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Document the Results of Full-scale Fire Tests in Houses

by

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Abstract

This report summarizes the results of a one-year project with the primary objective of documenting the results of six full-scale fire tests carried out on houses in Kemano BC in 2001. During the year, however, Forintek worked with a Ph.D. student at Carleton University to go beyond this objective and to compare the results of the experiments with the predictions of fire models.

These full-scale fire tests were conducted in order to assess the performance of wood-frame assemblies exposed to fire in furnished houses. The first item ignited in all tests was a waste-paper basket in contact with an item of upholstered furniture or a mattress. The fires were allowed to follow their natural course for a significant period of time without intervention by fire fighters so that the houses' wood-frame structures were challenged in a realistic fashion. Each experiment was instrumented to measure temperatures at up to 50 locations within rooms and building assemblies.

Observations taken onsite and a quick review of the raw data, allowed important conclusions to be drawn:

- Fire spread quickly from the waste-paper basket to upholstered furniture or mattresses. Subsequent fire development was rapid with flashover occurring rather early. The temperature in the room of fire origin got much hotter than in standard fire-resistance tests.
- Properly designed wood-frame walls and ceilings act as a significant barrier to fire spread.
- The contents of a house (in particular, upholstered furniture and mattresses) are more of a fire-safety threat than the wood-frame structure. In all fires, untenable conditions developed before the structure was involved in fire.
- In very large fires, a firewall provides a significant barrier to the spread of fire between two buildings of combustible construction.

A detailed analysis has also been undertaken whereby the fires were simulated using available fire models in order to assess whether the models give a good representation of real fires and of the performance of wood-frame assemblies. The results of this analysis, summarised below, were very encouraging.

- The predictions of Forintek's computer model WALL2D for the temperature between 15.9 mm fire-rated gypsum and wood studs in walls agreed very well with the measured values. Both experiment and theory demonstrated that fire-rated gypsum delays the involvement of studs in fire for a very long period of time.
- The predictions of BREAK1, a commercially available computer model, were very close to the times at which window glass was observed to crack.
- Using measured fire temperatures and a simple model, the rate of burning during the early stages of the fires, in which it was primarily a couch that was burning, was similar to that of upholstered furniture observed in a comprehensive European furniture study.
- A simple model for predicting the maximum temperature rise in a fire-room with closed doors and windows was found to give predictions in good agreement with the experiments.

This report summarises the findings of four of the six tests conducted in Kemano. Each of these four tests has, however, been studied in more detail than originally planned. Forintek scientists will continue to study the data from the Kemano fires. In particular, simulation of these fires using available computer models will continue. If fires in wood-frame structures can be modeled accurately, one can begin to assess the advantages and disadvantages of various design options. In the end, the computer models will be used to evolve recommendations on how to improve the fire-safety performance of housing.

Acknowledgements

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Forintek fire scientists are pleased to acknowledge the assistance of Carleton University whose involvement in the project ensured that the principle objectives were achieved. The efforts of Mr. Steve T. Craft, a Ph.D. student in Fire Safety Engineering at Carleton University, who undertook part of the work as a directed studies project, are particularly appreciated. Also appreciated is the interest and insight provided by Professor George Hadjisophocleous of Carleton University who jointly supervised Mr. Craft.

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1 Objectives

To document the results of six full-scale fire tests carried out on houses in Kemano, BC in 2001-2002.

2 Introduction

In Canada, more than 95% of one- and two-family houses, and most low-rise apartment buildings are of wood-frame construction. A recent review of Canadian and American fire loss statistics revealed that wood-frame housing constructed in compliance with current North American building codes is among the safest in the world (Richardson, 2001). The statistics suggest that fires involving a building's contents are the leading cause of fire deaths and that most of these deaths occur before the building's structure is involved in fire.

Nonetheless, from time to time, concern has been expressed that, since wood is combustible, its use as a building material compromises fire safety. While often erroneous, such concerns cannot be treated lightly. Consequently, Forintek has a long tradition of undertaking research to identify how wood building products can be used in the construction of fire-safe Canadian housing. In that vein, research undertaken at Forintek is reflected in building codes, and test and performance standards related to wood-frame construction in Canada and in those countries that are our major export markets, most notably the USA, Asia and Europe.

The high costs of conducting research has meant that Forintek has, for the most part, had to assess the fire performance of wood building products using laboratory tests in which the assemblies are relatively simple and small, and the fire exposure idealised. In recent years, Forintek has also been developing computer models to simulate fire growth and severity in a building, and to predict the ability of wood-frame walls and floors to withstand fire and inhibit fire spread through a building. This computer model development and validation has had to rely on data generated in laboratory tests.

The invitation to participate in the Kemano Public Safety Initiative (KPSI) offered Forintek the chance to test the predictive capabilities of its models when wood-frame assemblies are exposed to "real" fires in furnished houses. This was a unique opportunity that would have been impossible to envision without the invitation of the organisers of KPSI. The costs would have been prohibitive.

Forintek and its partners conducted six fire experiments at Kemano. The experiments were designed to establish large fires that would challenge the buildings' wood-frame structures. The first item ignited in all tests was a waste-paper basket in contact with a piece of upholstered furniture or a mattress. Fires were allowed to follow their natural course for a significant period of time without intervention by fire fighters. The objectives of these fire experiments were to monitor fire growth and smoke movement in houses; assess the fire resistance of gypsum-board-protected wood-frame walls and ceilings; assess the ability of masonry walls between row houses to limit fire spread from one unit to another; and assess the roles played by door openings, light fixtures, electrical-outlet boxes, bathroom ceiling-vents and heating ducts in the spread of fire and smoke within the houses.

This paper describes four of the experiments and presents much of the data generated. In addition, although not originally planned, the fires are being simulated on the computer in order to determine whether current fire models give a good representation of these fires and of the performance of wood-frame assemblies. Preliminary comparisons of the predictions of models and the experimental measurements are presented.

3 Background

Alcan established the village of Kemano, British Columbia (BC) in the 1950s and, by the early 1990s, provided housing for almost one hundred families. Residents of the town operated the company's powerhouse that provided the electricity required by its aluminium smelter in Kitimat. In recent years, the powerhouse was upgraded and, due to advances in technology, is now operated semi-automatically. As Kemano is in a remote location and is difficult to access and maintain, Alcan decided to close the village and to relocate its employees and their families. The last residents moved out in July of 2000 and rotating crews now operate the powerhouse.

With the co-operation of Alcan and the former residents of Kemano, the Office of the Fire Commissioner of BC and the Kitimat Fire Department initiated the Kemano Public Safety Initiative (KPSI). The KPSI was intended to provide the extremely rare opportunity to use the buildings in a modern town for firefighter training and fire-safety research. Firefighters from around BC were invited to participate in training exercises designed to improve their skills under real-world conditions. The National Research Council Canada (NRC) was invited to undertake research projects with the ultimate goal of improving the fire safety of Canadian housing. To make these training exercises and research projects as realistic as possible, residents from around BC donated furniture and household effects to furnish the empty houses.

In order to leverage its resources, NRC invited various industries to participate in KPSI under partnership arrangements. Forintek scientists immediately recognised that such participation would afford them the unique opportunity to assess the performance of wood products and wood-frame assemblies when exposed to fire in furnished houses as opposed to laboratory tests, and at minimal cost. It provided the opportunity to determine whether current models, developed at Forintek and elsewhere, give a good representation of such fires and of the performance of wood-frame assemblies. It would also allow Forintek to address criticisms levelled from time to time that wood-frame construction does not perform well in "real" fires.

As a consequence, Forintek accepted NRC's invitation to participate in KPSI. A research plan was prepared whereby Forintek in partnership with NRC and with the assistance of Weyerhaeuser Company would conduct a series of fire experiments in fully furnished houses in Kemano.

4 Staff

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5 Proposed Approach

The primary objective of this project was to document the results of the six full-scale fire tests carried out in houses in Kemano, BC in 2001-2002. Early in the fiscal year, however, it was learned that, to fulfill his requirements for his Ph.D. degree, Mr. S.T. Craft needed one additional course beyond what was being offered by Carleton University. To meet his needs, a directed studies project was designed whereby he would assess the ability of current models to predict the outcome of the six fire experiments conducted in Kemano. This offered Forintek the opportunity to go beyond the original objective of this project, which was to document the results of the tests, and to actually compare the results of the experiments with the predictions of models. Much of the work reported herein was undertaken by Mr. Craft under the joint supervision of Dr. Mehaffey and Prof. Hadjisophocleous at Carleton University.

6 Results and Discussion

Mr. Craft began working on his directed studies project in the spring and had completed his work by the end of the summer. Most of his findings were incorporated into a paper entitled "Fire experiments in furnished houses". Co-authored by J.R. Mehaffey, S.T. Craft, L.R. Richardson and M. Batista, the paper was presented by J.R. Mehaffey at the *4th International Seminar on Fire and Explosion Hazards* (4th ISFEH) September 8-12 in Londonderry, Northern Ireland. The paper, which will appear in the Seminar Proceedings, is appended to this report as Appendix I. A version of the paper was also presented by L.R. Richardson during the Research Review Session convened at the ASTM E5 meetings in Tampa Bay, December 7-10.

By January 2004, WALL2D, Forintek's model to predict the thermal response of a wood-stud wall exposed to fire, had been revised to address not just standard temperature exposures but fires with an arbitrary heating phase. As a consequence some of Mr. Craft's predictions were reworked. A paper entitled "Analysis of fire experiments conducted in wood-frame houses" written by J.R. Mehaffey, S.T. Craft and L.R. Richardson has been accepted for presentation at the 5th International Conference on Wood & Fire Safety to be held April 18-22, 2004 in the Slovak Republic. The paper builds on the paper presented at the 4th ISFEH and summarises the more recent progress made in assessing the ability of current models to predict the outcome of the six fire experiments conducted by Forintek in Kemano. This second paper, which will appear in the Conference Proceedings, is appended to this report as Appendix II.

A short overview of the comments of these two papers follows.

6.1 The first item ignited

The first item ignited in all six tests was a plastic waste-paper basket with diameter of 200 mm and height 300 mm. The lower 100 mm was filled with polyurethane chips and the upper 200 mm with shredded newspaper. A propane torch was used to ignite the contents through a hole near the bottom of the basket.

Following the experiments in Kemano, a similarly filled plastic waste-paper basket was ignited under a furniture calorimeter hood at the National Research Council. The peak flame height was 0.8 m and the average flame height 0.7 m (both measured from the top of the basket). The basket burned vigorously for one minute (from 40 seconds to 100 seconds after ignition) at a peak heat release rate of 30 kW.

In the Kemano tests, the waste-paper basket was placed in contact with an item of upholstered furniture or a mattress. Statistics suggest that ignition of upholstered furniture or mattresses by smokers' materials are the leading causes of deaths due to fire. In these tests, however, the interest was not in early fire development, but in quickly establishing a large fire that would challenge the house's wood-frame structure. In all six experiments, the fire moved quickly from the waste-paper basket to the upholstered furniture or mattress nearby.

6.2 Tests 1 and 2

Tests 1 and 2 were conducted in similar living rooms. In the original layout, each living room had doors to a corridor and a dining room, and a fireplace along one wall. Before running the tests, the doors and fireplace were blocked off by wood-stud walls protected by gypsum board. The floor of the "renovated" living room was a rectangle 3.4 m deep and 4.8 m long. The floor to ceiling height was 2.5 m.

In Test 1, the ceiling and walls were lined with regular gypsum board: the new walls with 12.7 mm board, and the old walls and the ceiling with 9.5 mm board. In Test 2, the ceiling and walls were lined with new, 15.9 mm fire-rated gypsum board.

The window to the living room comprised three panes: a central fixed pane 1.47 m x 1.42 m (high) and two sliding end-panes 0.55 m x 1.42 m (high). Each "pane" was, in fact, a double-pane. The end panes were removed to provide ventilation for the fire.

The contents of the two living rooms were as closely matched as possible, given the furniture had been donated. Included were a three-seater couch, a two-seater couch, an upholstered chair, two bookshelves with paper, a coffee table, a side table with a lamp, a television on a television stand, and a carpet.

In both tests, a waste-paper basket was placed in contact with the 3-seater couch and was ignited. A chronology of critical events in the two tests is provided in Table 1.

Table 1 Chronology of critical events in Tests 1 and 2

Event	Time in Test 1 (min:s)	Time in Test 2 (min:s)
Ignition of waste-paper basket	0:00	0:00
Room experiences flashover	2:40	4:00
Window cracks	3:05	4:30
Window falls out	4:15	5:15
Suppression commences	10:00	20:00

In Test 1, the 9.5 mm gypsum board began falling from the ceiling 2.5 minutes after ignition; that is, just before flashover. As the house had stood abandoned in a region with rainy winters, the board was likely moist. Suppression was initiated 10 minutes after ignition by breaking down a covered-over door. The sudden inflow of air caused temperatures in the room to drop. Water was applied to the fire 12.5 minutes after ignition.

In Test 2, 15.9 mm fire-rated gypsum board began falling from the ceiling 19 minutes after ignition. Suppression was initiated soon afterwards (20 minutes after ignition) through the open window and hence took much less time to complete.

6.2.1. Fire temperature and heat release

The fire temperatures were measured by a set of thermocouples at the geometric centres of the rooms. Although efforts were made to ensure the fires in Tests 1 and 2 were similar, the fire developed much faster; that is the fire temperatures climbed faster, in Test 1 than in Test 2. This resulted from the earlier involvement of the couch in Test 1. Following flashover, that is full-room involvement, the temperatures of the fires were strikingly similar and much hotter than the ISO 834 time-temperature curve.

An estimate was made of the rate of heat release throughout the fire using the fire temperature as input to simple analytical models. The findings suggest that, before and after flashover, the fire was not limited by the supply rate of air through the window, but by the maximum burning rate of the fuel (that is, the fire was fuel-surface controlled). In fact, before flashover, when only the 3-seater couch is burning, the heat release rate was similar to that observed for "quickly developing, high peak heat release rate" upholstered furniture in a European study (Sundstrom, 1995).

6.2.2. Breakage of windows

The times to glass breakage (cracking) were calculated using the computer model BREAK1 (Joshi, 1991) using the temperatures measured in the fire as input. The predicted and measured times for cracking of the inside pane of the windows are in good agreement as summarised in Table 2.

Table 2 Predicted and measured times for window cracking

Test	Predicted time (min:sec)	Measured time (min:sec)	Window fall out (min:sec)
1	2:35	3:05	4:15
2	4:00	4:30	5:15

The windows cracked earlier in Test 1 due to the more rapid temperature rise in that test. The fallout of the windows was likely governed by loss of strength of the aluminium frames at elevated temperatures than by the properties of the glass.

6.2.3. Performance of gypsum board

Forintek developed WALL2D (Takeda, 1998, 2003) to predict the thermal response of fire exposed wood-stud walls protected by fire-rated gypsum board. WALL2D computes heat transfer through and thermal decomposition of gypsum boards, wood studs, and glass-fibre or mineral wool insulation as well as the contraction of gypsum boards and opening of joints between boards. WALL2D's predictions for temperature profiles in wood-stud walls agree well with the results of standard fire-resistance tests.

WALL2D models fire exposures in which temperature increases monotonically following the ISO 834 curve or the analytical form $\Delta T_h = \beta\ t^{1/6}$ (Mehaffey, 1999). WALL2D had to be revised in order to simulate the fire exposure observed in Test 2, in which the temperature exhibits heating and cooling phases. However, it turned out to be a major revision to include a cooling phase. As a temporary measure then WALL2D was revised to model fire exposures in which the temperature increases monotonically following an arbitrary curve. To simulate Test 2 the measured temperature-time curve depicted in Figure 1 was approximated by the "straight-line" curve depicted in Figure 1.

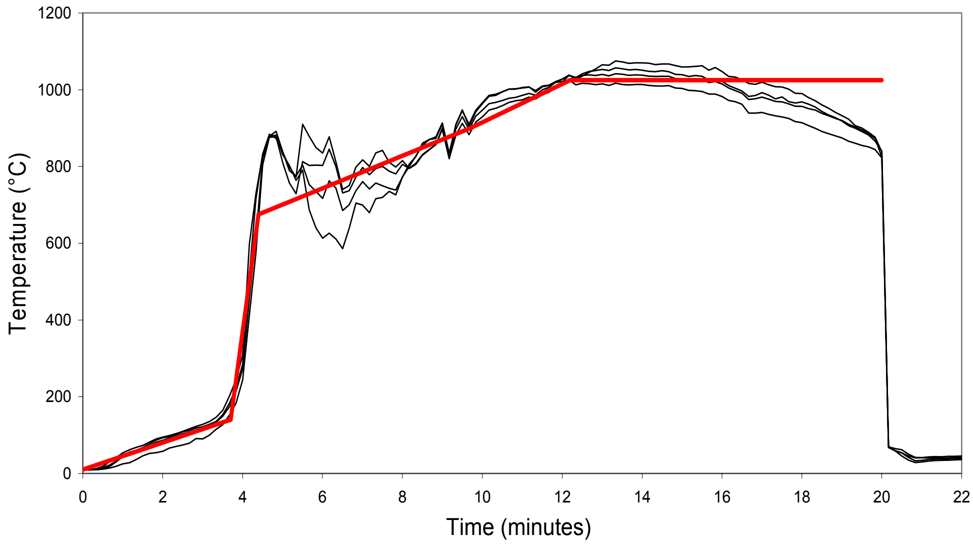

Figure 1 Approximation of the fire temperature measured in Test 2

WALL2D was used to predict the thermal response of the walls in Test 2. Figure 2 shows a typical comparison. The solid lines represent the temperature measured between the 15.9 mm fire-rated gypsum board and wood studs at two locations within the walls. The dashed line is model's predictions of the temperature at these locations assuming the fire exposure is given by the fit given in Figure 1.

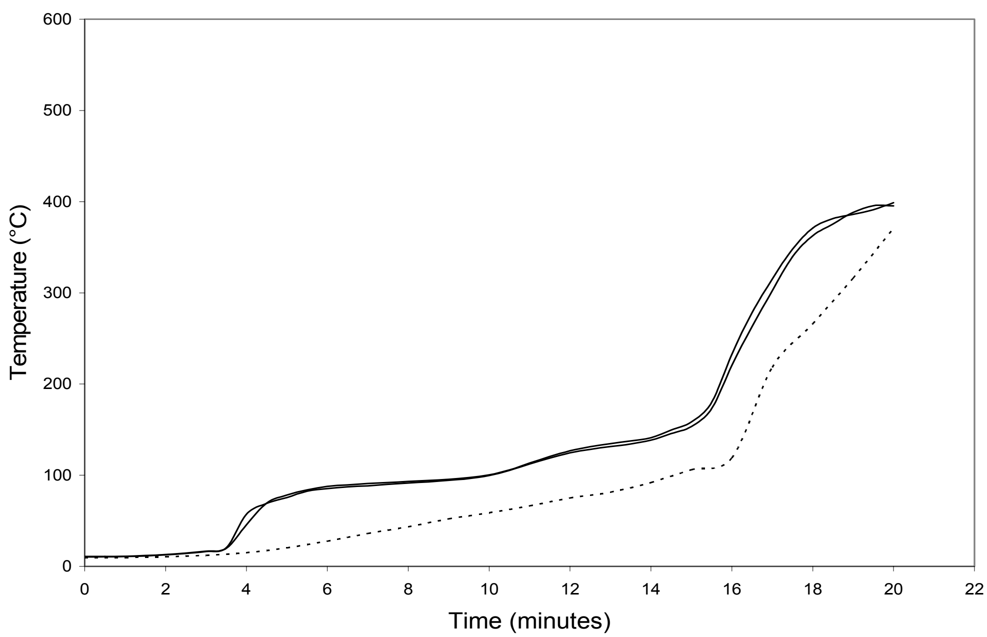

Figure 2 Comparison of predicted and measured temperatures within a wall in Test 2

The agreement between theory and measurement is quite good. The studs were well protected by the fire-rated gypsum board and contributed little if anything to the fire within the living room.

6.3 Test 3

6.3.1. Performance of concrete-block party wall

A bedroom on the second storey of a semi-attached house was fully furnished. Fire was started in a waste-paper basket in contact with a bed. The purpose of the test was to assess the ability of a concrete-block party wall to prevent or delay the spread of fire to the adjoining house. A chronology of events in the test is provided in Table 3.

Table 3 Chronology of critical events in Test 3

Time (min:sec)	Event
0:00	Ignition of waste-paper basket
4:15	Bedroom experiences flashover
6:15	Window falls out
6:30	Eaves above window ignite
15:15	Fire spreads to bedroom across the wall
17:25	Flames burn through roof
19:15	Fire stops at block wall
37:15	Fire drops to first storey
96:15	Fire spreads to roof on other side of party wall

The concrete block wall ran to the under side of the combustible roof sheathing and to the inside of the combustible façade. The roof sheathing and façade were continuous from one building to the other, as were the combustible eaves. Nonetheless it took over 1.5 hours for fire to advance from one side of the block wall to the other.

A favourable breeze likely prevented rapid fire spread from one unit to the other along the façade and eaves. Aluminium shingles on the roof inhibited fire spread on the roof because the shingles had to be melted first before flames could advance. This is a significant effect as many aluminium alloys melt at temperatures as high as 650°C. Nonetheless, the results suggest a firewall constructed of concrete blocks with a parapet and without continuous combustible elements connecting opposite sides of the wall provides a significant barrier to the spread of fire between two buildings of combustible construction.

6.4 Test 4

6.4.1. Impact of restricted ventilation

A basement recreation room was furnished with a 3-seater couch, a coffee table, a desk with a television on top, and a carpet covering the concrete floor. There were no windows in the room and the door was closed. The waste-paper basket was placed in contact with the 3-seater couch and was ignited. The temperatures recorded in the centre of the room are shown in Figure 3.

The fire showed a peak in temperature of 300°C about 6.25 minutes after ignition. By this time, much of the oxygen in the room had been consumed and only smouldering could be supported. Twenty minutes after ignition fire fighters opened the door. Temperatures recorded by the lowest thermocouples exhibited a drop in temperature as fresh air entered. Shortly thereafter the room experienced flashover.

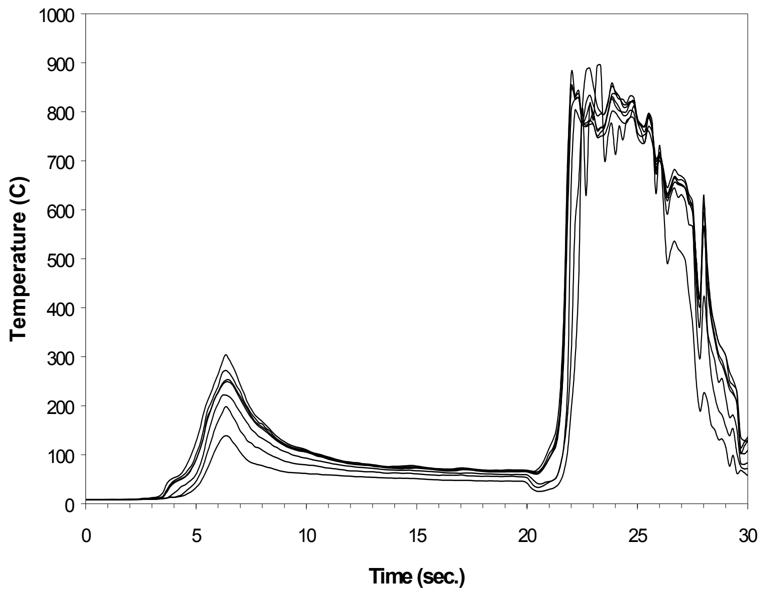

Figure 3 Temperatures measured in fire in a basement recreation room

A model (Mowrer, 1999) was employed to predict the maximum temperature rise in the fire assuming no oxygen entered the fire room. It was assumed in the model that the fraction of heat lost to room boundaries was 0.75, midway between Mowrer's recommended range of 0.6 to 0.9. The agreement between the predicted and measured value of temperature rise (290°C) was extremely encouraging.

7 Conclusions

This report summarizes the results of a one-year project to document the results of six full-scale fire tests carried out on houses in Kemano, BC in 2001-2002. Early in the fiscal year, however, a directed studies project was designed for a Carleton University Ph.D. student, Mr. S.T. Craft, whereby he would assess the ability of current models to predict the outcome of the six fire experiments conducted in Kemano. This offered Forintek the opportunity to go beyond the original objective of this project and to actually compare the results of the experiments with the predictions of models.

Observations taken onsite and a quick review of the raw data, allowed important conclusions to be drawn:

- During the experiments, fire was observed to spread quickly from the waste-paper basket to upholstered furniture or mattresses. Subsequent fire development was rapid with flashover occurring rather early. The temperature in the room of fire origin got much hotter than in standard fire-resistance tests.

- Properly designed wood-frame walls and ceilings can act as a significant barrier to fire spread.
- The contents of a house (in particular, upholstered furniture and mattresses) are more of a fire-safety threat than the wood-frame structure. In all fires, untenable conditions developed before the structure was involved in fire.
- In very large fires, a firewall provides a significant barrier to the spread of fire between two buildings of combustible construction.

A detailed analysis of the data has also been undertaken whereby the fires were simulated using currently available fire models. This analysis has intended to assess whether the models give a good representative of these six real fires and of the performance of wood-frame assemblies exposed in these fires. The results of this analysis, summarised below, were very encouraging.

- Using measured fire temperatures as input, Forintek's computer model WALL2D was employed to predict the temperature between 15.9 mm fire-rated gypsum and wood studs in the walls of one of the houses. The agreement between the predicted temperatures and measurement was very good. Both experiment and theory demonstrated that the studs were well protected by the fire-rated gypsum board despite the very high temperatures attained in the fire. In fact, the studs did not contribute to the severity of the fire before suppression commenced.
- Using measured fire temperatures as input, a commercially available computer model BREAK1 was employed to predict the time at which windows cracked in two of the experiments. Despite the lack of detailed information about the properties of the window's glass, the predictions of BREAK1 were very close to the times at which window glass was observed to crack.
- Using measured fire temperatures and geometrical properties of the fire room and windows as input, an analytical model was employed to predict the heat release rate in one of the fires. The prediction during the early stages of the fire, in which it was primarily a couch that was burning, was reminiscent of the performance of upholstered furniture observed in a comprehensive European furniture study.
- An analytical model was employed to predict the maximum temperature rise in one of the fires assuming no oxygen entered the fire room. The agreement between this prediction and the measured value in an experiment in which the room had no windows and its door was closed was very good.

This report summarises the findings of only four of the six tests conducted in Kemano. Each of these four tests has, however, been studied in more detail than originally planned. It is anticipated that Forintek scientists will continue to study the data from the Kemano fires in subsequent years. In particular, simulation of these fires using available computer models will continue. If fires in wood-frame structures can be modeled accurately, one can begin to assess the advantages and disadvantages of various design options. In the end, the computer models will be used to evolve recommendations on how to improve the fire-safety performance of housing.

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Appendix I

Fire Experiments in Furnished Houses

FIRE EXPERIMENTS IN FURNISHED HOUSES

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ABSTRACT

Six fire experiments were conducted to assess the performance of wood-frame assemblies exposed to fire in furnished houses. The first item ignited in all tests was a waste-paper basket in contact with upholstered furniture or a mattress. Fires were allowed to follow their natural course for a significant period of time without intervention by fire fighters so that the houses' wood-frame structures were challenged in a realistic fashion. Each experiment was instrumented to measure temperatures at up to 50 locations within rooms and building assemblies. During the experiments, fire spread quickly from the waste-paper basket to a piece of upholstered furniture or a mattress. Subsequent fire development was rapid with flashover occurring within a few minutes. The test data allow several important conclusions to be drawn. Properly designed wood-frame walls and ceilings can act as a significant barrier to fire spread. The contents of a house (in particular, upholstered furniture and mattresses) are more of a fire-safety threat than the wood-frame structure. In all fires, untenable conditions developed quite a while before the structural members were involved in fire. A detailed assessment of the test data is underway. The fires are being simulated on the computer in order to determine whether current models give a good representation of these fires and of the performance of wood-frame assemblies in these houses. Preliminary comparisons of the predictions of models and the experimental measurements are presented.

INTRODUCTION

In Canada, more than 95% of single-family and two-family houses are of wood-frame construction. A recent review (1) of statistics revealed that fires involving household contents are the leading cause of fire deaths in houses and that most of these deaths occur before the house's structure is involved in fire. Nonetheless, concern is often expressed that, since wood is combustible, its use as a structural building material compromises fire safety. In response to this concern, Forintek undertakes research to identify how and where wood products can safely be used in the construction of housing. The high cost of conducting research has meant that the fire performance of wood products is usually assessed in laboratory tests in which assemblies are simple and small, and the fire exposure is idealised.

Kemano, a small "company town" in Canada, was recently closed and some of its buildings made available for research. In partnership with researchers at the National Research Council Canada (NRC) and with the assistance of Weyerhaeuser Corporation, Forintek accepted an invitation to undertake research in the town. This afforded the unique opportunity to assess the performance of wood-frame assemblies when exposed to fire in furnished houses as opposed to in laboratory tests.

Six fire experiments were conducted. The experiments involved large fires that challenged the houses' wood-frame structures. The first item ignited in all tests was a waste-paper basket in contact with a piece of upholstered furniture or a mattress. Fires were allowed to follow their natural course for a significant period of time without intervention by fire fighters. The objectives of these fire experiments were to monitor fire growth and smoke movement in houses; assess the fire resistance of gypsum-board-protected wood-frame walls and ceilings; assess the ability of masonry walls between row houses to limit fire spread from one unit to another; and assess the roles played by door openings, light fixtures, electrical-outlet boxes, bathroom ceiling-vents and heating ducts in the spread of fire and smoke within the houses.

This paper describes four of the experiments and presents some of the data generated. A detailed assessment of the test data is underway. The fires are being simulated on the computer in order to determine whether current models give a good representation of these fires and of the performance of wood-frame assemblies. Preliminary comparisons of the predictions of models and the experimental measurements are presented.

THE FIRE TEST PROGRAM

A brief description of the objectives of and experimental set-up for four of the experiments conducted in Kemano follows.

Test 1

A living room on one side of a semi-detached house was fully furnished, and the ceiling and walls lined with regular gypsum board. Windows were left partially open and doors to the living room closed in. Fire was started in a waste-paper basket. The purpose of the test was to assess the ability of wood-frame assemblies protected by regular gypsum board to contain a real-world fire in the room of fire origin.

Test 2

Test 2 was similar to Test 1 except that the ceiling and walls of the living room were lined with fire-rated gypsum board. The purpose of the test was to assess the ability of wood-frame assemblies protected by fire-rated gypsum board to contain a real-world fire in the room of fire origin. There was also the intention to generate data in a real-world fire in order to validate computer models developed at Forintek to predict the thermal response of fire-rated wood-frame assemblies.

Test 3

A bedroom on the second storey of a semi-attached house was fully furnished. The window was left partially open and the door to the corridor was open. The ceiling and walls were lined with regular gypsum board. Fire was started in a waste-paper basket. The purpose of the test was to assess the ability of a concrete-block party wall to prevent or delay the spread of fire to the adjoining house.

Test 4

A recreation room in a house was fully furnished. There were no windows in the room and the door to the room was closed. The ceiling and two interior walls were lined with regular gypsum board and the two walls in contact with the concrete basement were lined with 6 mm plywood on furring strips. Fire was started in a waste-paper basket. The purpose of the test was to assess the ability of regular gypsum board to protect the wood-joist ceiling in a ventilation-starved basement fire.

The First Item Ignited

The first item ignited, in all six tests was a plastic waste-paper basket with a diameter of 200 mm at the base and a height of 300 mm. The lower 100 mm of the basket was filled with polyurethane chips and the upper 200 mm with shredded paper. A hole was made in the side of the basket near the bottom and a propane torch was used to ignite the contents through the hole.

Following the experiments in Kemano, a similarly filled plastic waste-paper basket was ignited under a furniture calorimeter hood at NRC. The peak flame height (above the top of the basket) was 0.8 m. The average flame height was 0.7 m above the top of the basket or 1.0 m above the bottom of the basket.

A brief chronology of events in this test is provided in Table 1.

Time (min:sec)	Event
0:00	Ignition of polyurethane chips by propane torch
0:15	Brownish smoke plume rises above the basket
0:40	Shredded paper suddenly bursts into flames
1:30	Side of waste-paper basket begins to melt
1:40	Waste-paper basket collapses and fire intensity reduces

Table 1. Chronology of events: Waste-paper basket fire

Fig. 1 depicts the heat release rate of the burning basket as a function of time. The waste-paper basket burned vigorously for about one minute (from approximately 40 seconds to 100 seconds). During this minute of vigorous burning the rate of heat release was close to 30 kW.

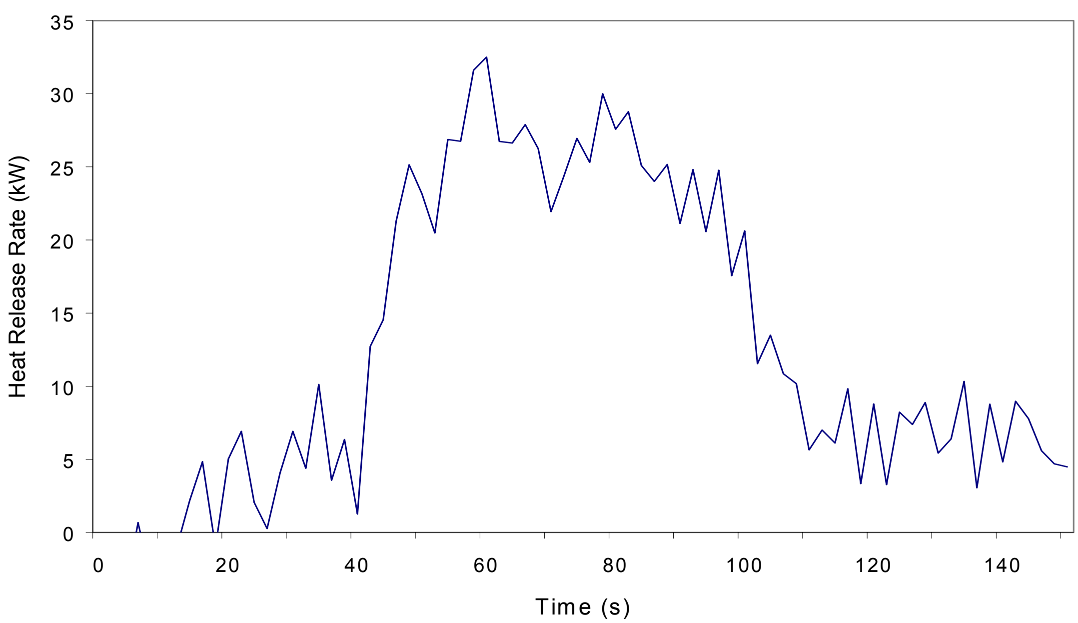

Figure 1. The heat release rate of the waste-paper basket fire

In the tests conducted in Kemano, the waste-paper basket was placed in direct contact with a piece of upholstered furniture or a mattress. Statistics suggest that ignition of upholstered furniture or a mattress by smokers' materials is the leading cause of deaths due to fire. In fact, smouldering cigarettes are the most common ignition source in fires in which upholstered furniture or a mattress is the first item ignited. In this test series, the interest was not so much in early fire development, but in establishing, relatively quickly, a large fire that would challenge the building's wood-frame structure.

It can be inferred from Fig. 1 and Table 1 that, in Kemano, the waste-paper basket would also have burned vigorously for only about one minute. This was sufficient for the fire to spread quickly from the waste-paper basket to the upholstered furniture or mattress.

Instrumentation

The most direct route from Ottawa, where Forintek's Fire research Group is located, to Kemano is to fly 4000 km to Vancouver; fly another 600 km to Terrace; take a one hour bus ride to Kitimat; and take a 3 hour ferry ride to Kemano's docks; and finally a ½ hour truck ride to the town.. Building materials (gypsum board and wood studs) had to be shipped in from Kitimat.

The opportunity to undertake fire experiments in real houses was too appealing to pass up. However, the logistics of conducting experiments in a difficult to access, remote location presented numerous challenges. Furthermore, the buildings had to be instrumented and the six tests conducted within a two-week period. Consequently the type and level of instrumentation had to be kept simple.

In all experiments, at least one thermocouple tree was placed in the room of fire origin and in several experiments, thermocouple trees were placed in neighbouring rooms and in an attic space above the room of fire origin. Each thermocouple tree comprised a vertically oriented string of thermocouples located 150, 300, 450, 600, 900, 1200, 1500 and 1800 mm below the ceiling. The time-dependent temperature profile throughout the depth of various wood-frame assemblies (walls and/or ceilings) was also measured by thermocouples placed within those assemblies.

TESTS 1 AND 2: PERFORMANCE OF GYPSUM BOARD

Experimental Setup

Tests 1 and 2 were conducted in two living rooms that were mirror images of one another, situated on opposite sides of a party wall in a semi-attached house. In the original building layout, each living room had doors to an entrance corridor and to a dining room, and had a fireplace on the wall opposite the party wall. Before running the tests, the doors and fireplace were blocked off by wood-stud walls protected by gypsum board. The floor of the "renovated" living room was a rectangle 3.4 m deep and 4.8 m long. The floor to ceiling height was 2.5 m.

The difference between the two living rooms was the interior finish. In Test 1, the ceiling and walls in the living room were all lined with regular gypsum board: the new walls with 12.7 mm board, and, as it was discovered following the test, the old walls and the ceiling with 9.5 mm board. When the house was constructed in the 1950s, the use of 9.5 mm regular gypsum board was not common for most housing. However, these houses were constructed in sections and after transport to Kemano, assembled. Weight mattered; hence the thinner gypsum board. In Test 2, the original gypsum board was removed, and the ceiling and walls in the living room were lined with 15.9 mm fire-rated gypsum board. The floor in both Tests was lined with carpet over a sub-floor of wooden boards.

The window to the living room comprised three panes: a central fixed pane 1.47 m x 1.42 m (high) and two sliding end panes each 0.55 m x 1.42 m (high). Each “pane” was, in fact, a double-pane. The top of the window was 570 mm below the ceiling. Before the tests started, the sliding end panes were removed to provide ventilation for the fire.

The two rooms were then furnished as indicated in Table 2.

Item No.	Description of Item	Mass
1	Couch (3 seats)	40 kg
2	Couch (2 seats)	32 kg
3	Bookshelf + paper	16 kg
4	Small table + lamp	2 kg
5	Bookshelf + paper	36 kg
6	Television + table	23 kg
7	Coffee table	5 kg
8	Upholstered chair	18 kg
9	12.7 mm carpet	75 kg

Table 2. Furnishings in the living room: Tests 1 and 2

Care was taken to ensure the contents of the two living rooms were as closely matched as possible, given the furnishings were not purchased, but had been donated by citizens of the Province of British Columbia. The mass of each item had to be estimated since scales were not available on site.

In both tests, a waste-paper basket was placed between the 3-seater couch and the upholstered chair such that it was in contact with the couch and then it was ignited.

Observations

A brief chronology of critical events in the two tests is provided in Table 3.

Event	Time in Test 1 (min:s)	Time in Test 2 (min:s)
Ignition of waste-paper basket	0:00	0:00
Room experiences flashover	2:40	4:00
Window cracks	3:05	4:30
Window falls out	4:15	5:15
Suppression commences	10:00	20:00

Table 3. Chronology of critical events in Tests 1 and 2

In Test 1, the 9.5 mm gypsum board began falling from the ceiling 2 minutes and 30 seconds after ignition; that is, just before flashover. As the house had stood abandoned throughout the winter in a region with rainy winters, the board was likely moist. Since experiments were planned for the second storey of the house, suppression was initiated 10 minutes after ignition. As this was also a training exercise for the fire services, suppression was accomplished not through the open window, but by

breaking down one of the covered-over doors. The sudden inflow of air caused temperature within the room to begin to drop. Water was applied to the fire about 12 minutes and 30 seconds after ignition.
In Test 2, 15.9 mm fire-rated gypsum board began falling from the ceiling 19 minutes after ignition. Once again, since experiments were planned for the second storey of the house, suppression was initiated soon afterwards (20 minutes after ignition). Suppression was accomplished through the open window in Test 2 and hence took much less time to complete.

Fire Temperature

The average upper layer temperatures, as functions of time, measured by a thermocouple tree at the geometric centre of the rooms, are depicted in Fig. 3.

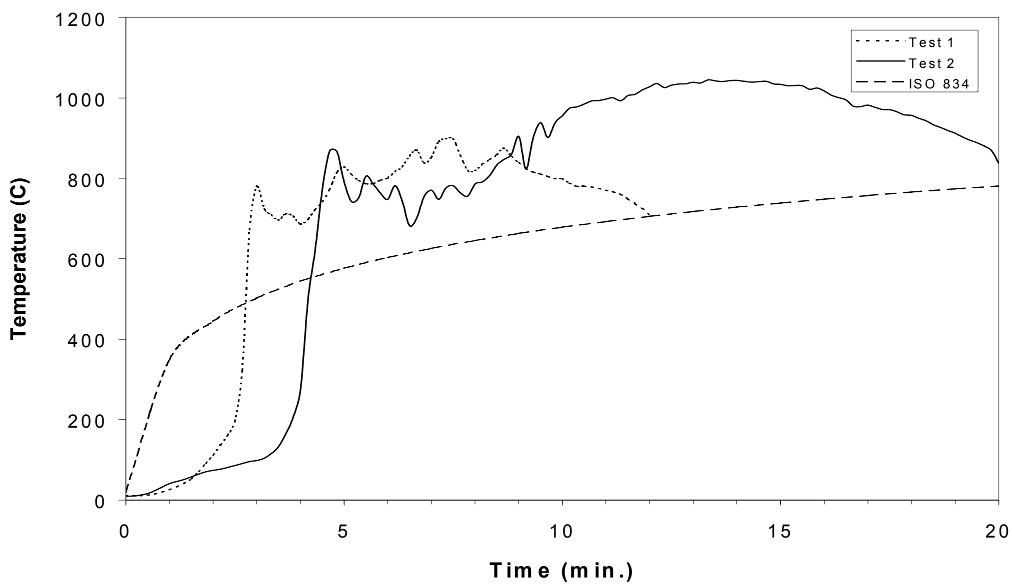

Figure 2. Temperatures in Tests 1 and 2 compared to the ISO 834 time-temperature curve.

Although efforts were taken to ensure the fires in Tests 1 and 2 followed roughly the same time-temperature curve, it is evident that the fire developed much faster in Test 1 than in Test 2. Visually this appeared to result primarily from the earlier involvement of the couch in Test 1. Following flashover, however, the temperatures of the two fires were strikingly similar. Both fires became much hotter than the standard time-temperature curve defined in ISO 834 (2).

Rate of Heat Release

As is evident from the temperature data in Test 2, the fire began to cool 15 minutes after ignition. The gypsum board on the back wall of the room became visible at about the same time. Clearly the combustible contents of the room were burning out suggesting the fire was now fuel-surface controlled.

To investigate whether this was the case, an estimate was made of the rate of heat release of the fire. As oxygen consumption calorimetry was not employed on site, it was necessary to estimate the rate of heat release from knowledge of the temperature of the fire. An estimate of the heat release rate before flashover was obtained using the McCaffrey, Quintiere and Harkleroad (MQH) model (3). The MQH correlation for temperature rise in the hot upper layer, ΔT_h (K), as a function of the heat release rate of the fire Q (kW), is given by Eqn. 1. By rearranging Eqn. 1 one can solve for the heat release rate given the fire temperature.

$$\Delta T_h = 480\left(\frac{\dot{Q}}{c_p T_0 \rho_0 A\sqrt{gh}}\right)^{2/3}\left(\frac{h_k A_T}{c_P \rho_0 A\sqrt{gh}}\right)^{-1/3} \qquad (1)$$

Similarly an estimate of the heat release rate during the post-flashover stage was obtained by employing a parametric model developed by Matsuyama et al. (4) and summarised in Eqn 2.

$$\frac{\Delta T_h}{T_0} = 1.62\left(\frac{\dot{Q}}{c_p T_0 \rho_0 A\sqrt{gh}}\right)^{2/3}\left(\frac{h_k A_T}{c_P \rho_0 A\sqrt{gh}}\right)^{-1/3} \qquad (2)$$

The predicted heat release rate for Test 2 is presented in Fig. 3.

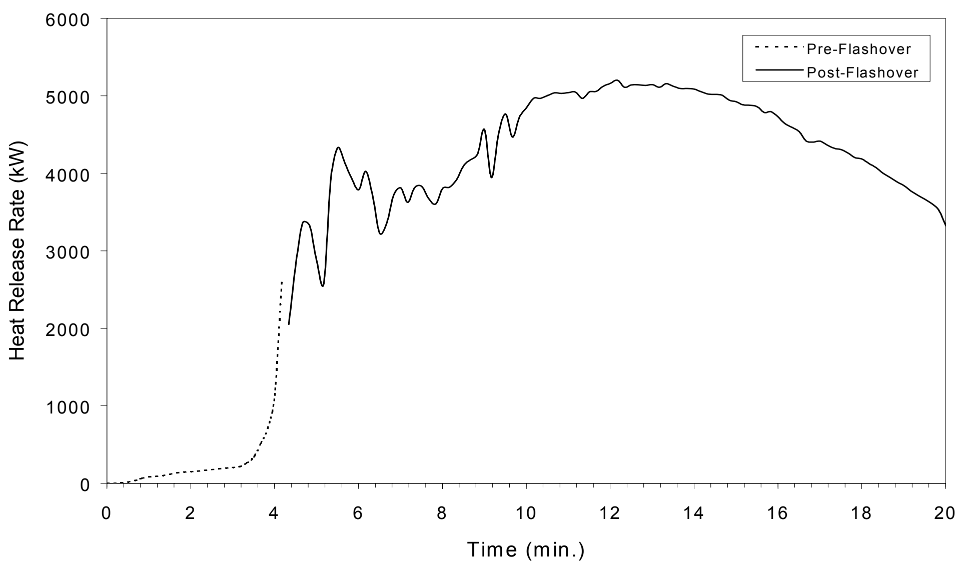

Figure 3. An estimate of the heat release rate during Test 2

In solving for heat release rate, the following input data were employed: initial temperature T_0 = 288 K; specific heat of air c_P = 1.1 kJ kg^{-1} K^{-1}; density of air ρ_0 = 1.2 kg m^{-3}; ventilation factor $Ah^{1/2}$ = 1.86 $m^{5/2}$ (prior to window fallout) and $Ah^{1/2}$ = 4.37 $m^{5/2}$ (after window fallout); boundary thermal properties $A_T(k\rho c)^{1/2}$ = 48.4 kJ $s^{-1/2}$ K^{-1} (prior to window fallout) and $A_T(k\rho c)^{1/2}$ = 46.8 kJ $s^{-1/2}$ K^{-1} (after window fallout); and effective heat transfer coefficient $h_k = (k\rho c/t)^{1/2}$.

The heat release rate in the fire may not exceed a maximum ventilation-controlled limit given by 1,500 $Ah^{1/2}$ (kW). Before window fallout (that is, before 5 minutes 15 seconds) the maximum possible heat release rate is therefore 2,800 kW and after window fallout 6,600 kW. Fig. 3 suggests the fire was fuel-surface controlled in both the pre-flashover and post-flashover regimes.

Although the estimates summarised in Fig. 3 are rough, the prediction during pre-flashover, in which it is primarily the 3-seater couch that is burning, is reminiscent of the performance of "quickly developing, high peak heat release rate" upholstered furniture observed in a comprehensive European study (5).

Breakage of Windows

The times to glass breakage (cracking) were calculated using the computer model BREAK1 (6) and compared to the observed breakage times in Tests 1 and 2. To replicate the exposure of the upper sections of the glazing, the temperature history from a thermocouple 610 mm below the ceiling was used in the simulations since the top of the window was 570 mm below the ceiling. As the thermal properties of the glass onsite were unknown, the default values provided in BREAK1 were used. No account was made for the fact that the windows were about 50 years old.

In Test 1, the first sign of breakage on the inside pane of the window was recorded at 3 minutes and 5 seconds and the entire window fell out at 4 minutes and 15 seconds. BREAK1 predicted the window would crack at 2 minutes and 35 seconds. In Test 2, the first sign of window cracking on the inside pane was at approximately 4 minutes and 30 seconds and the entire window fell out 5 minutes and 15 seconds. BREAK1 predicted the window would crack at 4 minutes. The fallout of the windows was more likely governed by loss of strength of the aluminium frames at elevated temperatures rather than by the properties of the glass.

Due to the lack of detailed information about the window's glass properties, the predictions of BREAK1 were sufficiently encouraging that no attempt was made to simulate breakage employing double-pane breakage models.

Performance of Gypsum Board

Forintek has developed the computer model WALL2D (7) to predict the thermal response of fire exposed wood-stud walls protected by fire-rated gypsum board. WALL2D comprises modules which compute heat transfer through and thermal decomposition of gypsum boards, wood studs, and glass-fibre or mineral wool insulation as well as the contraction of gypsum boards and opening of joints between gypsum boards. WALL2D's predictions for time-dependent temperature profiles in wood-stud walls agree well with the results of standard fire-resistance tests.

Currently, WALL2D is being revised to model any fire exposure with an arbitrary temperature-time relationship. In its present form, WALL2D cannot account for a fire exposure involving a cooling phase, it can only model fire exposures in which the fire temperature increases monotonically according to the standard fire-resistance test ISO 834 or according to the simple analytical form $\Delta T_h = \beta\ t^{1/6}$ (8).

To simulate the fire exposure observed in Test 2, the measured temperature-time curve depicted in Fig. 2 was fit to the form $\Delta T_h = \beta\ t^{1/6}$. As Fig. 4 demonstrates, $\beta = 355\ K\ s^{-1/6}$ gives a good fit of the data following flashover.

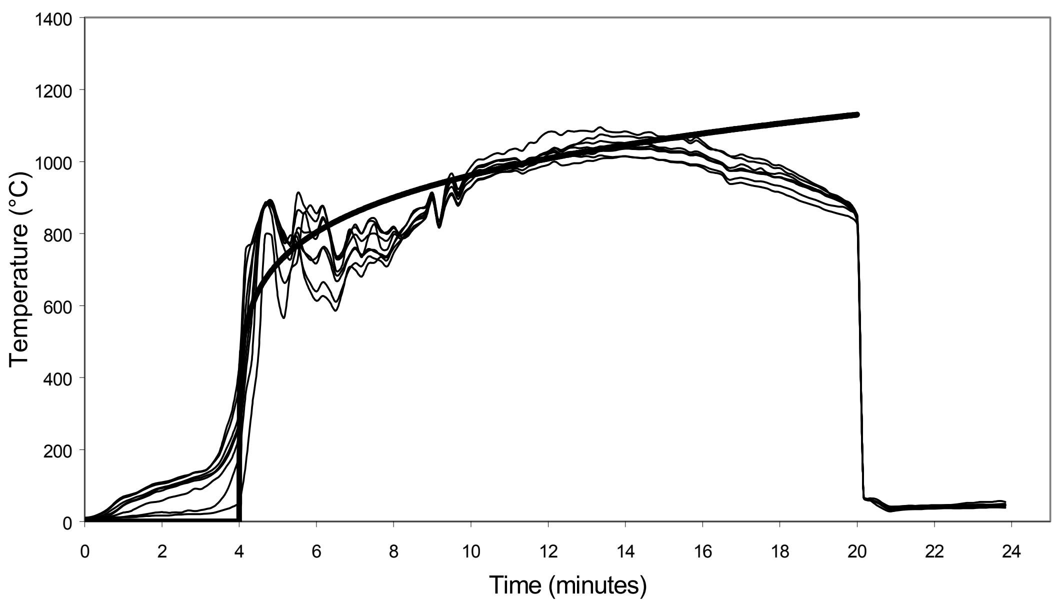

Figure 4. Fit of $\Delta T_h = \beta t^{1/6}$ (β = 355) to the temperature data of Test 2.

Employing this temperature-time relationship, WALL2D was used to predict the thermal response of the walls in Test 2. Fig. 5 shows a typical comparison. The solid lines represent the temperature measured between the 15.9 mm fire-rated gypsum board and wood studs. The dashed line is the temperature at these locations assuming the fire exposure is given by $\Delta T_h = \beta t^{1/6}$ with $\beta = 355$ K $s^{-1/6}$.

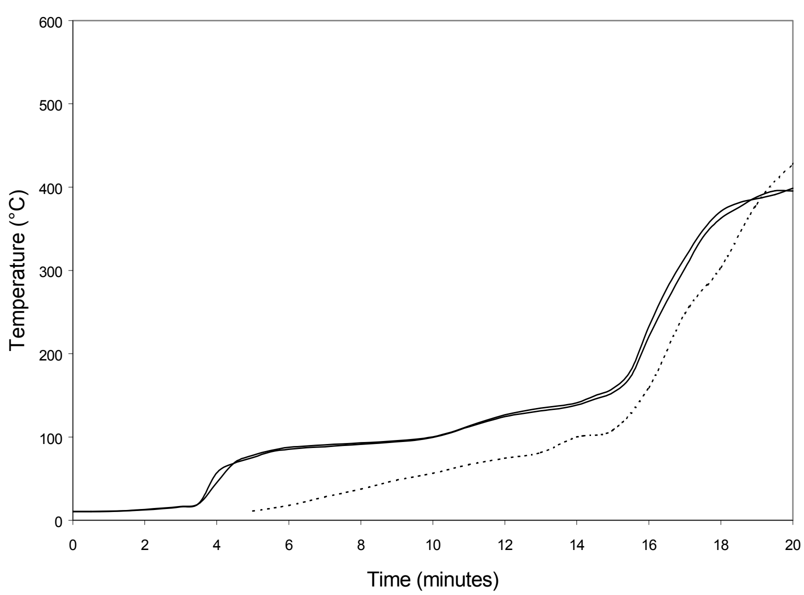

Figure 5. Comparison of predicted and measured temperatures within a wall in Test 2.

The agreement between theory and measurement is quite good. Clearly the wood studs were well protected by the fire-rated gypsum board despite the very high temperatures. In fact, the studs would have contributed little if anything to the severity of the fire within the living room.

TEST 3: PERFORMANCE OF A CONCRETE-BLOCK PARTY WALL

A bedroom on the second storey of a semi-attached house was fully furnished. The window was left partially open and the door to the corridor was open. The ceiling and walls were lined with regular gypsum board. Fire was started in a waste-paper basket in contact with a bed. The primary purpose of the test was to assess the ability of a concrete-block party wall to prevent or delay the spread of fire to the adjoining house. A brief chronology of events in the test is provided in Table 4.

Time (min:sec)	Event
0:00	Ignition of waste-paper basket
4:15	Bedroom experiences flashover
5:05	Window cracks
6:15	Window falls out
6:30	Eaves above window ignite
15:15	Neighbouring bedroom on fire
17:25	Flames burn through roof
18:15	Roof above bedroom on fire
19:15	Fire stops at block wall
37:15	Fire drops to first storey
96:15	Fire breaks out on neighbouring roof

Table 4. Chronology of critical events in Test 3

The concrete block wall ran to the under side of the combustible roof sheathing and to the inside of the combustible façade. Both the combustible roof sheathing and combustible façade were continuous from one building to the other, as were the combustible eaves. Nonetheless it took more than an hour and a half for fire to advance from one side of the block wall to the other.

A favorable breeze likely prevented rapid fire spread from one unit to the other along the façade and eaves. Aluminium shingles on the roof inhibited fire spread on the roof because the shingles had to be melted first before flames could advance. This is a significant effect as many aluminium alloys melt at temperatures as high as 650°C.

The results suggest that a firewall constructed of concrete blocks with a parapet and with no continuous combustible elements connecting opposite sides of the wall provides a significant barrier to the spread of fire between two buildings of combustible construction.

TEST 4: IMPACT OF RESTRICTED VENTILATION

A recreation room in a house was fully furnished. There were no windows in the room and the door to the room was closed. The ceiling and two interior walls were lined with regular gypsum board and the two walls in contact with the concrete basement were lined with 6 mm plywood on furring strips. The primary purpose of the test was to assess the ability of regular gypsum board to protect the wood-joist ceiling in a ventilation-starved basement fire.

The room was furnished with a 3-seater couch, a coffee table, a desk with a television on top, and a carpet covering the concrete floor. The waste-paper basket was placed between the 3-seater couch and coffee table such that it was in contact with the couch and then it was ignited.

The temperatures recorded on a thermocouple tree in the centre of the room are shown in Fig. 6. The fire showed a peak in temperature of about 300°C roughly 6 minutes and 15 seconds following ignition. By this time, much of the oxygen in the room had been consumed and presumably only smouldering could be supported. Twenty minutes after ignition fire fighters opened the door to the room. The temperatures recorded by the lowest thermocouples exhibited a drop in temperature as fresh air entered. Shortly thereafter the room experienced flashover.

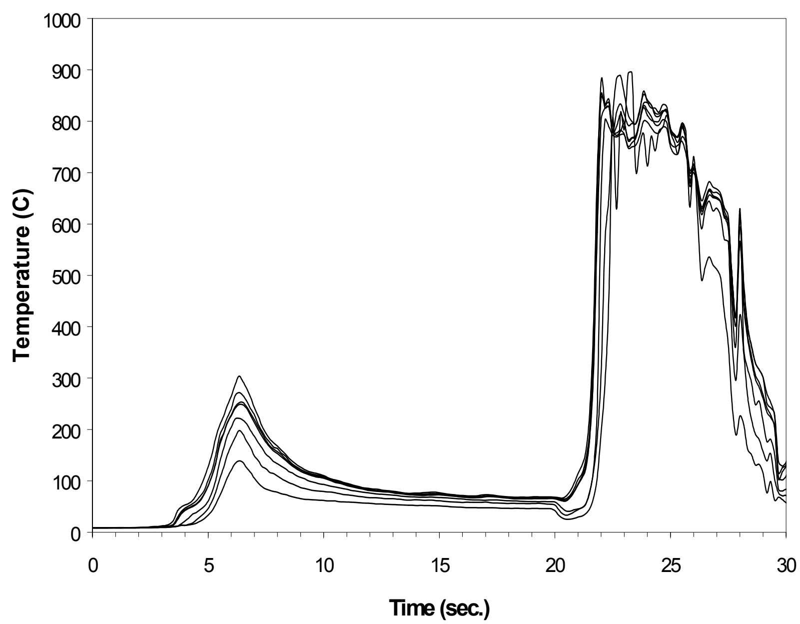

Figure 6. Temperatures measured in a basement recreation room.

Following Mowrer (9), the maximum temperature rise can be calculated assuming no oxygen enters the room. The limiting temperature rise associated with oxygen limited heat release is given by Eqn 3.

$$\Delta T_{g,\lim} = \frac{H_C}{r_{air}} \frac{\chi_{O_2,\lim}}{c_p} \left(1 - \chi_1\right) \qquad (3)$$

where

$\Delta T_{g,\lim} =$ maximum temperature rise associated with oxygen limited heat release (K)

$\frac{H_C}{r_{air}} =$ heat of combustion divided by air stoichiometric ratio (3000 kJ/kg for most fuels)

$\chi_{O_2,\lim} =$ fraction of O_2 that can be consumed before extinction (~ 0.4)

$c_p =$ specific heat of air (1.0 kJ/kgK)

$\chi_1 =$ loss fraction (unknown)

Since the heat loss fraction is unknown and the temperature is very sensitive to its value, the temperature rise observed has been used to calculate the heat loss fraction. The temperature rise observed in the room is approximately 290 K as can be seen from Fig. 6. Rearranging Eqn. 3 and solving for the heat loss fraction yields a value of 0.76. This seems very reasonable, since Mowrer notes that values can range from 0.6 to 0.9.

CONCLUSIONS

During the experiments, fire was observed to spread quickly from the waste-paper basket to upholstered furniture or mattresses. Subsequent fire development was rapid with flashover occurring rather early. The temperature in the room of fire origin got much hotter than in standard fire-resistance tests.

Observations taken onsite and subsequent analysis, allowed several preliminary conclusions to be drawn:

- Properly designed wood-frame walls and ceilings can act as a significant barrier to fire spread.
- The contents of a house (in particular, upholstered furniture and mattresses) are more of a fire-safety threat than the wood-frame structure. In all fires, untenable conditions developed before the structure was involved in fire.
- In very large fires, a firewall provides a significant barrier to the spread of fire between two buildings of combustible construction.

A detailed assessment of the test data is underway. The fires are being simulated on the computer using models developed at Forintek (7, 8) in order to see whether the models give a good representative of these six real fires and of the performance of wood-frame assemblies exposed in these fires. If fires in wood-frame structures can be modeled accurately, one can begin to assess the advantages and disadvantages of various design options. In the end, the computer models will be used to evolve recommendations on how to improve the fire-safety performance of housing.

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Special thanks go to Dr. R. Thomas of the National Research Council Canada (NRC) who negotiated an invitation for Forintek to undertake this work and who assisted in running the experiments. The on-site assistance of Mr. J.C. Garant of Forintek's Sainte Foy Laboratory, and of Dr. J.R. Shaw and Mr. J.E. Moller of Weyerhaeuser is also gratefully acknowledged.

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Appendix II

Analysis of Fire Experiments Conducted in Wood-frame Houses

Analysis of Fire Experiments Conducted in Wood-frame Houses

James R. Mehaffey[1], Steve T. Craft[2] and Leslie R. Richardson[1]

To be presented at the 4th International Conference Seminar on Wood & Fire Safety
April 18-22, 2004 in the Slovak Republic
(To appear in the Conference Proceedings)

SUMMARY

Results of fire experiments conducted in furnished houses allow several important conclusions to be drawn. Properly designed wood-frame walls and ceilings were significant barriers to fire spread. The contents of a house (upholstered furniture and mattresses) were more of a fire-safety threat than the wood-frame structure. Untenable conditions developed before the structural members were involved in fire. In addition, preliminary comparisons of fire model predictions and experimental measurements are promising.

INTRODUCTION

In Canada, more than 95% of single-family and two-family houses are of wood-frame construction. Canadian fire statistics (1) indicate that 54% of structure fires, and 78% of deaths and 62% of injuries in structure fires occur in one- and two-family houses. Statistics also reveal that fires involving contents are the leading cause of fire deaths in houses and that most deaths occur before the house's structure is involved in fire. Nonetheless, concern is often expressed that, since wood is combustible, its use as a structural building material compromises fire safety.

In an effort to reduce fire losses, Forintek undertakes research on the fire performance of wood products and buildings constructed with those products. The purpose is to identify how and where wood products can safely be used. The high cost of research means that the fire performance of wood products is usually assessed in laboratory tests in which assemblies are simple and the fire exposure idealised.

Kemano, a "company town", was recently closed and some of its buildings made available for research. Forintek took advantage of this opportunity to assess the performance of wood-frame assemblies when exposed to fire in furnished houses. Experiments were designed to challenge the houses' wood-frame structures and allowed to follow their natural course for a significant period of time without intervention by fire fighters. While six fire experiments were conducted, this paper describes only four.

THE FIRST ITEM IGNITED

The first item ignited in each test was a plastic waste-paper basket with diameter 200 mm and height 300 mm. The lower 100 mm was filled with polyurethane chips and the upper 200 mm with shredded paper. A propane torch was used to ignite the contents through a hole near the bottom of the basket. A similarly filled plastic waste-paper basket was ignited under a furniture calorimeter hood. Figure 1 depicts the heat release rate of the basket. The basket burned vigorously for one minute (from 40 seconds to 100 seconds) at a heat release rate close to 30 kW.

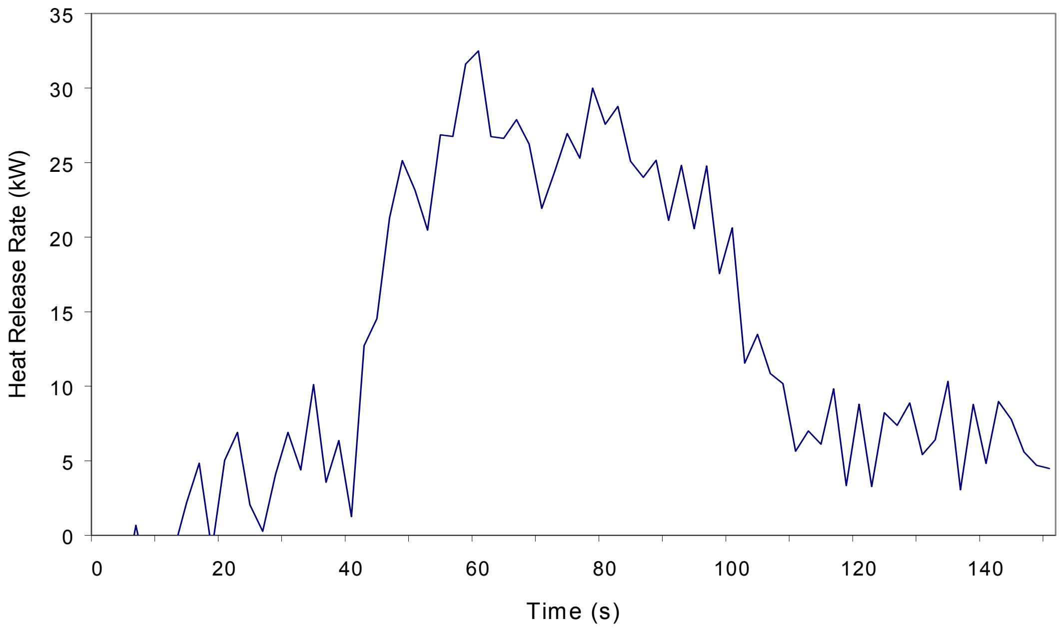

Figure 1: The Heat Release Rate of the Waste-paper Basket Fire

In the Kemano tests, the waste-paper basket was placed in contact with an item of upholstered furniture or a mattress. Statistics suggest that ignition of upholstered furniture or mattresses by smokers' materials are the leading causes of deaths due to fire. In these tests, the interest was not in early fire development, but in quickly establishing a large fire that would challenge the house's wood-frame structure.

TESTS 1 AND 2: PERFORMANCE OF GYPSUM BOARD

Tests 1 and 2 were conducted in similar living rooms. In the original layout, each living room had doors to a corridor and a dining room, and a fireplace along one wall. Before running the tests, the doors and fireplace were blocked off by wood-stud walls protected by gypsum board. The floor of the "renovated" living room was a rectangle 3.4 m deep and 4.8 m long. The floor to ceiling height was 2.5 m.

In Test 1, the ceiling and walls were lined with regular gypsum board: the new walls with 12.7 mm board, and the old walls and the ceiling with 9.5 mm board. In Test 2, the ceiling and walls were lined with new, 15.9 mm fire-rated gypsum board.

The window to the living room comprised three panes: a central fixed pane 1.47 m x 1.42 m (high) and two sliding end-panes 0.55 m x 1.42 m (high). Each "pane" was, in fact, a double-pane. The end panes were removed to provide ventilation for the fire.

The rooms were furnished as indicated in Table 2. The contents of the two living rooms were as closely matched as possible, given the furniture had been donated. The mass of each item was estimated since scales were not available on site.

Table 2: Furnishings in the Living Room: Tests 1 and 2

Item No.	Description of Item	Mass
1	Couch (3 seats)	40 kg
2	Couch (2 seats)	32 kg
3	Bookshelf + paper	16 kg
4	Small table + lamp	2 kg
5	Bookshelf + paper	36 kg
6	Television + table	23 kg
7	Coffee table	5 kg
8	Upholstered chair	18 kg
9	12.7 mm carpet	75 kg

In both tests, a waste-paper basket was placed in contact with the 3-seater couch and was ignited. A chronology of critical events in the two tests is provided in Table 3.

Table 3: Chronology of critical events in Tests 1 and 2

Event	Time in Test 1 (min:s)	Time in Test 2 (min:s)
Ignition of waste-paper basket	0:00	0:00
Room experiences flashover	2:40	4:00
Window cracks	3:05	4:30
Window falls out	4:15	5:15
Suppression commences	10:00	20:00

In Test 1, the 9.5 mm gypsum board began falling from the ceiling 2.5 minutes after ignition; that is, just before flashover. As the house had stood abandoned in a region with rainy winters, the board was likely moist. Suppression was initiated 10 minutes after ignition by breaking down a covered-over door. The sudden inflow of air caused temperature in the room to drop. Water was applied to the fire 12.5 minutes after ignition.

In Test 2, 15.9 mm fire-rated gypsum board began falling from the ceiling 19 minutes after ignition. Suppression was initiated soon afterwards (20 minutes after ignition) through the open window and hence took much less time to complete.

Fire Temperature/Heat Release

The average upper layer temperatures, as functions of time, measured by a thermocouple tree at the geometric centre of the rooms, are depicted in Figure 2.

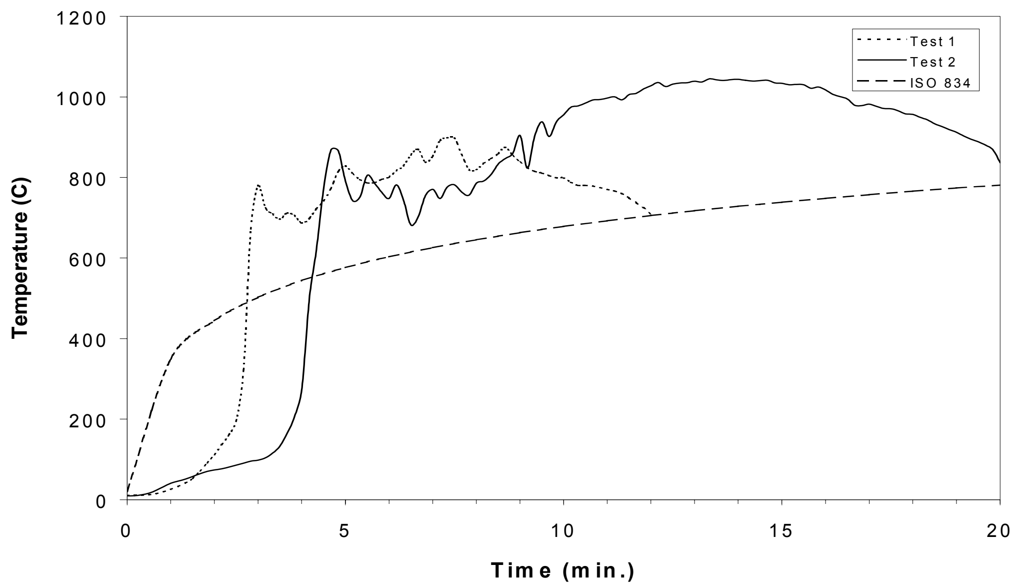

Figure 2. Temperatures in Tests 1 and 2 compared to the ISO 834 curve.

Although efforts were made to ensure the fires in Tests 1 and 2 were similar, the fire developed much faster in Test 1 than in Test 2. This resulted from the earlier involvement of the couch in Test 1. Following flashover, the temperatures of the fires were strikingly similar and much hotter than the ISO 834 (2) time-temperature curve.

In Test 2, the fire began to cool 15 minutes after ignition. The gypsum board on the back wall of the room became visible at this time. Clearly the combustible contents of the room were burning out suggesting the fire was now fuel-surface controlled.

To investigate whether this was so, an estimate was made of the rate of heat release using the fire temperature. An estimate of the heat release rate before flashover was obtained using the McCaffrey, Quintiere and Harkleroad (MQH) model (3). The MQH correlation for temperature in the hot upper layer, ΔT_h (K), as a function of the heat release rate of the fire Q (kW), is given by Equation 1. By rearranging Equation 1, one can solve for the heat release rate given the fire temperature.

$$\Delta T_h = 480\left(\frac{\dot{Q}}{c_p T_0 \rho_0 A\sqrt{gh}}\right)^{2/3}\left(\frac{h_k A_T}{c_P \rho_0 A\sqrt{gh}}\right)^{-1/3} \quad (1)$$

An estimate of the heat release rate in the post-flashover stage was obtained by employing a model developed by Matsuyama et al. (4) and summarised in Equation 2.

$$\frac{\Delta T_h}{T_0} = 1.62\left(\frac{\dot{Q}}{c_p T_0 \rho_0 A\sqrt{gh}}\right)^{2/3}\left(\frac{h_k A_T}{c_P \rho_0 A\sqrt{gh}}\right)^{-1/3} \quad (2)$$

The predicted heat release rate for Test 2 is presented in Figure 3. The following input data were employed: initial temperature T_0 = 288 K; specific heat of air c_P = 1.1 kJ kg^{-1} K^{-1}; density of air ρ_0 = 1.2 kg m^{-3}; ventilation factor $Ah^{1/2}$ = 1.86 $m^{5/2}$ (before window fallout) and $Ah^{1/2}$ = 4.37 $m^{5/2}$ (after window fallout); boundary thermal properties $A_T(k\rho c)^{1/2}$ = 48.4 kJ $s^{-1/2}$ K^{-1} (prior to window fallout) and $A_T(k\rho c)^{1/2}$ = 46.8 kJ $s^{-1/2}$ K^{-1} (after window fallout); and effective heat transfer coefficient $h_k = (k\rho c/t)^{1/2}$.

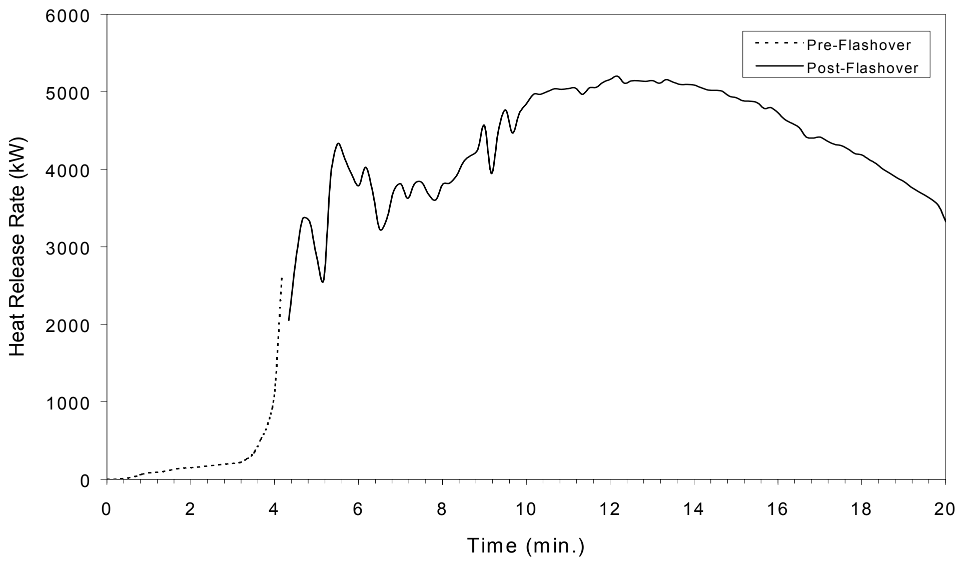

Figure 3: An estimate of the heat release rate during Test 2

The heat release rate cannot exceed the ventilation-controlled limit of 1,500 $Ah^{1/2}$ (kW). Before window fallout (5.25 minutes) the maximum possible heat release rate is therefore 2,800 kW and after window fallout 6,600 kW. Figure 3 suggests the fire was fuel-surface controlled in both the pre-flashover and post-flashover regimes.

The estimates of Figure 3 are rough, yet the prediction during pre-flashover, when the 3-seater couch burns, is reminiscent of the performance of "quickly developing, high peak heat release rate" upholstered furniture in a European study (5).

Breakage of Windows

The times to glass breakage (cracking) were calculated using the computer model BREAK1 (6). To replicate the exposure of the upper sections of the glazing, the temperature history from a thermocouple 610 mm below the ceiling was used in the simulations since the top of the window was 570 mm below the ceiling.

In Test 1, the first sign of breakage on the inside pane was recorded at 3 minutes and 5 seconds and the window fell out at 4 minutes and 15 seconds. BREAK1 predicted the window would crack at 2 minutes and 35 seconds. In Test 2, the first sign of cracking on the inside pane was at 4 minutes and 30 seconds and the window fell out 5 minutes and 15 seconds. BREAK1 predicted the window would crack at 4 minutes. The fallout of the windows was more likely governed by loss of strength of the aluminium frames at elevated temperatures rather than by the properties of the glass.

Performance of Gypsum Board

Forintek developed WALL2D (7) to predict the thermal response of fire exposed wood-stud walls protected by gypsum board. WALL2D computes heat transfer through and thermal decomposition of gypsum boards, wood studs, and glass-fibre or mineral wool insulation as well as the contraction of gypsum boards and opening of joints between boards. WALL2D's predictions for temperature profiles in wood-stud walls agree well with the results of standard fire-resistance tests.

WALL2D models fire exposures in which temperature increases monotonically following an arbitrary curve, the ISO 834 curve or the analytical form $\Delta T_h = \beta\, t^{1/6}$ (8). To simulate the fire exposure observed in Test 2, the measured temperature-time curve depicted in Figure 2 was approximated by the curve depicted in Figure 4.

WALL2D was used to predict the thermal response of the walls in Test 2. Figure 5 shows a typical comparison. The solid lines represent the temperature measured between the 15.9 mm fire-rated gypsum board and wood studs at two locations within the walls. The dashed line is model's predictions of the temperature at these locations assuming the fire exposure is given by the fit given in Figure 4.

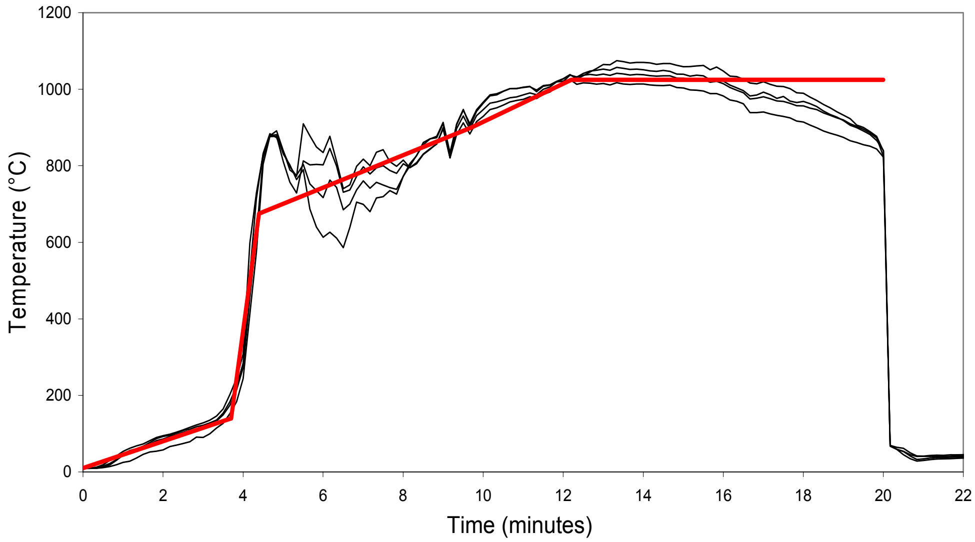

Figure 4: Fit of the temperature data of Test 2.

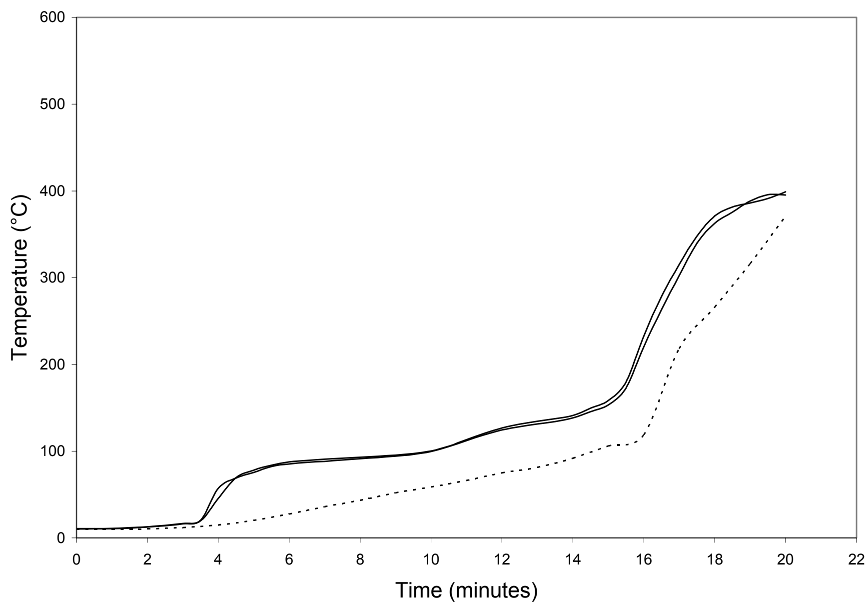

Figure 5: Comparison of predicted and measured temperatures within a wall in Test 2.

The agreement between theory and measurement is quite good. The studs were well protected by the fire-rated gypsum board despite the high temperatures. In fact, the studs would have contributed little if anything to the fire within the living room.

TEST 3: PERFORMANCE OF A CONCRETE-BLOCK PARTY WALL

A bedroom on the second storey of a semi-attached house was fully furnished. Fire was started in a waste-paper basket in contact with a bed. The purpose of the test was to assess the ability of a concrete-block party wall to prevent or delay the spread of fire to the adjoining house. A chronology of events in the test is provided in Table 4.

Table 4: Chronology of critical events in Test 3

Time (min:sec)	Event
0:00	Ignition of waste-paper basket
4:15	Bedroom experiences flashover
6:15	Window falls out
6:30	Eaves above window ignite
15:15	Neighbouring bedroom on fire
17:25	Flames burn through roof
19:15	Fire stops at block wall
37:15	Fire drops to first storey
96:15	Fire breaks out on neighbouring roof

The concrete block wall ran to the under side of the combustible roof sheathing and to the inside of the combustible façade. The roof sheathing and façade were continuous from one building to the other, as were the combustible eaves. Nonetheless it took over 1.5 hours for fire to advance from one side of the block wall to the other.

A favourable breeze likely prevented rapid fire spread from one unit to the other along the façade and eaves. Aluminium shingles on the roof inhibited fire spread on the roof because the shingles had to be melted first before flames could advance. This is a significant effect as many aluminium alloys melt at temperatures as high as 650°C. Nonetheless, the results suggest a firewall constructed of concrete blocks with a parapet and without continuous combustible elements connecting opposite sides of the wall provides a significant barrier to the spread of fire between two buildings of combustible construction.

TEST 4: IMPACT OF RESTRICTED VENTILATION

A basement recreation room was furnished with a 3-seater couch, a coffee table, a desk with a television on top, and a carpet covering the concrete floor. There were no windows in the room and the door was closed. The waste-paper basket was placed in contact with the 3-seater couch and was ignited. Temperatures recorded in the centre of the room are shown in Figure 6.

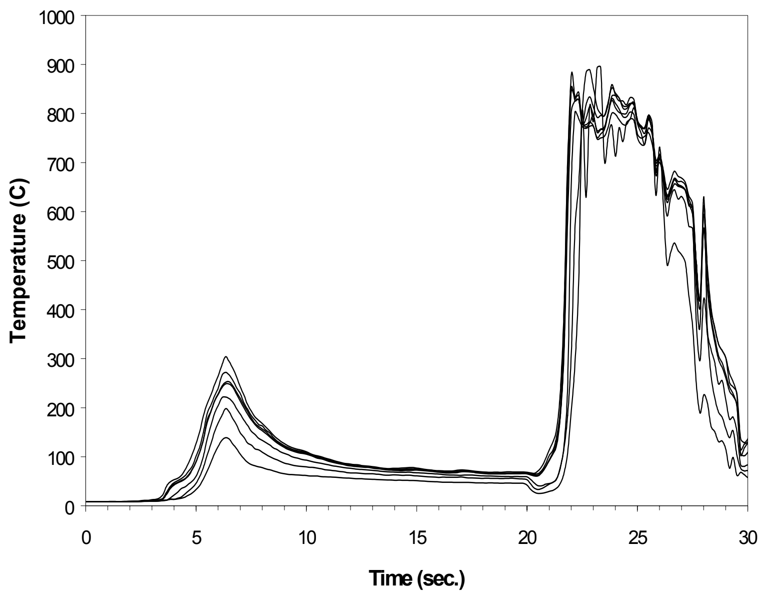

Figure 6: Temperatures measured in a basement recreation room.

The fire showed a peak in temperature of 300°C about 6 minutes and 15 seconds following ignition. By this time, much of the oxygen in the room had been consumed and only smouldering could be supported. Twenty minutes after ignition fire fighters opened the door. Temperatures recorded by the lowest thermocouples exhibited a drop in temperature as fresh air entered. Shortly thereafter the room experienced flashover.

Following Mowrer (9), the maximum temperature rise can be calculated assuming no oxygen enters the room using Equation 3.

$$\Delta T_{g,\lim} = \frac{H_C}{r_{air}} \frac{\chi_{O_2,\lim}}{c_p} (1 - \chi_1) \qquad (3)$$

$\Delta T_{g,\lim} =$ maximum temperature rise associated with oxygen limited heat release (K)

$\frac{H_C}{r_{air}} =$ heat of combustion / air stoichiometric ratio (3000 kJ/kg for most fuels)

$\chi_{O_2,\lim} =$ fraction of O_2 that can be consumed before extinction (~ 0.4)

c_p = specific heat of air (1.0 kJ/kgK)

χ_1 = loss fraction (unknown)

The observed temperature rise was used to calculate the heat loss fraction. The temperature rise in the room is approximately 290 K as can be seen from Fig. 6. Rearranging Eqn. 3 and solving for the heat loss fraction yields a value of 0.76. This seems very reasonable, since Mowrer notes that values can range from 0.6 to 0.9.

CONCLUSIONS

Fire spread quickly from the waste-paper basket to upholstered furniture or mattresses. Subsequent fire development was rapid with flashover occurring early. The temperature in the room of fire origin got much hotter than in standard fire-resistance tests. Several preliminary conclusions can be drawn:

- Properly designed wood-frame walls and ceilings act as a significant barrier to fire spread.
- The contents of a house (in particular, upholstered furniture and mattresses) are more of a fire-safety threat than the wood-frame structure. In all fires, untenable conditions developed before the structure was involved in fire.
- In very large fires, a firewall provides a significant barrier to the spread of fire between two buildings of combustible construction.

A detailed assessment of the test data is underway. The fires are being simulated using models developed at Forintek (7, 8) to see whether the models give good predictions the performance of wood-frame assemblies exposed to real fires.

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