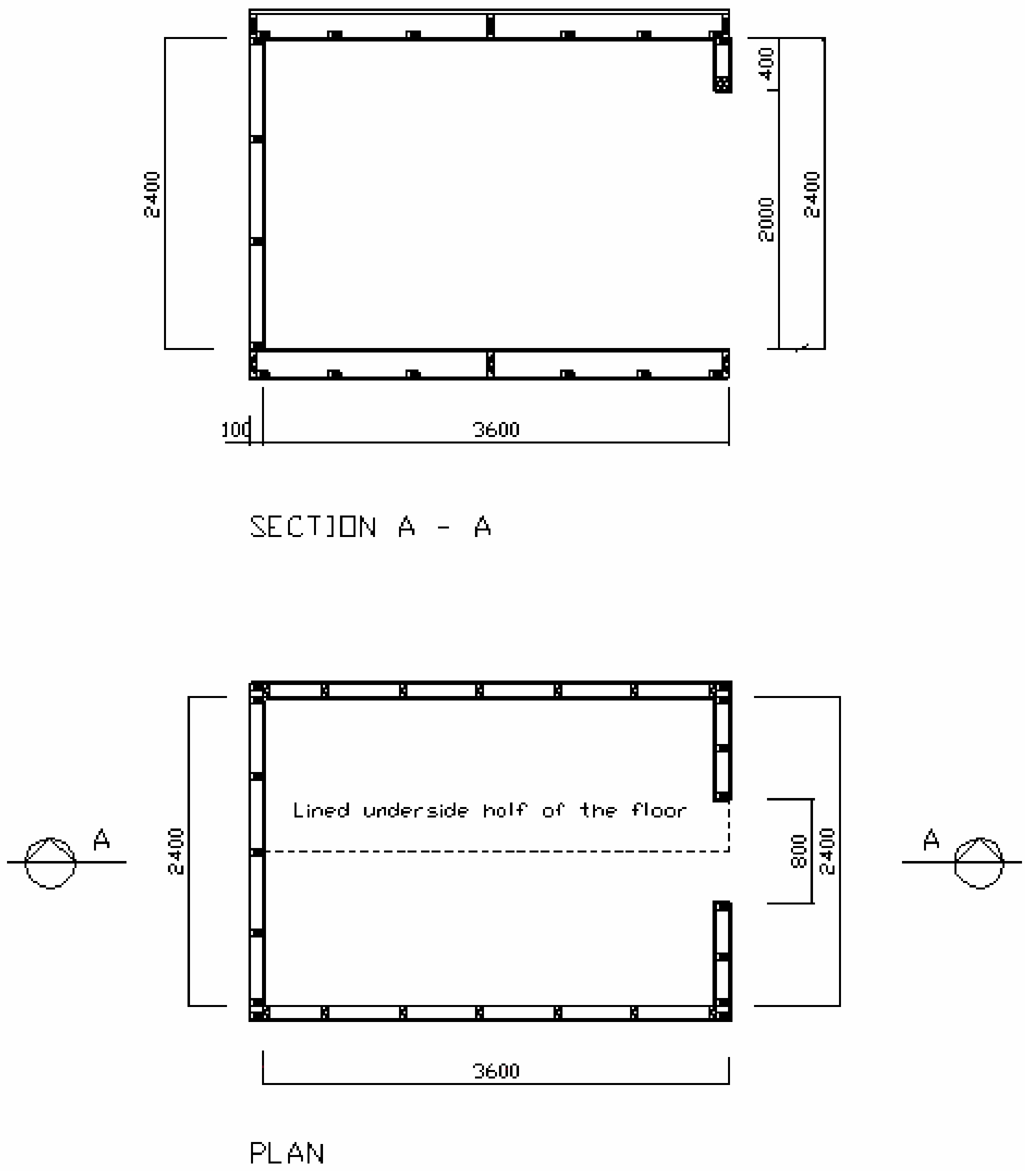

Figure 1: Plan and section drawings of the room construction

The walls consisted of ex 100 mm x 50 mm framing timber, studs at 600 centres and nogs at 800 centres. The walls were lined on both sides with 12.5 mm fire resistance rated gypsum plasterboard in accordance with the Winstone Wallboards Ltd, 60 minute fire resistance rated system GBTL 60 [5]. All fastener heads were stopped and sheet joints tape reinforced and stopped as per the manufacturer's specifications.

The room was constructed on a wheeled cradle in a self-contained construction annex. This allowed the room to be sheltered from the weather during construction, and then relocated outside for the actual test. During the construction period, the moisture content of the different timbers was monitored and stabilised to 12%.

4. FUEL

Timber cribs were used to provide the fuel load in this experiment. Cribs are described in the SFPE Handbook [9] as “regular, three dimensional arrays of sticks. Each stick is of a square cross-section and of a length much greater than its thickness.” The sticks are placed in rows of alternating orientation, with an air space separating horizontally adjacent sticks.

Cribs were chosen over a range of alternatives, including real furniture, and pool fires. Real furniture was disregarded in the development of the project as it would have led to uncertainties in its measurability in terms of fire load, and the degree of repeatability is by its very nature inherently less than that for timber cribs. Any furniture selected for the experiment would then limit the application of the results to scenarios with similar room contents. Cribs were chosen to provide the fuel because [10]:

- they provide the best simulation of burning furniture, at least for an observational point of view
- the interaction of cribs with the environment of the room is perhaps closer to, though not the same as, that of the burning furniture, and
- the crib’s radiation characteristics most closely match that of a furniture fire.

4.1. Fuel load

The key factor was to determine what size of fuel load would be necessary to achieve a 60 minute equivalent fire resistance time fire. The size of the fuel load was determined to be 500 kg using Law’s correlation [11]. (Refer to the calculation included in Appendix 1.)

Alternative correlations were evaluated, resulting in fuel loads ranging from 300 kg to more than 500 kg. The Law’s correlation (refer Appendix 1) was considered to be the most appropriate for application in this experiment as it was based on data from fully developed compartment fires where timber cribs were used as the fuel source.

4.2. Crib design

Design of the crib specification was reached on reference to the calculations for burning rates detailed in the SFPE Handbook [9].

Untreated, roughly sawn (i.e. not dressed) Radiata Pine sticks were used, with a final moisture content of 12% at the time of testing.

The basic stick dimensions were:

- Profile 25mm x 25mm
- Length 550mm
- Spacing 50mm

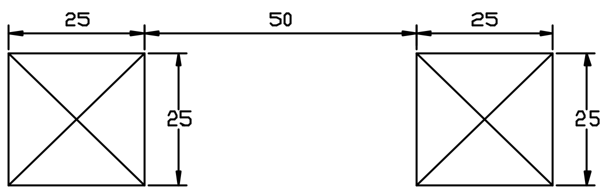

Figure 2: Crib stick dimensions and spacings

The crib configuration resulted in eight sticks per layer, with each crib constructed of 40 layers. This approximated to 50 kg for each crib set. A crib set consisted of two half cribs, which were divided horizontally for manageability.

The crib sticks were secured one to the next using air-powered steel-wire staples. The staples were estimated to contribute 400 g per crib and this value was taken into account when measuring the mass of each crib used in the final experiment.

4.3. Ignition of the crib

Ignition of a single crib (crib No.1 refer Figure 3), was achieved by placing a small paper towel (200 mm square) into the centre of the base. The towel was soaked in methylated spirits to ensure it would ignite readily and with sufficient energy to ignite the surrounding sticks, without unduly accelerating the burning rate. Ignition was achieved using a taper inserted from the side of the crib, between the lowest level of crib sticks.

5. LAYOUT OF THE ROOM

Cribs were placed symmetrically within the room, approximately 200 mm from the walls and with a spacing of 260 mm between each crib. This layout provided the following benefits:

- It created a symmetry of cribs in relation to the lining of the floor (refer Figure 3).
- There was clear space around the central thermocouple tree, such that direct flame impingement was unlikely until flashover occurred and there was therefore full room involvement.
- It permitted clear observation through to the back of the room from the door, which was particularly valuable in the initial phase.

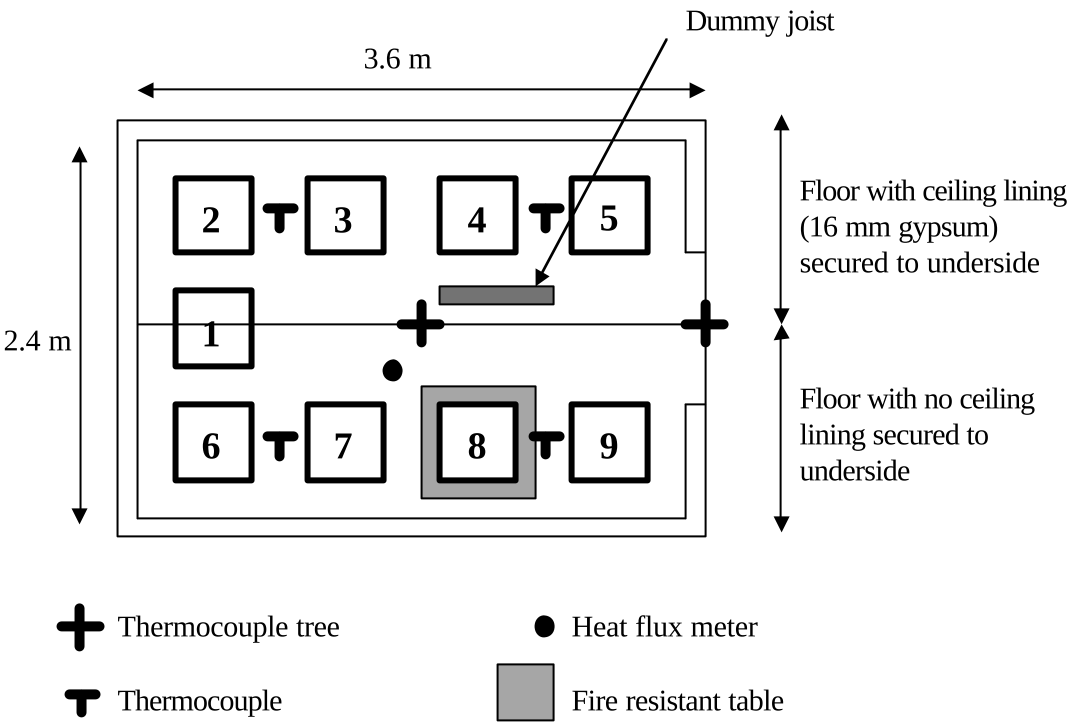

Figure 3: Diagrammatic layout of the room

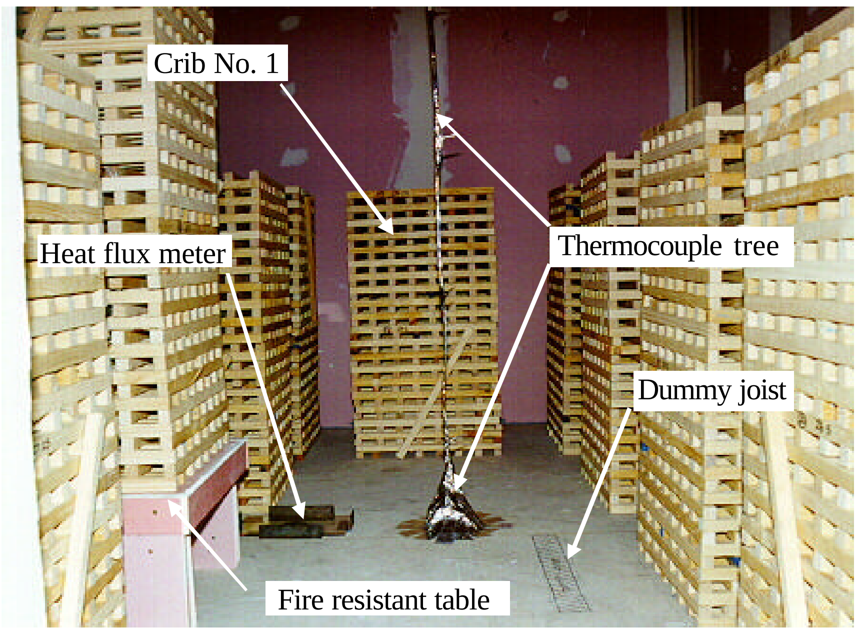

Figure 4: Room interior

5.1. Instrumentation

The principal instrumentation consisted of the following:

- disc thermocouples located on the back of exposed surfaces and within the floor and ceiling construction cavities (refer Figure 5 and Figure 6)
- two thermocouple trees suspended within the room, one in the centre and the other in the doorway (refer Figure 3)
- a heat flux meter set into the floor, as close to the centre of the room as was practicable
- a dummy joist placed into a lined floor cavity, as close to the centre of the room as was practicable. (refer Figure 3)
- two furnace-type thermocouples at the wall-ceiling junction (more robust than thermocouple trees to record flashover temperatures).

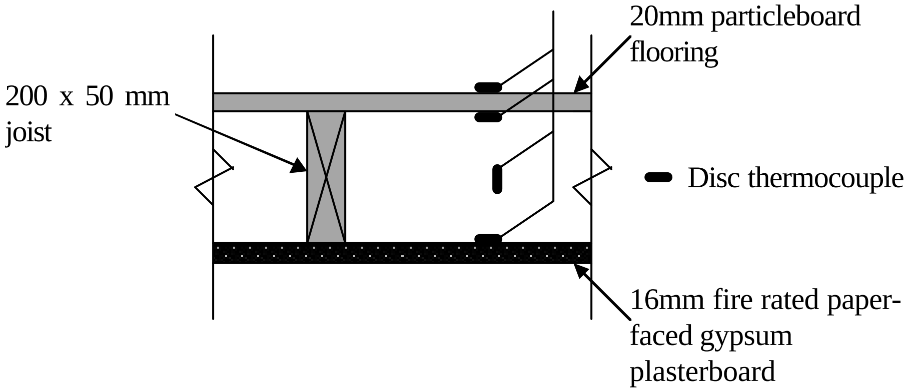

Figure 5: Room ceiling instrumentation layout

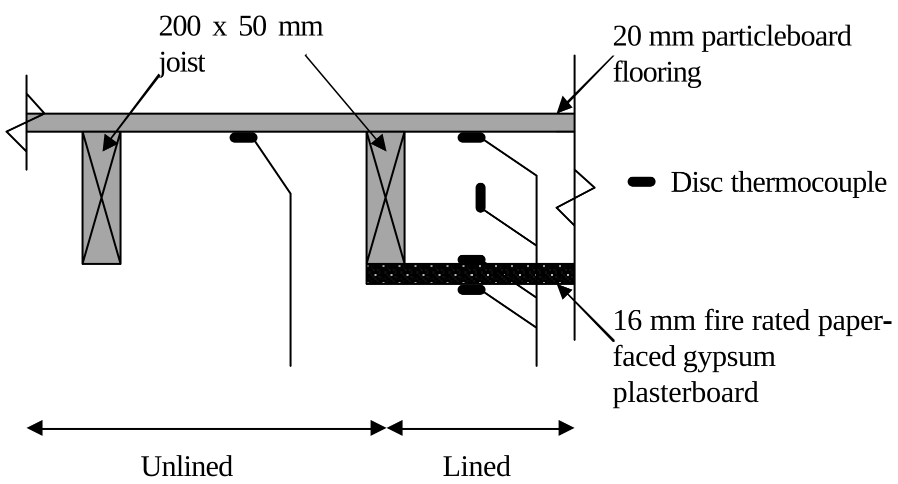

Figure 6: Room floor instrumentation layout

6. FAILURE MECHANISM

The first stage of failure is the complete charring of the particleboard flooring – this enables the fire to begin attacking the joists directly. It was assumed by this time that any large objects resting on the floor would either have been consumed by the fire before the particleboard failed or would be of sufficient dimensions to straddle the framework of joists and thereby be prevented from penetrating the ceiling lining sufficiently to fall into the lower fire compartment.

The second stage of failure is the collapse of the floor as a whole. At this stage the joists have been eroded by the fire to the point where they are unable to support themselves, let alone any objects being supported by them.

Any measurement in excess of 300°C was taken to indicate that the char front had reached the thermocouple.

7. EXPERIMENTAL RESULTS

7.1. Crib test burns

Two test burns were conducted to evaluate the performance of sample cribs, and to provide data on the expected performance of the cribs in relation to the floor (refer Figure 7). The tests, conducted in the open, proved that the cribs would have no difficulty in igniting the flooring; however after some 20 minutes, the crib would collapse to the floor. Within the collapsed crib, there remained sufficient fuel to continue to burn for another 20 plus minutes, albeit at a considerably slower rate.

It was concluded that the collapsed crib would actually slow the rate at which the flooring would be consumed, by shielding the floor from the higher levels of radiation present due to flaming within the room and effectively reducing the oxygen supply available. In a real fire, furniture or collapsed material can be expected to shield the floor; however this would only be in distinct areas. To explore this further in the full-scale room experiment, one crib set, crib No. 8 (refer Figure 3), was positioned on a fire resistant table 300 mm above the floor. The aim was to prevent the crib from collapsing directly onto the floor and thereby exposing the floor to the direct radiation from the flaming fire in the room as a whole.

Indicator sticks (refer Figure 7) were placed vertically at 200 mm intervals from one face of the sample cribs to check that fire spread by radiation was likely to occur.

Figure 7: Crib test burn

7.2. Full-scale room burn

The actual fire compares favourably with the ISO standard Temperature-time curve, (refer Figure 8), particularly when the temperature-time integrals are compared, (refer Figure 9).

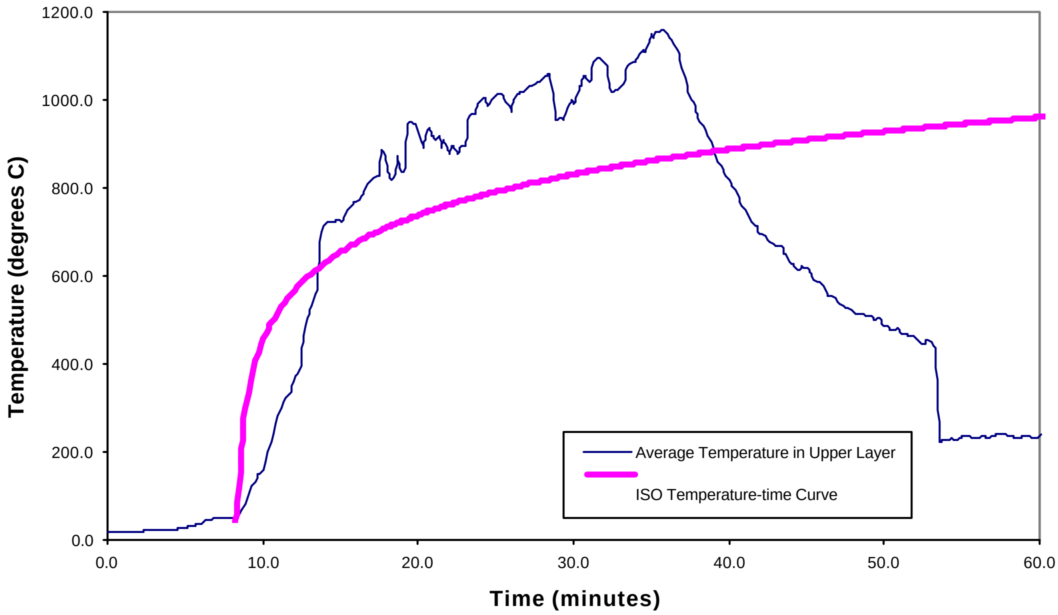

Figure 8: Graph of room fire curve vs ISO Standard temperature-time

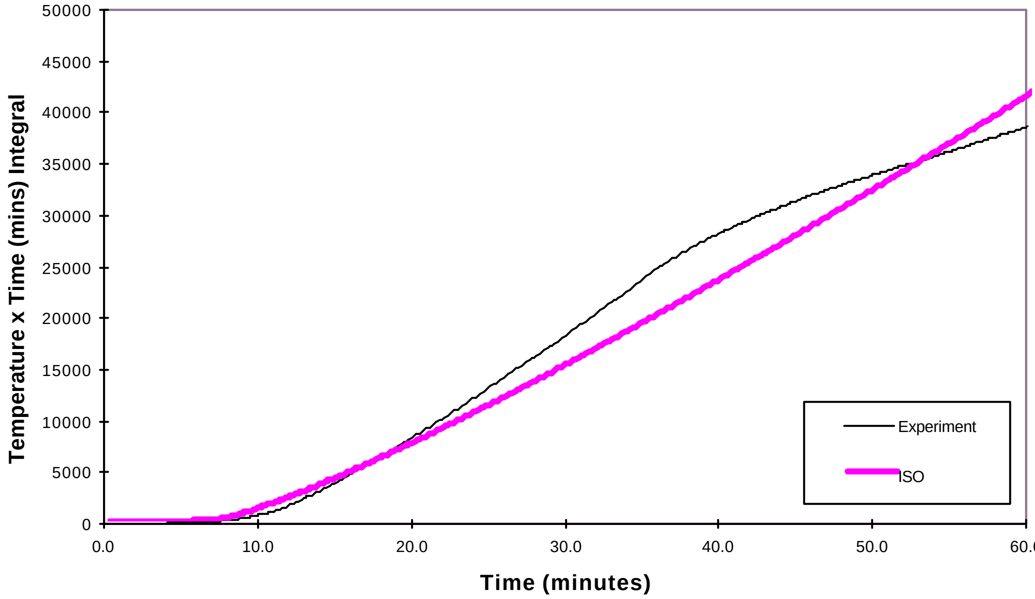

Figure 9: Comparison of the temperature-time integral for the room fire curve with the ISO Standard temperature-time curve

The temperature over time of the manually ignited first crib (crib No.1, refer Figure 3) was also measured. In both cases, thermocouples were positioned centrally in the cribs, 100 mm above the base. The fire growth within this crib compared extremely favourably with those of the crib test burns (refer Figure 10).

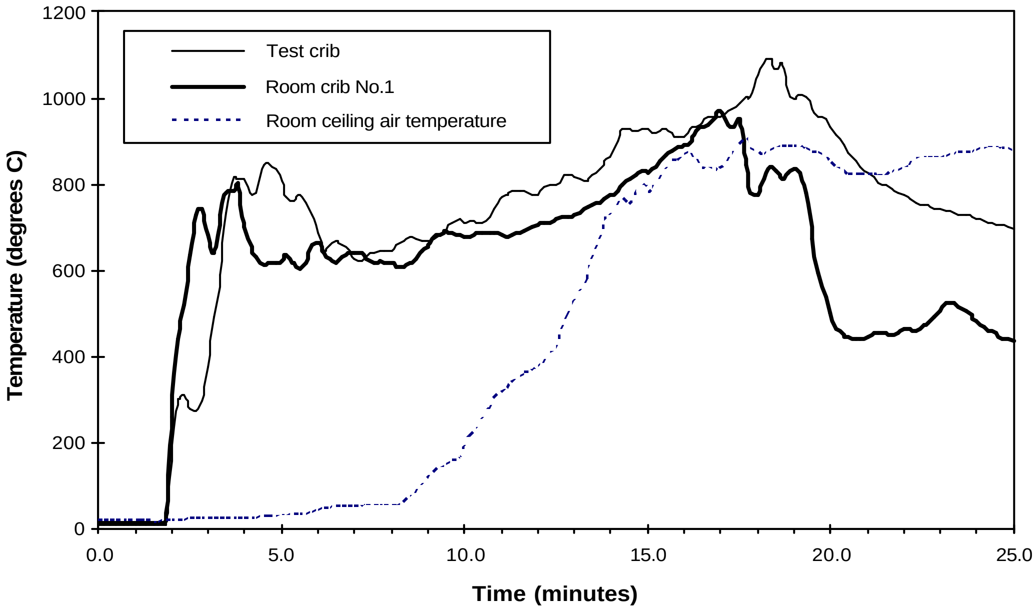

Figure 10: Temperature-time curves comparing test crib temperatures with those for the first crib ignited in the full-scale room test, Crib No. 1

The temperature-time curves of the test crib burns were shown to be remarkably close to that of the first crib ignited in the room burn, crib No. 1. The conditions varied between the two crib burns, one with improved ventilation, the other with radiative feedback. From the results, it would appear that these have either very nearly cancelled each other out, or had little overall effect on the burning rate.

Firstly, the test crib was burnt on a single sheet of particleboard, which was free standing within the main fire lab building. It therefore had good ventilation from all sides equally. The room burn crib was positioned 200 mm from the back wall of the room, facing the door. Ventilation was therefore predominantly from the one side only, that facing the door.

Secondly, in terms of radiative feedback, the test crib would have received very little compared to that of the crib in the room.

It is important to note that the data from the room crib relates to crib No. 1 only and no others. All other cribs became involved in the fire from the resulting radiative and convective heating conditions within the compartment.

In the full scale experiment, flaming was first observed to spread to the top of crib No. 3, as a direct result of radiative and convective heating within the room. This occurred 14 minutes and 30 seconds after crib No. 1 was ignited. This is consistent with the graph of room air temperature shown in Figure 10, and slightly later in the heat flux measurements shown in Figure 11. The fire continued to grow until full room involvement was achieved at 16 minutes and 30 seconds with the fire becoming ventilation controlled at this time. These observations are also consistent with the heat flux measurements. The apparent slight delay in the response of the heat flux measurements is largely attributable to the meter being located near the centre of the room (refer Figure 3).

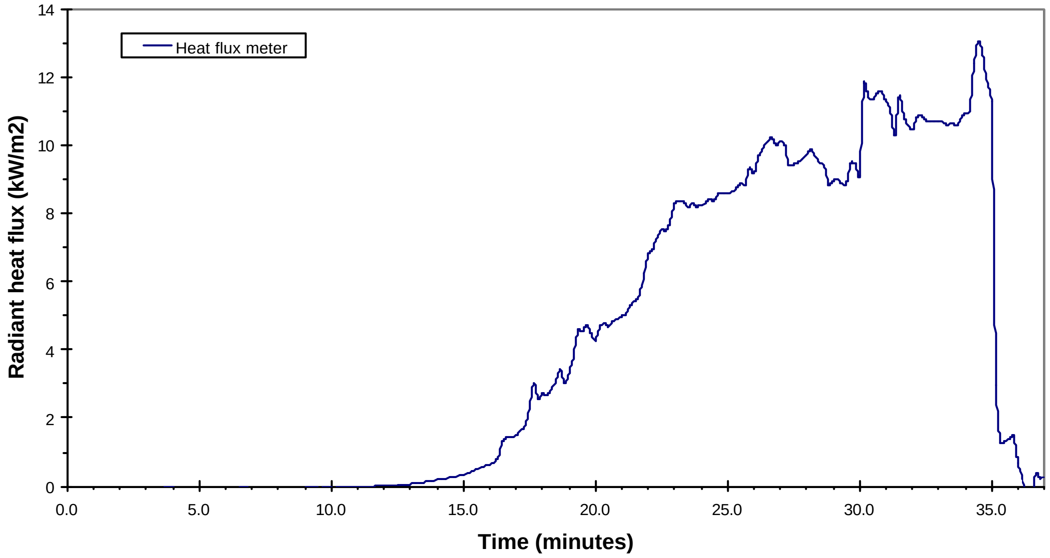

Figure 11: Heat flux meter readings

7.3. Physical results

As observed in the crib tests, when the structure of a crib failed due to the degree of its consumption by fire, the collapsed material protected the floor very effectively. At the conclusion of the full-scale experiment, after some 80 minutes, the particleboard directly under the cribs (over cavities 1 and 2, Figure 12) was charred to an average depth of 15 mm.

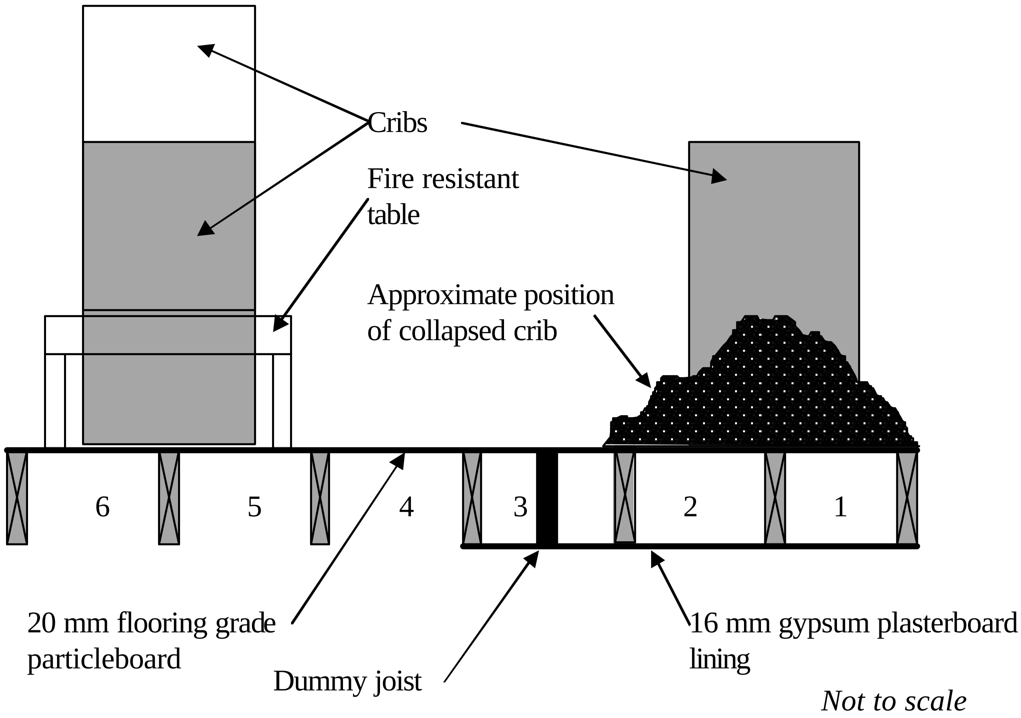

Figure 12: Diagrammatic section through room

There was no evidence of flaming within floor cavity No. 1, which showed no evidence of flaming having entered. The particleboard still retained some residual strength, the depth of charring varying from 5mm at the wall to 15mm over the joist separating cavity No. 1 from No. 2. There was some evidence of flaming having entered cavity No. 2, with the joist separating floor cavity No. 2 from No. 3 only slightly charred on the side facing into cavity No. 2, while the other joist showed considerable damage. Cavity No. 3 was significantly damaged. From both observation and the thermocouple recordings from the dummy joist, the particleboard floor over this cavity charred completely in little more than 30 minutes from the start of the experiment. The joists were significantly charred with an average of less than 10% good material remaining. The joists between cavity Nos. 4, 5, and 6 were likewise charred, resulting in the collapse of floor sections.

It is believed that the following factors were responsible for the path the fire took.

- The table raised one of the cribs off the floor – this prevented the collapsed material from protecting the floor. This increased the rate at which the fire was able to attack the particleboard over a larger area of floor. (refer Figure 12).

- Once the fire had broken through into a cavity with no ceiling lining, the ventilation conditions altered, not just in the immediate vicinity of the cavity, but also for the room as a whole. From this point the fire had the potential to attack both sides of the floor simultaneously. This situation could not occur in the other half of the floor while the lining remained in place. The lining effectively prevented this by maintaining a sealed cavity.

- A light breeze of around 1 m/s was recorded at the time of the test, approaching the door at 45 degrees in the direction of the fire resistant table. The breeze was never constant, and as such its real impact on the fire is difficult to quantify. All that can be said is that it was observed in the direction the smoke took on occasion during the early smouldering of the particleboard and in the subsequent flaming. It is possible that it influenced the direction the fire took, concentrating on the side of the table and crib Nos. 6, 7, 8, and 9 (refer Figure 3).

7.4. Analysis of instrument data

The first stage of failure of the flooring was recorded by the thermocouples located within in the lined section of floor (cavity No.2, Figure 12). After 31 minutes from the start of the experiment, the temperatures recorded by all thermocouples within the one floor cavity section increased rapidly to over 500°C. In reviewing what remained of the floor after the test, it is believed that the sudden temperature rise can be attributed to a small localised failure of the particleboard between collapsed mounds of cribs. The collapsed cribs continued to protect large sections of particleboard over cavity Nos. 1 and 2 (refer Figure 12).

The timing is consistent with the recorded observations made during the test. After approximately 31 minutes, embers were observed falling from the unlined section of floor (cavity Nos. 4 and 5, Figure 12). Embers continued to fall in increasing quantities from the unlined section of floor for the following four minutes. During this time the fire resistant table fell through the floor, between the remains of the floor joists. At 35 minutes, a large section of this half of the floor collapsed completely. The collapse of the floor modified the fire environment, significantly altering the ventilation conditions.

While the floor in this area had failed, this was not indicated by the thermocouples in cavity No. 4. It is suggested that the thermocouples were slower to record a rise in temperature as any flaming issuing from the room was not confined within the cavity by a lining (as it was for cavity No. 2), and therefore not carried to the thermocouples. Once a hole had developed, the altered ventilation conditions may well have increased the rate of combustion, and at the same time effectively cooled the underside of the floor as a result of rising cool air being drawn upwards into the room.

In the original experiments [2] carried out on the main fire furnace at BRANZ, the times for the particleboard to fail are very similar, suggesting that while the furnace created a more severe fire scenario, the results are valid. In these experiments, charring of the particleboard was deemed complete from 32 minutes. The time at which charring is deemed to occur is the time a particular thermocouple records temperatures in excess of 300°C (in this case thermocouples located on the back face of the particleboard).

The second stage of failure that of the floor structural elements, was recorded by the dummy joist. The joist began to char significantly from approximately 32 minutes, as the diagrams in Figure 13 illustrate.

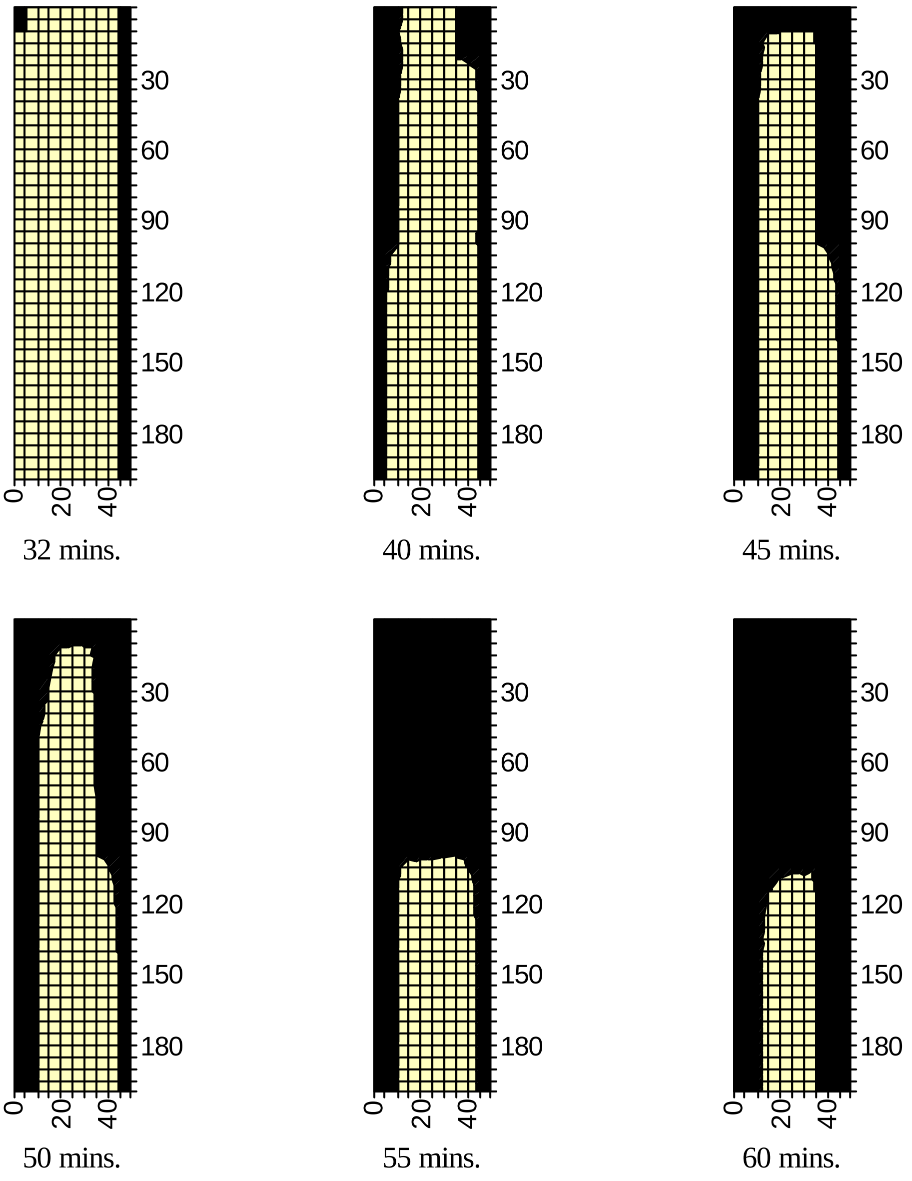

Figure 13: Dummy joist char diagrams

It is clear from Figure 13 that the structure of the floor was seriously compromised long before the 60 minute fire resistance rating of the floor/ceiling system was reached. It is also likely that had the floor been loaded with a larger fire resistant object, it would have failed more convincingly.

It is significant to note that the dummy joist was located within a lined floor cavity not covered with a crib set, (cavity No. 3, Figure 12). This section of floor did not become covered with collapsed crib debris during the course of the fire, and therefore remained fully exposed throughout the experiment.

7.5. Charring rates

Carrying out the experiment using a full-scale room where both the floor and ceiling were essentially of identical construction has provided much data on their respective performances. Analysis of the data is based on the assumption that temperatures of 300°C or greater indicate the onset of charring in timber members [11]. Charring rates have been calculated for the particleboard used in the floor and ceiling assemblies, and for the dummy joist located in the floor assembly (refer Figure 14). For the particleboard, the effective charring rate figures C_{ef} (mm/minute) were calculated as:

$$C_{ef} = \left(\frac{d_o}{\Delta t_{300}} \right) \tag{1}$$

where d_o is the original depth of particleboard, and Δt_{300} is the time for the back face temperature to read 300°C (completion time), measured from the time the exposed face first reaches 300°C (onset time). For the joists, charring was deemed to be complete when 300°C was recorded in the centre of the dummy joist, i.e. 50 mm wide joists were considered to be 100% charred when the temperature at a depth of 25 mm from each side exceeded 300°C. It was considered that the vertical orientation of the joist would mean that the fire would attack each side equally.

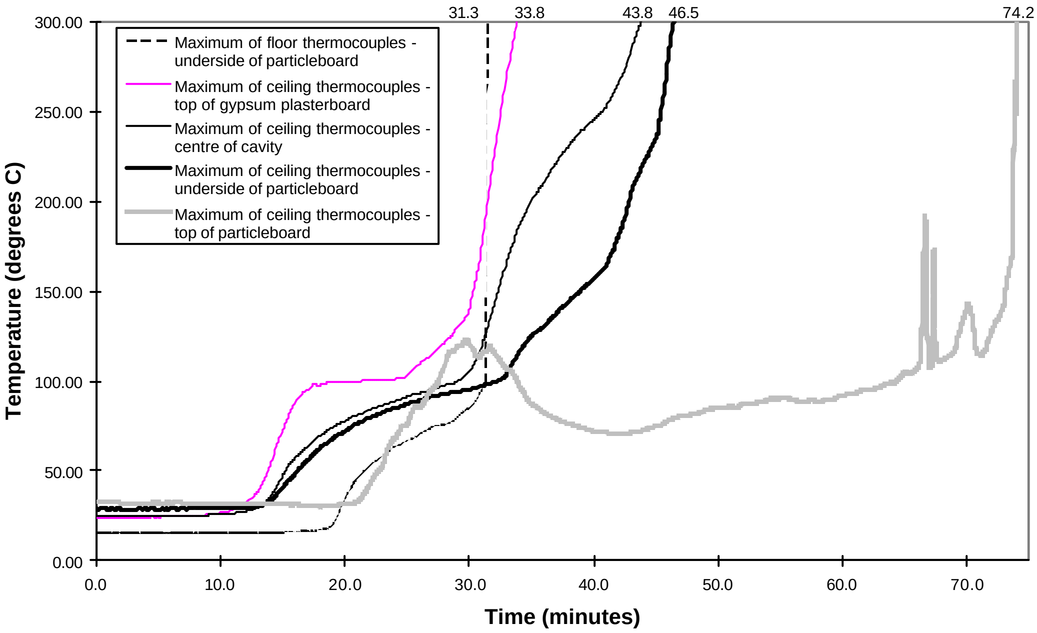

Figure 14: Maximum thermocouple readings, time to exceed 300°C

The charring of the particleboard on the floor of the test room occurred while the ventilation conditions remained unchanged. The charring of both the dummy joist and the particleboard on top of the ceiling assembly occurred after the ventilation conditions for the room as a whole had been altered by the collapse of the unlined section of floor. By this time, much of the crib material had been consumed, and from 38 minutes temperatures in the compartment fell to a plateau of around 450°C, until approximately 67 minutes, when involvement of the walls unduly modified the thermocouple readings.

Table 2: Calculated timber charring rates based on times for temperatures to exceed 300°C

Item		Location	Material	Charring			
			depth (mm)	Onset time (min)	Completion time (min)	Duration (min)	Rate (mm/min)
(a)	Particle-board	Floor	20	2 (estimated)	31.3 (1880 sec)	29.3	0.68
(b)	Particle-board	Ceiling	20	46.5	73.8 (4430 sec)	27.3	0.73
(c)	Dummy joist	Floor	25*	31.3	61 (3660-sec)	29.7	0.84

* *Half the 50 mm width of a joist*

The charring rates in Table 2 reflect the changing ventilation conditions within the room, occurring from 38 minutes.

The calculated charring rates were then applied to the joists in the ceiling assembly, and the estimated performance times compared to observations recorded during the experiment. The time for the onset of charring was taken to be 33.8 minutes, the time at which the first recorded temperature in the ceiling cavities exceeded 300°C.

Table 3: Estimated times for ceiling joists to completely char, based on the calculated charring rates in Table 2

Charring rate (mm/min) from Table 2		Material depth (mm)	Estimated duration (min)	Estimated time for 100% char (min)
(a)	0.68	25*	36.8	70.6
(b)	0.73	25*	34.2	68.0
(c)	0.84	25*	29.8	63.6

* *Half the 50 mm width of a joist*

The estimated times for the ceiling joists to completely char correlate well with observations of the experiment. The ceiling of the room collapsed at approximately 74 minutes. Taking the charring rate for the ceiling particleboard, the estimated time for a joist to char completely is 68 minutes. This is consistent with the observed time to ceiling collapse. This also fits with the 73.8 minutes recorded for the time at which temperatures first exceeded 300°C on the top (exterior) face of the ceiling assembly particleboard.

Hadvig [4] presents a simple method for estimating the charring rates, based on the internal surface area of the room and the area of the vertical opening. This method estimates the charring rate to be 0.76 mm/min (refer Appendix 4), consistent with the range determined from the experiment.

8. CORRELATION BETWEEN SMALL-SCALE AND FULL-SCALE EXPERIMENTS

In the original series of furnace-based experiments [2], the charring rate for the uncovered particleboard, when taking into account the initial delay time for the exposed surface to first reach 300°C, was calculated at 0.77 mm/min. This correlates well with the range of char rates calculated for the full-scale room experiment, (refer Table 2), and the Hadvig [4] estimate of 0.76 mm/min (refer Appendix 4).

The resulting times to first-stage failure of the floor are also very similar:

- Full-scale room experiment 31.3 minutes
- Full-scale furnace experiment 32 minutes

It is therefore considered that the results agree well enough for the original correlation between the small-scale cone calorimeter tests and the full-scale main furnace experiments to be proposed in modified form. These original experiments also evaluated the performance of some potential flooring overlay products:

- Fibre-cement board 6 mm
- Fire rated gypsum plasterboard 12.5 mm
- Calcium silicate board 12 mm

For each of these materials, thermocouples located on the underside of the particleboard recorded the time taken to exceed 300°C. These times are given in Table 4.

Table 4: Particleboard flooring performance enhanced by overlays, results from the full-scale furnace tests

Floor covering material (laid directly on particleboard)	Time to record 300°C on underside of particleboard. (minutes)	Effective delay in the time to record 300°C on underside of particleboard (minutes)
Particleboard (no overlay)	32	–
Fibre cement board	48	16
Calcium silicate board	60	28
Fire rated gypsum plasterboard	82	50

The correlation between the cone calorimeter results and those from the full-scale test is illustrated in Figure 15. This has been modified from that published earlier [2] using the particleboard result from the full-scale room experiment, in place of that from the full-scale furnace test. This has the effect of being slightly more conservative.

The cone calorimeter tests were carried out at an irradiance of 75 kW/m². Thermocouples located on the underside of the particleboard recorded the back face temperature as in the full-scale main furnace experiments, and times noted when the temperature exceeded 300 °C.

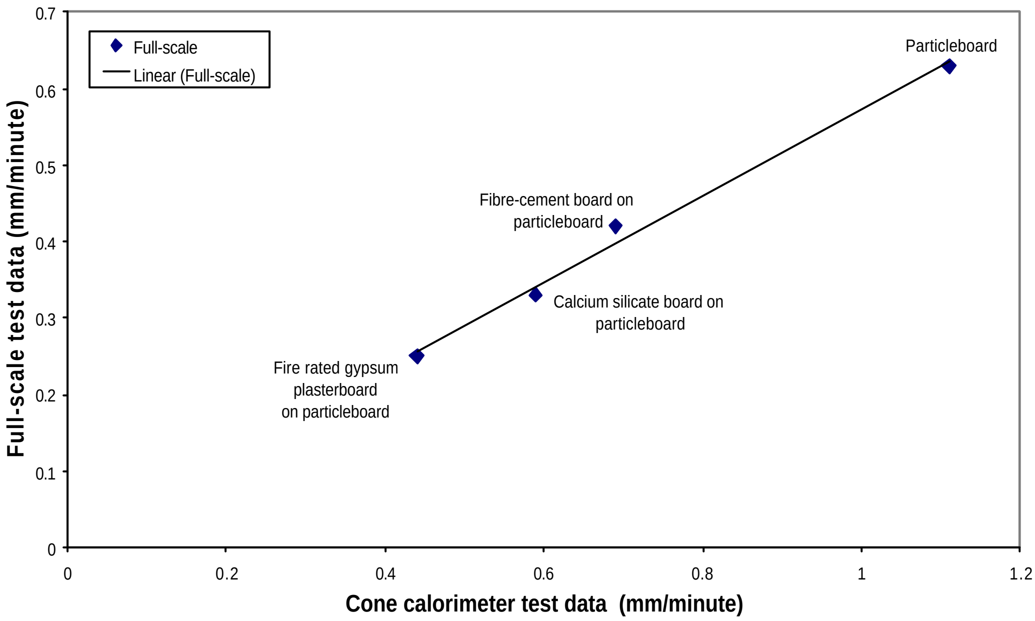

Figure 15: Correlation between the effective charring rates determined from the cone calorimeter and the full-scale furnace tests, taking into account the initial delay time to reach 300 °C on the exposed surface

The equation of the best fit line in Figure 15 allows the effective charring rate for the full-scale fire-resistance test C_{fr} (mm/min) to be estimated from the results of small-scale cone calorimeter tests. The equation of the best fit line is:

$$C_{fr} = 0.62 \times C_{cc} - 0.04 \tag{2}$$

Using the C_{fr} value it is possible to determine what depth of particleboard D_{pb} is necessary to prevent the fire from attacking the joists within the time specified by the required fire-resistance rating R_t (min) for the floor.

$$D_{pb} = R_t C_{fr} \quad \text{(only valid for } D_{pb} \le 20\,\text{mm)} \tag{3}$$

It is therefore proposed that if the value obtained for D_{pb} is less than the original thickness of particleboard, then it constitutes an “acceptable solution”. If however the value of D_{pb} is greater than the original thickness, an alternative overlay system is required.

A similar process is proposed to evaluate the performance of an overlay system. The charring rate can be measured for the complete overlay system (overlay + particleboard) using small-scale cone calorimeter tests. As before, the char rate at full-scale can be estimated using equation (2). An overlay system is deemed satisfactory if the original thickness of the overlay and particleboard D_o satisfies equation (4).

$$D_o \geq R_t C_{fr} \tag{4}$$

It should be noted that the equations provide an estimation for the duration of charring, not including the initial delay time for the exposed face of the particleboard to first reach the 300°C threshold. The initial time delay in the case of the main furnace experiment was eight minutes, while in the room experiment, it is estimated from crib temperature measurements to be two minutes.

As far as this experiment is concerned, the results indicate that there is no significant difference in the performance of the particleboard between the lined and unlined sections of flooring. This is consistent with the earlier full-scale furnace experiments.

9. COMPARISON BETWEEN THE PERFORMANCE OF THE FLOOR AND CEILING ASSEMBLIES

It is interesting to note the close proximity of the times at which 300°C was first exceeded within the cavities of the floor and ceiling assemblies. The floor reached this temperature at 31.3 minutes (1880 seconds) while in the ceiling it occurred at 33.8 minutes (2030 seconds). This temperature is deemed to signify the on-set of charring in timber. The critical point at this time is that for the floor – it indicates that the char front has progressed completely through to the underside of the particleboard, to the point where it is unable to carry any load. At the same time within the ceiling, temperatures within the cavity exceeding 300°C represent the onset of charring of the joists in the ceiling assembly. While the structure of the ceiling has begun to be attacked, unlike the floor, it remains capable of carrying loads imposed from the floor above well beyond 33.8 minutes.

The respective performances of the floor and the ceiling assemblies suggest that both will perform similarly in terms of providing a barrier to prevent fire from spreading beyond the room of origin, if they are completely unloaded. The floor performed better than the ceiling in the areas directly beneath the mounds of embers from the cribs; however the existence of these mounds cannot be relied upon.

After the particleboard was consumed by the fire, at 31.3 minutes, the effectiveness of the floor to maintain firecell separation becomes entirely dependent on the integrity of the gypsum plasterboard , the strength of its fastening system, and the structural integrity of the remaining joists supporting it. The firecell would be deemed to have failed if for example, any object not already consumed in the fire penetrated the gypsum plasterboard. The experiment would suggest that joists located in sections of the floor remaining clear of any debris are not likely to be capable of carrying load for the duration of the 60 minutes fire resistance rating.

10. CONCLUSIONS

In hindsight, it would have been more satisfactory to have the floor constructed with the lower "level" completely enclosed this would have prevented the ventilation conditions changing during the experiment. However, to apply the results from this experiment would only lead to a slightly increased conservatism.

The experiment illustrated that there is indeed an issue in regard to downward fire spread. While the Approved Documents (1995) [1] identified this matter with Acceptable Solution paragraph C3/AS1 2.16.1, the evidence would suggest that it is not essential for the "overlay" referred to in the text to be non-combustible. For example, simply increasing the depth of the particleboard would delay the point at which the joists begin to be attacked. The issue is one of strength. If the remaining floor retains sufficient residual strength to contain elements within the compartment of fire origin for the duration of the specified fire resistance rating, then it has performed its intended function.

Floor coverings will enhance the performance of the floor. Based on the earlier experimental work [2], it is estimated that some carpets will increase the fire-resistance of the floor by up to 10 minutes.

In a real fire, it is fair to rely on items of furniture to slow the rate at which the fire attacks the floor, just as the cribs protected the floor where they collapsed in the experiment. Furniture or collapsed material is however, highly unlikely, to entirely cover the floor. It is therefore considered essential to provide some additional passive fire protection to the floor in order for it to achieve the 60 minutes rating. If it is deemed necessary for the compartment to have a 60 minute fire resistance rating, then this should apply equally to the floor.

The aim of the experiment was to evaluate the performance of a fire resistance rated ceiling/timber floor assembly and to this end it clearly demonstrated there is a need to review the procedures for testing such assemblies for fire spread in both directions.

11. RECOMMENDATIONS

The existing test method has been demonstrated to be inadequate for determining the fire resistance rating of a floor/ceiling assembly in terms of downward fire spread.

Resulting from this research, it is recommended that the adequacy of a flooring material or overlay system be assessed by requiring the temperature on the underside of the flooring material to be kept below 300 °C, when exposed from above to conditions representative of a standard fire resistance test.

While fire spread in the downward direction is identified as an issue both in the Acceptable Solutions and in the work reported here, it does not appear to be a common occurrence in real fires. However, this does not mean downward fire spread should therefore be ignored. There is also a lack of comprehensive data from real fires, and this may contribute to the corresponding lack of data relating to fires where the fire has spread downwards through the floor. It is also worth noting that no manufacturer has a non-combustible overlay product designed and marketed for this application in New Zealand.

The current situation is likely to remain until sufficient real-fire data has been collected. Once it has, it will be possible to make some rational decisions about the seriousness of the threat of downward fire spread and the corresponding need for code provisions and corresponding fire tests.

12. APPENDICES

Appendix 1: Estimation of fire resistance time, M. Law's Correlation

M. Law's Correlation for estimation of the fire resistance time, t_f is given by [11],

$$t_f = K' \frac{M_f}{(A_w A_T)^{\frac{1}{2}}}$$

where:

K'	is a constant whose value is close to unity
M_f	is the total fire load (kg wood equivalent) (kg)
A_w	is the area of ventilation (m²)
A_T	is the total internal surface area of the compartment (m²).

Using the following input data:

t_f	=	60 minutes
K'	=	1
A_w	=	1.6 m²
A_T	=	43.5 m²

and solving for M_f results in an estimation that 500.6 kg of wood is required.

Appendix 2: Schedule of events in the room burn experiment

Time	Minutes	Notes
14:21	0	Crib No. 1 ignited
14:24	3	Flaming reaches top of crib No. 1
14:25	4	First visible smoke emitted from top of doorway
14:29	8	Flaming approximately 0.5 m above crib No. 1
14:29.5	8.5	Flaming reaches ceiling
14:31	10	Flaming still originating from centre of crib No.1, less than 50% of crib involved
14:33	12	Considerable flaming across ceiling, very clean smoke
14:34	13	Flaming now spread across top timbers of crib No.1
14:34.3	13.3	Flaming now reaches the sides of crib No.1
14:35	14	Charring visible on top sticks of crib Nos. 2 and 3 (from ceiling jet) Smoke layer through door has descended to 1700 mm above the floor, white to grey colour
14:35.5	14.5	Flaming on top of crib No.2, crib No.1 fully involved
14:36	15	Flaming on tops of all cribs, smoke blacker but remains thin
14:36.5	15.5	Smoke layer through door has descended to 1000 mm above the floor, thick black, back wall no longer visible
14:37	16	Entrained air visible drawing light grey smoke back into room at angle due to wind effects Flaming spreads across back half of floor, enveloping centre thermocouple tree
14:37.5	16.5	Full Room Involvement. Ventilation controlled, flaming beyond room. Thick black smoke issues from room. Smoke layer within room has descended to 300 mm above the floor
14:38	17	Flaming across entire floor
14:40	19	Considerable flaming extends beyond room, now pulsing. Smoke layer through door has risen to 900 mm above the floor.
14:42	21	Room lining material falls in small quantities.
14:44	23	Flames extend through the door up to 3 m above room ceiling, smoke comparatively clear
14:46	25	Whisps of smoke issue from the top of the walls/ceiling assembly junction
14:48	27	Crib No. 9 observed to collapse to floor across doorway
14:51	30	Failure of the particleboard flooring. Embers fall to ground from under the centre of the room

Time	**Minutes**	**Notes**
14:51.5	30.5	Considerable embers falling, hole in floor approximately 500 mm diameter. Ventilation conditions alter significantly
14:52	31	Ventilation condition changes noted in plume, flame extensions less
14:54	33	Large section of floor fails, damaging some instrumentation and taking the heat flux meter with it. Fallen material is extinguished to prevent further instrument damage.
14:54.5	33.5	Flaming externally declines to virtually nil, smoke colour changes to lighter grey/brown
14:56	35	All flaming within room
14:57	36	All cribs reduced to mounds of embers
14:59	38	Half of the floor (unlined side) has collapsed. Flaming breaks out under wall (unlined floor side)
15:02	41	Flaming confirmed in all wall cavities
15:20	59	Interior wall linings failing
15:26	65	Back wall linings fall
15:28.5	67.5	Flaming breaks through to exterior at centre of side wall (lined floor side)
15:29	68	Flaming breaks through to exterior of door wall. Ceiling collapses inwards in centre front (above door)
15:33	72	Ceiling assembly collapses in all but one rear corner
15:34.5	73.5	Ceiling collapses completely
15.37	76	Back wall collapses
15:40	79	Experiment stopped, fire extinguished

Appendix 3: Schedule of events in the crib test burn

Time	Minutes	Notes
1:48	0	Ignition of crib
1:54	6	Charring/soot visible on top sticks at centre of crib
1:55	7	Flaming extends above crib
1:56	8	Flaming spread to 3 stick bays from centre. Flaming extends 1 to 1.5 m above crib
2:01	13	Flaming reaches sides of crib, approximately 200 mm above floor
2:05	17	Charring visible on first indicator stick at 150 mm
2:06	18	Charring visible on second indicator stick at 300 mm Charring visible on third indicator stick at 450 mm
2:07	19	Charring visible on forth indicator stick at 600 mm First indicator stick ignites Flooring ignites
2:08	20	Crib collapses Second indicator stick ignites, burns slowly
2:15	27	Second indicator stick self-extinguishes
2:18	30	Experiment stopped, crib extinguished

Appendix 4: Charring-rate estimation method detailed by S. Hadvig

For vertical openings, such as windows and doors the geometrical opening factor, F, is defined as [4],

$$F = \frac{A\sqrt{h}}{A_t} \quad (\mathrm{m}^{1/2})$$

where:

A is the total area of windows, doors, and other openings in walls (m²).

A_t is the total internal area of the fire compartment, including floor, walls, ceiling, windows, and doors (m²).

h is the weighted mean value of the height of vertical openings, weighted against the area of the individual openings (m).

In this experiment:

$$F = \frac{2 \times 0.8\sqrt{2}}{(2.4 \times 2.4 \times 2 + 3.6 \times 2.4 \times 4)} = 0.05$$

Charring rates are given for a range of opening factors

Opening factor F	0.02	0.04	0.06	0.08	0.12	0.30
Charring rate (mm/min)	0.40	0.67	0.82	0.89	1.00	1.14

Interpolating the table for an opening factor of 0.05 results in a charring rate of 0.76 mm/min.

13. REFERENCES

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