FPInnovations

info@fpinnovations.ca
www.fpinnovations.ca

ENCAPSULATION OF MASS TIMBER FLOOR SURFACES

REPORT TO FORESTRY INNOVATION INVESTMENT LTD.

Forestry Innovation Investment

Lindsay Ranger, P.Eng, M.A.Sc
Christian Dagenais, P.Eng., PhD.
Noureddine Bénichou, PhD.

March 31, 2020
PROJECT NO 301013624 – Encapsulation

Client: BC Forestry Innovation Investment
Suite 1200 – 1130 Pender Street West
Vancouver, B.C. V6E 4A4

Confidentiality Notice
This report has been prepared solely for your use and should not be quoted in whole or in part without our written consent. No responsibility to any third party is accepted as the report has not been prepared for, and is not intended for, any other purpose. The results presented relate only to the specimens/material tested or calibrated.

ENCAPSULATION OF MASS TIMBER FLOOR SURFACES
PROJECT NO. 301013624 – ENCAPSULATION

ACKNOWLEDGEMENTS
We would like to thank BC Forestry Innovation Investment Ltd. for funding this research. Also thank you to GHL Consultants Ltd. and George Hadjisophocleous at Carleton University for their valuable input. Thank you to the National Research Council Fire Laboratory for their hard work and creativity in designing and constructing the test setup.

AUTHORIZED BY:
Sylvain Gagnon, P.Eng.
Manager
Building Systems
Sylvain.gagnon@fpinnovations.ca

REVIEWER
Christian Dagenais, P.Eng., PhD.
Senior Scientist
Building Systems
Christian.dageanis@fpinnovations.ca

AUTHOR
Lindsay Ranger, P.Eng., M.A.Sc
Scientist
Building Systems – Sustainable Construction
343-292-6342
lindsay.ranger@fpinnovations.ca

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

Mass timber buildings are growing in popularity around the world. Mass timber is a sustainable construction material that is an alternative to steel or concrete, which are traditionally used in the construction of tall buildings. Currently, there are several barriers to the construction of mass timber buildings, including code restrictions, a lack of research data and associated additional costs with conducting research and preparing alternative solutions. Canada is considering revising the National Building Code of Canada (NBCC) [1] to allow wood construction in taller buildings in the 2020 edition. One of the major advantages of mass timber construction is that elements can be manufactured and prefabricated offsite, assemblies arrive onsite ready for assembly so that buildings can be erected quickly. This significantly reduces construction timelines and waste onsite.

Currently, mass timber building designs commonly incorporate a concrete floor topping. This can improve building acoustics by increasing the mass of the assembly, reduce floor vibration and create a smooth flat surface to install finish flooring on. The installation of concrete requires formwork, pouring and finishing the concrete and time to cure which adds to project schedules. One way to address this is to use mass timber elements that are prefabricated with concrete toppings preinstalled. Replacing the concrete floor toppings with dry alternatives, such as cement board, may also reduce construction timelines, while still ensuring adequate acoustic and vibration performance. Cement board needs only to be screwed in place and can be walked on immediately after installation; this reduction in construction time may reduce overall project costs and help make wood buildings more cost competitive than other types of construction.

2 BACKGROUND

2.1 Codes

The current 2015 edition of the NBCC introduced mid-rise wood construction, allowing up to six storeys. Prior to this edition, buildings using combustible (wood-frame) construction were only permitted up to four storeys. A significant amount of research was conducted by the National Research Council of Canada (NRC) Fire Research Laboratory in support of the mid-rise code change [2].

The adoption and uptake of this change has been positive across Canada. A growing desire for environmental sustainability is fostering the realization of expanded wood construction both locally and internationally. Several demonstration buildings have been funded through the GCWood program at Natural Resources Canada, which have showcased the possibilities for larger and taller wood buildings. Some examples include the 18-storey Brock Commons Tallwood House at the University of British Columbia and the 13-storey Origine building in Quebec City [3]. These projects had to conduct additional research and testing to receive approval from the Authority Having Jurisdiction.

The NBCC is currently in the process of finalizing its impending 2020 edition. As of now, it is anticipated that the new code will include provisions to allow up to 12-storey Encapsulated Mass Timber Construction (EMTC). EMTC will be a new 'type' of construction in the code, i.e., not combustible construction nor heavy timber construction.

These buildings will need to be sprinklered throughout in accordance with NFPA 13 [4], will require 2 hr fire-resistance ratings for structural fire separation elements, and the majority of mass timber will need to be encapsulated.

2.2 Encapsulation

Encapsulation is a concept of using materials to protect combustible wood elements from fire exposure. The wood is protected from the effects of fire by delaying the time at which the timber ignites and limiting the contribution of the wood elements to the fire. Encapsulation also inherently improves the fire resistance of an element, because it delays the wood surface's exposure to fire, thereby increasing the fire resistance failure time. EMTC buildings specifically achieve their level of fire safety from the rated encapsulation materials and minimum dimensions of structural mass timber elements.

The concept of encapsulation was studied during the Research Consortium for Wood and Wood-Hybrid Mid-Rise Buildings which involved fire research to support the NBCC code to allow up to six-storey buildings of combustible construction [2]. Several encapsulation materials were evaluated in the intermediate scale furnace at NRC during this project. Various temperature criteria were evaluated to determine which were best suited to be selected to define an encapsulation rating. At the interface between the wood substrate and the encapsulation material, failure was selected to be defined as an average temperature increase of 250 ^{o}C or a single point temperature increase of 270 ^{o}C; this was considered to be both technically based and conservative, seeing as protected wood does not ignite or contribute significant heat to a fire until the surface reaches 325 ^{o}C to 380 ^{o}C [2].

2.3 Encapsulated Mass Timber Construction

The following section is a summary of the proposed code change on EMTC [5]; the clause numbers that are given here are provided in the code change proposals.

EMTC buildings, up to twelve storeys, will permit structural elements to be of mass timber (e.g. beams, columns, walls, floors, roofs, etc.), so long as they are (3.1.18.3):

1. Arranged in heavy solid masses with no concealed spaces
2. Have essentially smooth flat surfaces with no thin sections or sharp projections
3. Meet the minimum dimensions

The minimum required dimensions for EMTC are outlined in Table 1.

Table 1. Minimum dimensions for EMTC (Table 3.1.18.3) [5]

Structural Timber Elements	Type of Dimension	Minimum Dimensions (mm)
Wall, floor and roof assemblies	Thickness/depth	96
Beams, columns and arches with two-sided or three-sided fire exposure	Cross-section	192 x 192
Beams, columns and arches with four-sided fire exposure	Cross-section	224 x 224

The new EMTC provisions will allow certain percentages of mass timber within a compartment to be exposed, but the exposed surfaces of most structural elements must be protected with encapsulation (3.1.18.4). They must be protected from adjacent spaces in the building (including in concealed spaces) using a material that provides an encapsulation rating of not less than 50 minutes, when tested in accordance with CAN/ULC-S146 *Standard Method of Test for the Evaluation of Encapsulation Materials and Assemblies of Materials for the Protection of Structural Timber Elements* [6]. The code change proposal notes that the suggested 50-minute encapsulation time is based on NRC research that demonstrates similar performance for two layers of 12.7 mm (½”) Type X gypsum board under standard fire exposure [2].

Encapsulation materials must be non-combustible, and certain materials are deemed to meet the 50-minute encapsulation rating requirements, which is based on research conducted by NRC, including small-scale, intermediate-scale, full-scale testing and data mining of previous research [2]. These include:

- Gypsum-concrete and concrete toppings not less than 38 mm thick on the top side of a mass timber floor or roof, and
- Two layers of Type X gypsum board, each not less than 12.7 mm thick, fastened directly to the mass timber, with a minimum of two rows of screws in each layer spaced not more than 400 mm o.c. Screws must penetrate not less than 20 mm into the wood and be between 20 to 38 mm from board edges. Joints must be staggered between layers.

The mass timber walls that are permitted to be exposed must have each exposed surface facing the same direction and have a flame spread rating (FSR) of not more than 150 when tested in accordance with CAN/ULC-S102 *Standard Method of Test for Surface Burning Characteristics of building Materials and Assemblies* [7]. The aggregate exposed mass timber wall and beam/column surface area permitted within a suite shall not exceed 35% of the total perimeter wall area. Partial mass timber ceilings are also permitted to be left exposed, so long as the area does not exceed 10% of the total suite ceiling area, and the surface has an FSR of not more than 150. If there are no mass timber walls exposed, then 25% of the ceiling can be left exposed if the FSR is not more than 75. There are exceptions which allow the exposure of beams, columns and arches within a fire compartment if their total aggregate area does not exceed 10% of the total perimeter wall area, and their FSR is not more than 150. There are no permissions for the exposure of mass timber floor tops.

2.4 CAN/ULC-S146

CAN/ULC-S146 [6] is the new test standard which has been developed to determine encapsulation ratings. The test method follows a procedure similar to a floor fire resistance test, exposing the assembly to the standard fire as given in CAN/ULC-101 *Standard Methods of Fire Endurance Tests of Building Construction and Materials* [8]. It requires that the test specimen and the encapsulation material be prepared in a horizontal orientation and requires application of fire exposure to the underside of the specimen. The test method itself is similar to CAN/ULC-S101 except that there is no applied load on the specimen and no requirement to measure temperatures on the unexposed surface. To date, no tests have been conducted in full conformance with this new standard. The method requires a wood substrate be constructed and the encapsulation material installed onto the wood. The encapsulation is not to be supported at all by the furnace walls. Nine thermocouples are installed at the surface between the wood substrate and the encapsulation material. The encapsulation rating is determined as the time that the average of the interface thermocouples increases by 250 ^{o}C or any one single point increases by 270 ^{o}C.

The encapsulation material and the method of securing the material to the wood substrate shall be representative of the construction for which classification is required. If the material incorporates joints, at least one joint should be incorporated in the test specimen.

The following is a summary of the most pertinent CAN/ULC-S146 requirements:

- Minimum wood substrate thickness of 76 mm
- Neither dimension of the assembly may be less than 3600 mm, with a total area not less than 13.4 m^2
- The outer edges of encapsulation material shall:
  - Not be supported on the walls of the furnace
  - Lie within the combustion chamber
  - Have a side clearance of not less than 25 mm from the furnace wall
- Any exposed surface of the wood substrate around the outer edges of the furnace should be protected from direct exposure to the fire and prevent any edge effect of hot gases on the encapsulation material
- Nine Type-K thermocouples installed at the interface at the centre, centre of each quarter and critical locations
- Metal fasteners to construct the wood substrate shall not protrude through to the surface

There is only one test method that is applied to evaluate the encapsulation rating of wall, ceiling and floor elements. The horizontal ceiling orientation of the test is appropriate for ceiling applications but may be more severe for wall and floor applications. Wall or floor toppings are not designed to be applied on a ceiling and therefore, may be more susceptible to fall-off sooner when installed as a ceiling, as opposed to their intended orientation. For a floor topping, the protection method receives structural support from the substrate beneath and may not be required to be adhered as securely to the surface. If a material is intended for a floor or wall it may require additional means to adhere the encapsulation method to a ceiling, such as additional screws, which may lead to cracking of the protection and a shorter encapsulation rating.

3 TECHNICAL TEAM

- Lindsay Ranger — Scientist, Building Systems, FPInnovations
- Christian Dagenais — Senior Scientist, Building Systems, FPInnovations
- Noureddine Bénichou — Principal Research Officer, National Research Council Canada
- Andrew Harmsworth — Principal, GHL Consultants Ltd.
- Matt Turco — GHL Consultants Ltd.

4 PROBLEM

Prefabricated timber elements can be assembled onsite very quickly, which is one of the major attractions of mass timber construction. However, the installation of concrete toppings above mass timber floor assemblies can slow down construction timelines. Concrete toppings require the installation of formwork, coordination with concrete deliveries, finishing and curing. Alternative floor topping methods which can be installed more quickly than cast-in-place concrete warrant investigation. The objective of this project is to determine whether a cement board floor topping could meet the encapsulation requirements for use in a mass timber building in accordance with the proposed NBCC 2020 EMTC requirements. The results from this study could lead to a reduction in construction timelines, and ultimately costs, for wood buildings.

The proposed EMTC code provisions require wood floor structures to be protected and meet an encapsulation rating of at least 50 minutes. Evaluating the encapsulation of a floor topping is challenging because the CAN/ULC-S146 and CAN/ULC-S101 test standards evaluate floors from underneath (as a ceiling), and floor toppings are not designed for ceiling applications. These toppings, such as concrete, are generally heavy for design (such as acoustics) and durability reasons, which increases the likelihood of premature cracking or fall-off when tested as a ceiling. There is a concern that, because of its weight, cement board may prematurely fall-off the ceiling in a standard CAN/ULC-S146 test. It is likely that temperatures near the floor in real fires are cooler due to buoyancy; this could support using a reduced fire exposure in standard tests which may also improve the encapsulation rating. The secondary objective of this work is to develop and evaluate the feasibility of a test method to evaluate the encapsulation of a floor topping in its intended orientation (on the floor) in a full-scale, or potentially intermediate-scale, floor furnace to achieve an accurate rating.

5 LITERATURE REVIEW

Existing literature and data were reviewed with respect to the encapsulation performance of cement board. This included looking at cement board under standard fire exposure, in accordance with CAN/ULC-S101 [8], as well as investigating temperatures beneath cement board in non-standard compartment fire tests, focusing on compartments constructed with wood or mass timber. Cement board is commonly used in compartment fire tests as a convenient method to replicate the weight and performance of a concrete topping.

5.1 Standard Fire Exposure

There have not yet been any tests conducted following the CAN/ULC-S146 standard, but there are some examples of smaller scale tests that give an indication of expected performance.

5.1.1 Mid-Rise Consortium Encapsulation Tests

In consideration of allowing mid-rise wood-frame buildings during the NBCC Mid-Rise Research Consortium, several cone calorimeter [9] and intermediate scale [2] tests were conducted to evaluate the encapsulation performance of Type X gypsum board, cement board and gypsum-concrete. In cone calorimeter tests, one layer of 12.7-mm cement board provided 11 minutes of encapsulation at an exposure of 75 kW/m^2, and two layers provided 35 minutes of encapsulation at an exposure of 50 kW/m^2. At an exposure of 50 kW/m^2, 25 mm of gypsum concrete provided 30 minutes of encapsulation, and 39 mm provided 47 minutes of encapsulation. In intermediate-scale tests, two cement board tests were completed; one with one layer of 12.7 mm (Test 3) and one with two layers of 12.7 mm (Test 8). Two gypsum-concrete tests were completed, using thicknesses of 25 mm (Test 7) and 38 mm (Test 6). The temperature profiles behind the face layer of the cement board and gypsum-concrete tests are shown in Figure 1. This graph demonstrates different encapsulation threshold criteria that were being evaluated during the project, i.e. an increase of 140 ºC, 195 ºC or 250 ºC. The time that the encapsulation criteria were reached in these tests is summarized in Table 2 (failure for the test with two layers was determined behind the base layer).

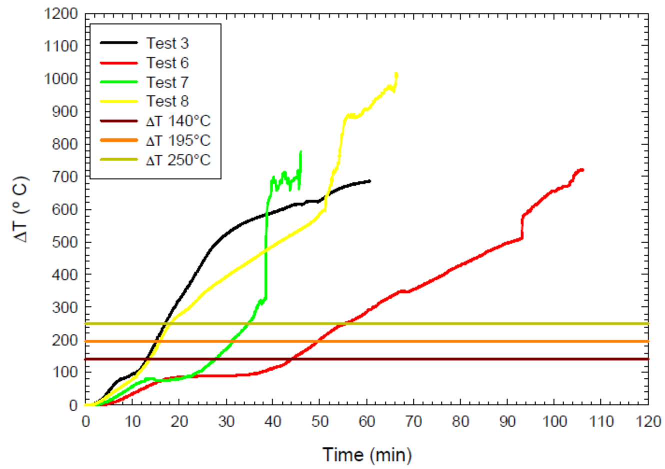


Figure 1. Average temperature rises beneath face layer encapsulation of cement board and gypsum-concrete [10]

Table 2. Encapsulation performance in intermediate scale tests [10]

Encapsulation Material	Test Number	Thickness (mm)	Number of Layers	Layer Position	Time to Increase		Fall-Off Time (Min)
					AVG 250 °C	Point 270 °C	
Cement Board	3	12.7	1	Face	17.1	16.0	> 60
	8	12.7	2	Face	18.2	16.0	50
				Base	45.3	42.5	65
Gypsum-Concrete	7	25	1	Base	35.0	28.8	38
	6	38	1	Face	55.7	55.1	93

One layer of 12.7-mm cement board achieved a rating of 16 minutes, and two layers reached 42.5 minutes, being assigned a rating of 43 minutes (ratings are rounded to the nearest whole minute). The cone calorimeter and intermediate-scale test results suggest that two layers of 12.7 mm cement board would be insufficient to meet the 50-minute encapsulation rating.

A 38-mm gypsum-concrete topping is permitted by the proposed EMTC provisions as an acceptable encapsulation material for the top side of a floor; in the intermediate scale tests, this type of assembly achieved an encapsulation rating of 56 minutes. Twenty-five mm of gypsum-concrete had an encapsulation time of 29 minutes. Increasing the thickness of the gypsum-concrete by 13 mm added 26 minutes to the encapsulation time. If the cement board thickness were increased from 12.7 mm to 15.9 mm (⅝”), this translates to a total increase in thickness of 13 mm when two layers are used. This additional depth may be enough to increase encapsulation time from 43 minutes to 50 minutes (by 7 minutes).

5.1.2 Comparison of Intermediate-Scale to Full-scale Exposure

NRC conducted tests to evaluate and compare the incident heat flux in their full-scale and intermediate-scale furnaces [11]. Heat flux exposure for floor specimens was slightly higher (approximately 18%) in the intermediate scale test as compared to the full-scale test (Figure 2); furnace size had a big impact on heat flux. If heat fluxes are higher in the intermediate scale furnace, this may have a negative impact on the evaluation of encapsulation materials, by decreasing the amount of time before the temperature criteria are met. It is possible that encapsulation materials may perform better in a full-scale test as compared to an intermediate scale test.

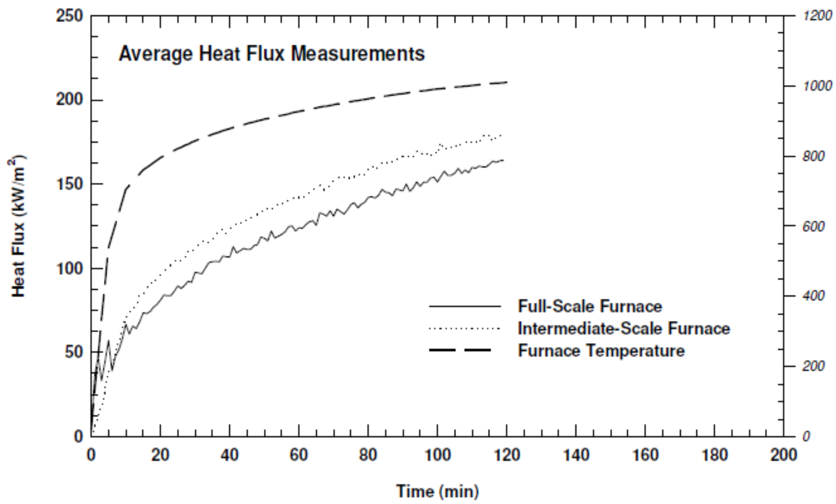


Figure 2. Comparison of heat flux in floor furnaces (full-scale vs. intermediate scale) [11]

It should also be noted that during this study, a comparison was done of the heat flux measurements in both the full-scale floor and wall furnaces. These tests indicated that heat flux at the surface in both wall and floor tests were nearly equivalent. Therefore, it would make sense to permit testing of wall assemblies in the CAN/ULC-S146 standard, as they are intended to be constructed in a vertical orientation.

The performance of gypsum board in intermediate-scale tests was compared to the performance of gypsum board in full-scale tests when directly applied to mass timber and exposed to a standard fire [2]. Two layers of 12.7 mm had an encapsulation time of 58 minutes in intermediate-scale tests and 58.8 min in a full-scale loaded fire resistance test directly applied to cross-laminated timber (CLT). This comparison would suggest that exposure is similar in the intermediate-scale and full-scale furnaces yielding similar encapsulation results.

5.2 Non-Standard Compartment Fire Exposure

Several non-standard compartment fires have been conducted in recent years to support mass timber construction in North America. In many of these tests, cement board was used on the floor to replicate a concrete topping because it can be quickly installed but still provides a similar weight to concrete, and it also delays the involvement of the wood floor elements.

5.2.1 ICC Code Change Tests

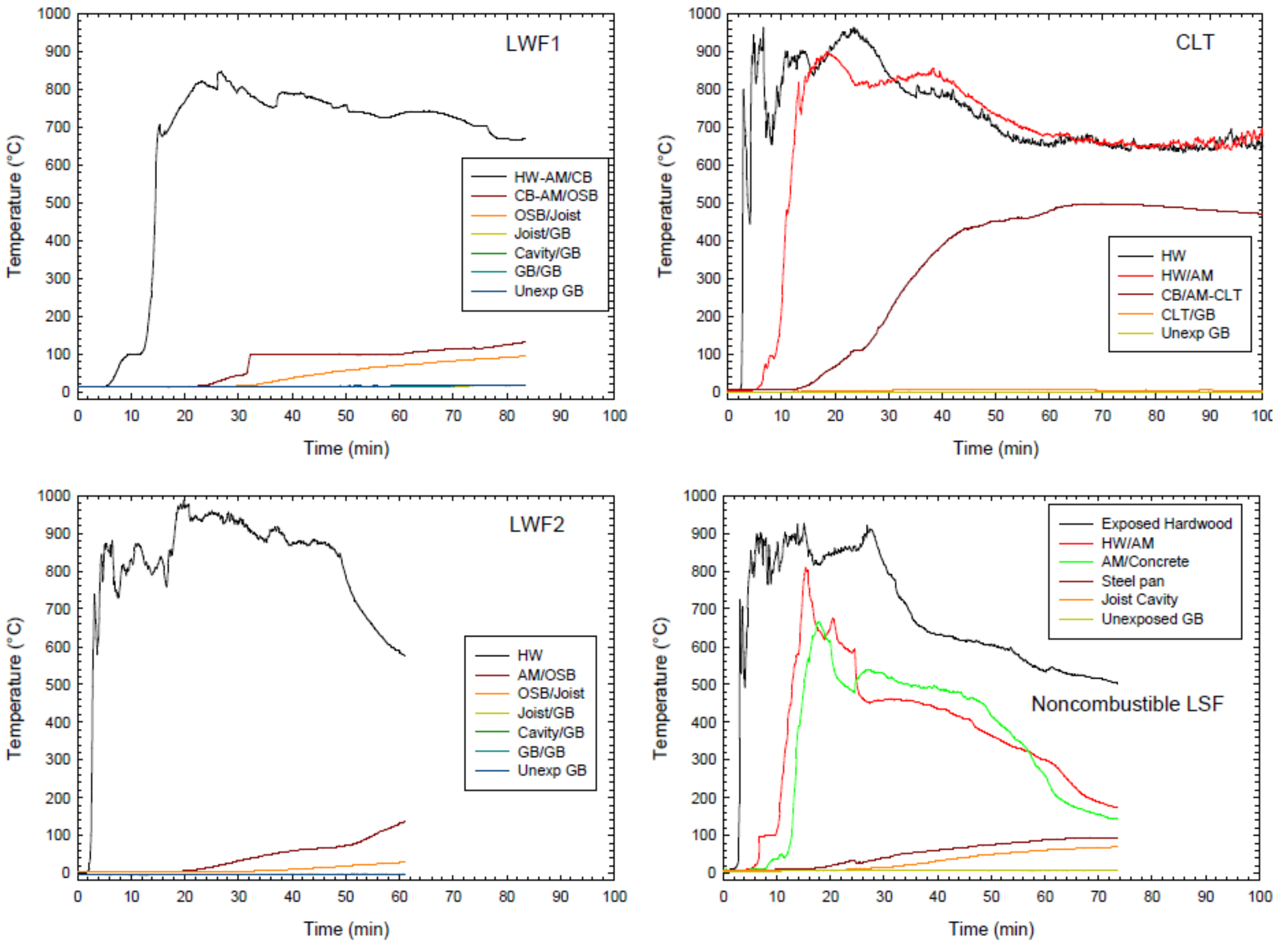
In two-storey CLT compartment tests conducted by the US Forest Products Laboratory (FPL) in support of the International Code Committee's (ICC) consideration of allowing up to 18-storey mass timber construction in the US, two layers of 12.7-mm cement board were used as a topping above the concrete slab on the main floor and above the CLT floor on the second storey [12]. Wood flooring was added above in the compartments. No thermocouples were installed beneath the cement board, and the wood floor surface was not evaluated after the tests.

5.2.2 Mid-Rise Consortium Compartment Tests

Real-scale compartment tests were conducted to support the Mid-Rise Research Consortium [2]. These tests included two-storey structures using light-wood-frame (LWF - two tests, 1 and 2), CLT and light-steel-frame (LSF) to benchmark the performance of a building of noncombustible construction that was prescriptively permitted by the 2010 NBCC compared to the performance of proposed mid-rise wood structures.

In the wood compartment tests, two layers of 12.7-mm cement board were used as an alternative to a concrete topping. A floating hardwood floor with an acoustic membrane was installed above the cement board on the main floor. In the CLT test, the cement board was installed directly above the CLT; in the light-wood-frame tests, the cement board was installed above a 15.9-mm thick OSB subfloor. On the second storey, no acoustic membrane or finished floor was installed. In the light-steel-frame test, a 0.46-mm steel pan and 38-mm lightweight concrete were used.

All of the tests were instrumented with various thermocouple trees and thermocouples inside the wall, ceiling and floor assemblies. The temperatures at various interfaces, including beneath the cement board (CB) or concrete in the bedroom (room of fire origin), are shown in Figure 3. The times at which the encapsulation criteria were met at this location are summarized in Table 3.



HW: Hardwood AM: Acoustic Membrane CB: Cement Board OSB: Orientated Strand Board GB: Gypsum Board
Figure 3. Mid-Rise Tests – Temperatures at floor assembly interfaces [2]

Table 3. Time to reach encapsulation criteria in mid-rise compartment tests [2]

Temperature Increase	CLT 2 x 12.7 mm CB	LWF 1 2 x 12.7 mm CB	LWF 2 2 x 12.7 mm CB	LSF 38 mm concrete
Avg. 250 °C	47.2 min	DNR	DNR (max 200 °C)	DNR (< 100 °C)
Single Point 270 °C	35.9 min (35.9-97.8)	78.7 min	DNR	DNR (< 100 °C)

CB: Cement Board * DNR - Did not reach

In LWF1, the OSB subfloor reached 150 °C after 60 minutes and did not increase significantly after that. In LWF2, the OSB subfloor in the bedroom reached a maximum of 200 °C. The LWF floor structural elements (subfloor and I-joists) were not affected by fire during the tests. In the LSF test, the temperatures stayed below 100 °C underneath the concrete subfloor.

In the CLT compartment, the encapsulation time of the two layers of cement board was 36 minutes based on the single point criteria (47 minutes based on the average increase of 250 °C). This was shorter than the encapsulation time measured in the light-wood-frame tests; the difference for these results is not known [2]. Maximum temperatures behind the cement board in the CLT test reached 400-500 °C around 60 minutes and then declined until the end of the test. Based on this information, it is apparent that the CLT surface ply charred, but there was no flaming combustion, which indicated that the CLT floor did not contribute to the growth and spread of fire [2].

5.2.3 Characterization of Fires in Multi-Suite Residential Dwellings

The NRC conducted a project to understand fires in low-rise multi-suite light-frame buildings, titled the *Characterization of Fires in Multi-Suite Residential Dwellings* (CFMRD) project [13]. It generated design fires for these structures based on a survey of similar buildings to assess the fuel load and its distribution.

Fourteen tests were conducted within a single storey structure with an area of 48 m^2. The size, number of rooms involved and the size of ventilation openings varied between tests. In the first test (PRF-01), the floor substructure included wood joists, 12.7-mm cement board, 15.9-mm OSB, a 0.4-mm underpad and 14-mm carpet (Figure 4). The floor structure was instrumented above each of these materials, see the floor instrumentation plan in Figure 5, which shows thermocouples as black dots.

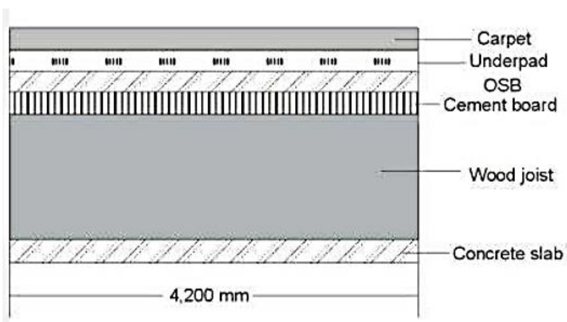


Figure 4. CFMRD PRF-01 floor assembly [14]

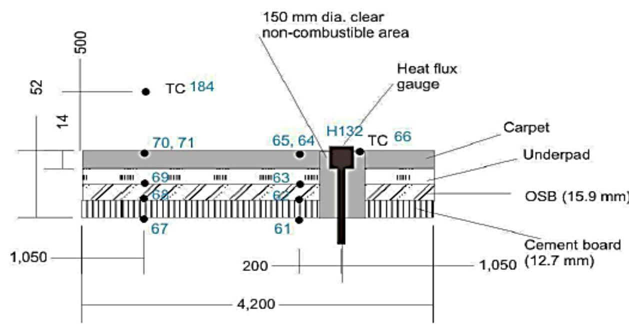


Figure 5. CFMRD PRF-01 floor instrumentation [14]

The temperatures in the north section of the bedroom floor in PRF-01 are shown in Figure 6 and in the south section in Figure 7 (the fire was initiated near the south-west corner of the room). In PRF-01, the fire was initiated in the primary bedroom and used the larger ventilation opening size. Within the floor, the various coverings provided additional protection from fire exposure beyond that of the cement board. Temperatures behind the cement board increased roughly 250 °C after 30 minutes in the north section and 25 minutes in the south section. This was more than the 16 minutes observed for one layer of 12.7-mm cement board in the intermediate scale tests. This floor design failed to withstand the fire, so the design was modified for the remaining tests; the cement board was replaced with gypsum board to improve fire resistance. This design was more robust and worked well.

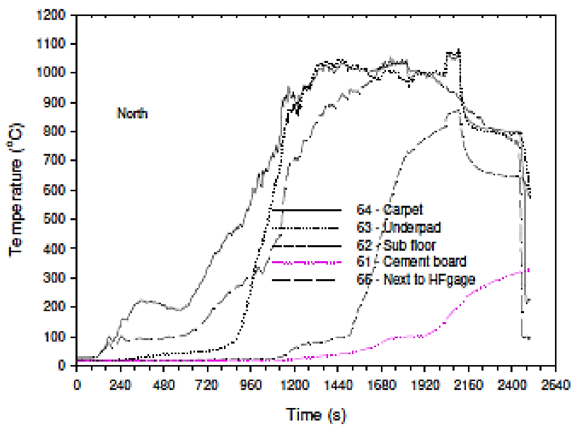


Figure 6. PRF-01 N Floor thermocouples [13]

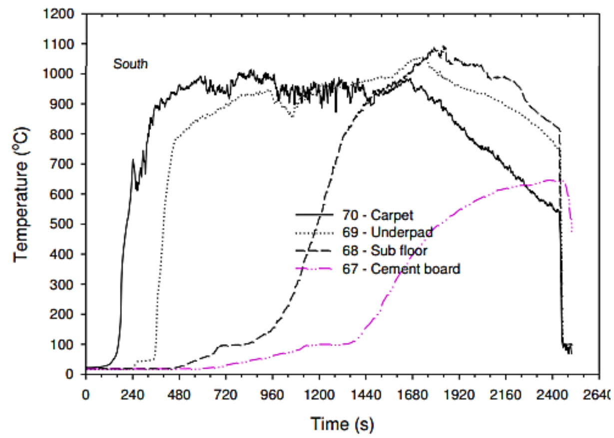


Figure 7. PRF-01 S Floor thermocouples [13]

5.2.4 Discussion

Literature related to the performance of cement board in standard and non-standard compartment tests was reviewed. There is limited data available related to the use of cement board as an encapsulation material, although it is commonly used in compartment tests to replicate a concrete topping. The encapsulation time of one layer of 12.7-mm cement board was found to be 16 minutes, and the time for two layers was 43 minutes in intermediate-scale tests. This was less than the encapsulation time of 38 mm of gypsum-concrete at 55 minutes in the same test series, but more than a 25-mm application with an encapsulation time of 29 minutes. Two layers of 12.7 mm of cement board would likely not reach a 50-minute rating in the CAN/ULC-S146 test, and this configuration does not provide equivalent performance to 38 mm of concrete. Two layers of 12.7 mm are equivalent in thickness to 25.4 mm; at this thickness the cement board had better performance than 25 mm of gypsum concrete. Increasing the thickness of the cement board to 15.9 mm for both layers should improve the performance and may be sufficient to reach the 50-minute rating.

In non-standard compartment tests, shorter encapsulation times were measured, as would be expected since fire exposure is more severe in compartment fires, where higher temperatures can be reached more quickly than in a standard fire. The encapsulation time of two layers of 12.7-mm cement board (covered with an acoustic membrane and finished hardwood flooring) was 36 minutes in the mid-rise CLT compartment test. In this test, temperatures behind the cement board reached a maximum of around 500 °C, indicating that the wood had charred (based on the onset of char around 300 °C) but that there was no flaming combustion, which indicated that the wood floor did not contribute to the growth and spread of fire, which is the intent of encapsulation.

In the CFMRD test, encapsulation time was between 25 to 30 minutes for one layer of 12.7-mm cement board which was also protected by a layer of OSB and typical flooring. In the south floor section, near where the fire was initiated, temperatures behind the cement board reached 600 °C, but in the north section, the maximum temperature was 300 °C. This suggests that encapsulation failure can be confined to a local area in a compartment fire based on the room temperatures and radiation at that location.

6 TEST DESIGN – FEASIBILITY ASSESSMENT

6.1 Proposed Test Design

A test method is being proposed to evaluate the encapsulation of a floor topping using a full-scale fire resistance furnace. The intent is to follow the CAN/ULC-S146 standard, as best as possible, but to modify the design to test the assembly on the floor of the furnace, to mitigate against the possibility of premature fall-off of the encapsulation material negatively impacting the encapsulation time. There are no other existing standards in Canada that evaluate the fire resistance of floors with exposure from above; exposure from below is considered to be a more severe scenario due to the buoyancy of hot gases. There is a test method to evaluate flame spread across the top of floor finishes, CAN/ULC-S102.2 *Standard Method of Test for Surface Burning Characteristics of Flooring, Floor Coverings, and Miscellaneous Materials and Assemblies* [15], but this only covers the propensity for flames to move across a surface.

The size of the assembly will be limited by the furnace wall dimensions, and this configuration will require the removal of five control thermocouples in the middle of the furnace (nine control thermocouples are required by the standard).

A 75 mm thick wood substrate will be placed in the pit, on the bottom of the furnace. The encapsulation material will be installed above the wood. To be able to accurately confirm that the fire exposure at the floor is equivalent to the exposure received for an assembly exposed to fire from beneath (ceiling), a second near identical (but mirrored, i.e., the wood surface will be on the unexposed side, and the cement board will be inside the furnace (exposed side)) assembly will be simultaneously installed in the furnace frame (as a ceiling). Additional instrumentation will be added including thermocouples at the surfaces of the cement board and along the height of the furnace on thermocouple trees. Plate thermometers and heat flux gauges will be used to compare temperatures and heat fluxes at the surfaces.

To confirm whether this test is possible, it needs to be determined whether temperatures at the bottom of the furnace are consistent with temperatures at the ceiling surface and whether the furnace can be accurately controlled with the removal of the five central control thermocouples.

6.2 Temperature Distribution in Full-Scale Furnace

NRC performed tests to determine the feasibility of conducting column tests in their existing floor furnace in 1960 [16]. An important factor was whether furnace temperatures would be consistent along the height of a column. Figure 8 shows the measured temperature distribution within the furnace using smoothed curves at various heights. The temperature distribution in the furnace was considered to be sufficient for their purposes; it was also better than the only other similar data available for another furnace [16]. In the section near the location of the burners, temperatures were higher. Temperatures measured at the top of the furnace (T5) and near the floor (T1) were very close.

The height of the burners is 760 mm from the floor of the furnace. The floor test assembly in this project will be roughly 125 mm thick, putting the height of the burners about 635 mm from the floor. At this height the temperatures were not greatly impacted by the burners. Based on this, it is expected that an assembly at the floor would be exposed to the same temperatures as a ceiling assembly.

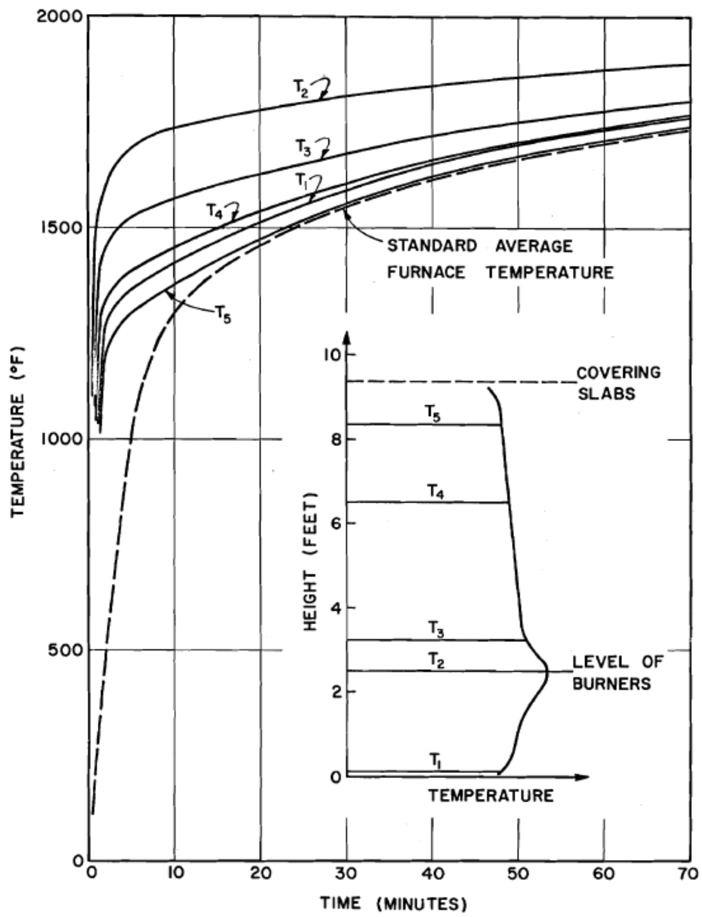


Figure 8. Vertical temperature distribution in full-scale furnace [16]

6.3 Temperature Control

The CAN/ULC-S101 and CAN/ULC-S146 standards require that the average of nine thermocouples be used to control the furnace temperature for a ceiling assembly. The control thermocouples must be in sealed porcelain tubes or steel or iron pipes. For floors, the thermocouples are to be placed 300 +/- 10 mm from the exposed surface of the test specimen. The distribution of the thermocouples should be sufficient to provide one thermocouple for every 1.5 m^2 of furnace cross-sectional area. The accuracy of the furnace control must be that the area under the time-temperature curve (taken from the average of the nine thermocouples) is within 10% of the corresponding area under the standard curve (in CAN/ULC-S101 this is for fire tests less than 1 hour, greater accuracy is required for longer tests). In the proposed test design, placing an assembly on the floor will require the removal of the five central floor thermocouples.

Data from three recent full-scale floor tests at NRC was reviewed to determine temperature variations between each of the nine furnace control thermocouples. Each of these tests used unprotected mass timber (i.e., had exposed wood surfaces). The tests included 2 x 6 nail-laminated timber (NLT) [17], 2 x 6 glued-laminated timber sections (GLT) [18] and 2 x 8 GLT [18].

The integral of the average furnace temperature (taken as the area under the curve), based on the four control furnace thermocouples located on the wall (TCs 6-9) that would remain after the removal of the five central control thermocouples (located on trees), was determined. This was compared to the area under the standard cure; the results are presented in Table 4. The average of these four thermocouples was within 1% of the standard curve in all of the tests. The average of TCs 6-9 was also compared to the average of TCs 1-5 and was found to be very close. This indicates that the four control thermocouples on the wall are sufficient to ensure the furnace temperature follows the standard fire curve.

Table 4. CAN/ULC-S101 wall control thermocouples - deviation from standard curve

Test Type	Test Duration	TC 6-9 Deviation
2 x 6 NLT	101 min	1.0%
2 x 6 GLT	152 min	1.0%
2 x 8 GLT	188 min	1.0%

6.4 Furnace Dimensions

The CAN/ULC-S146 standard requires that neither dimension of the assembly be less than 3,600 mm and the total area not be less than 13.4 m^2. The maximum dimensions for an assembly in the ceiling frame are 3,962 mm x 4,870 mm. The furnace interior dimensions are 3,708 mm x 4,616 mm. If an assembly were to be constructed on the floor, there would need to be approximately 50 mm tolerance around the sides to allow for ease of installation. This reduces the possible size of the assembly to 3,606 mm x 4,521 mm. Therefore, an assembly on the floor can be designed to meet the size and area requirements of the standard.

6.5 Appropriateness of Standard Fire Exposure for a Floor Topping

Non-standard compartment fire tests of wood or mass timber assemblies were reviewed to assess the fire exposure received at floor and ceiling surfaces to determine whether the same standard fire exposure is justified for a floor. If the two are exposed to similar temperatures and heat fluxes in non-standard fires, then it would be appropriate to also use the standard fire to test a floor top, as it is used for other assemblies (i.e., walls and ceilings). For most of the compartment tests reviewed, it was rare to have thermocouples installed right at the floor surface on thermocouple trees. Generally, the lowest measurement location would start about 0.5 m from the floor. It is possible that temperatures right at the floor level could have been cooler.

6.5.1 Characterization of Fires in Multi-Suite Residential Dwellings

Thermocouple trees were installed around the room(s) in the CFMRD tests [13]. Trees were installed at various heights between 0.4 m and 2.4 m (at the ceiling). The lowest temperatures taken were not right at the floor but close to it. At trees located in the south-west section of the bedroom (room of fire origin), there was little stratification of temperatures during the test. In the first test (PRF-01), temperatures were nearly identical at heights from 0.9 to 2.4 m, see Figure 9. In the third test (PRF-03), temperatures were also similar, although slight differences were apparent based on height, with temperatures up to 200 °C lower at 0.4 m during the fully developed phase of the fire, with the difference becoming larger during decay, see Figure 10. This trend was consistent for several of the tests. There were some examples where temperatures near the floor were lower than the ceiling in locations near a window opening due to a cooling effect from the inflow of fresh air [13]. Generally, from this research it would be conservative to say that temperatures were consistent along the height of the room during flashover and the fully developed stage.

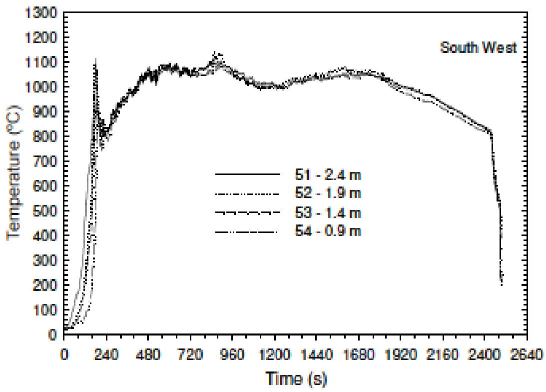


Figure 9. PRF-01 SW tree temperatures [13]

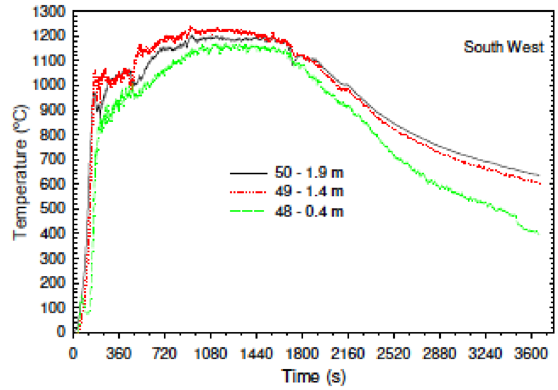


Figure 10. PRF-03 SW tree temperatures [13]

6.5.1.1 <u>Heat Flux</u>

Heat flux was measured during the CFMRD tests at the floor and the ceiling, as well as from the exterior. The floor and ceiling heat flux gauges were not placed at the same location in the rooms, so it is difficult to directly compare the results. Figure 11 to Figure 14 show the measured heat fluxes for tests PRF-01 to PRF-04. In some cases, higher heat fluxes were measured at the floor, depending on where the fire started and the location of the heat flux gauges. There are no clear discernable trends in relation to the heat flux measured at the floor versus at the ceiling.

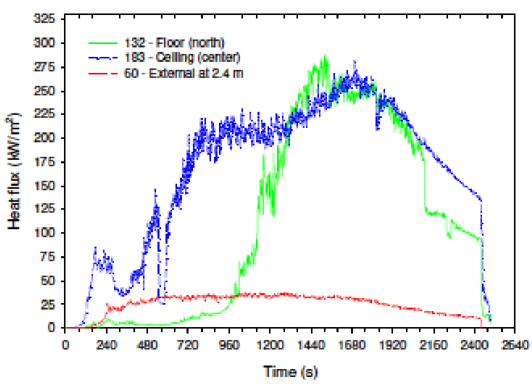


Figure 11. PRF-01 heat fluxes [13]

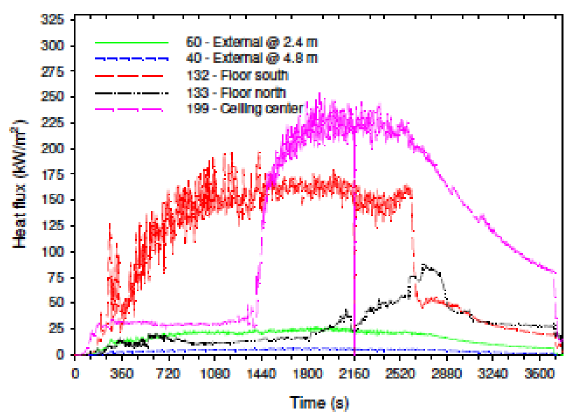


Figure 12. PRF-02 heat fluxes [13]

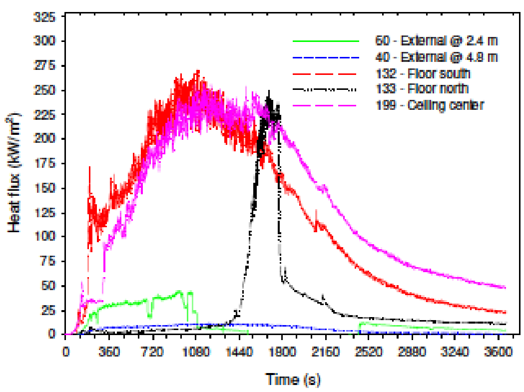


Figure 13. PRF-03 heat fluxes [13]

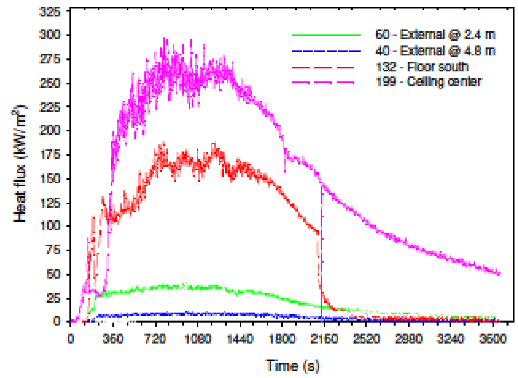


Figure 14. PRF-04 heat fluxes [13]

6.5.2 Fire Protection Research Foundation Tests

NRC conducted CLT compartment tests as part of a research project funded by the National Fire Protection Association (NFPA) Fire Protection Research Foundation (FPRF) to evaluate the contribution of mass timber to a compartment fire [19]. A series of six tests was completed with variables being the size of an opening at the front of the compartment and the degree and location of exposed mass timber surfaces. In these tests, the concrete floor was protected with two layers of 15.9-mm Type X gypsum board and two layers of 12.7-mm cement board, covered with a 7-mm laminated flooring.

Several thermocouple trees were installed throughout the compartments; installation locations are shown in Figure 15. Thermocouples were installed at heights between 0.6 to 2.6 m above the floor. The ceiling height was 2.7 m. A heat flux gauge was located on the floor, near the back of the compartment and at mid-height on one of the walls. There was also a plate thermometer at the centre of the ceiling that was used to calculate heat flux.

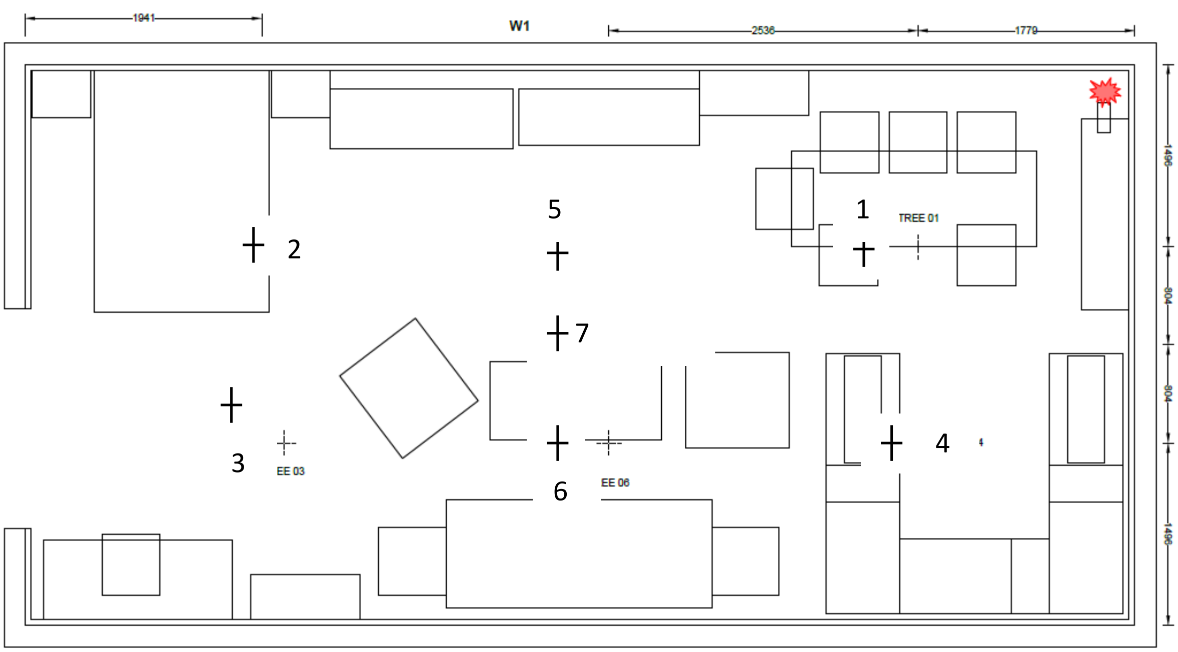


Figure 15. Thermocouple tree locations in FPRF tests [19]

For most of the tests, the temperatures measured at the thermocouple trees were generally consistent at various heights during flashover and the fully developed stage. If there was temperature deviation based on height, it typically occurred during the decay phase. Figure 16 demonstrates the temperature distribution within the compartment at the various thermocouple trees in Test 1-1. TC_060 in blue represents the temperatures measured 0.6 m above the floor. TC trees 2 and 3 were near the front of the compartment, TC trees 5 and 6 near the middle, and TC trees 4 and 1 were near the back. The fire was ignited at the back of the compartment. During flashover the temperatures in the room were essentially consistent at all locations. Following flashover or once the peak heat release rate had been reached, it is evident that the temperatures stratified and temperatures at the floor were generally lower than the temperatures at the ceiling (denoted by TC_260). The temperature difference was roughly between 100 °C and 300 °C between the highest and lowest thermocouples. As the fire decayed the differences became larger. There appears to have been less variation in the temperatures in TC trees 1 and 4 near the back of the compartment. This behaviour was similar in tests 1-1 through 1-5; test 1-6 had very high temperatures consistently at all locations for long durations into the test. The temperature profiles for some of the other tests are given in Appendix A.

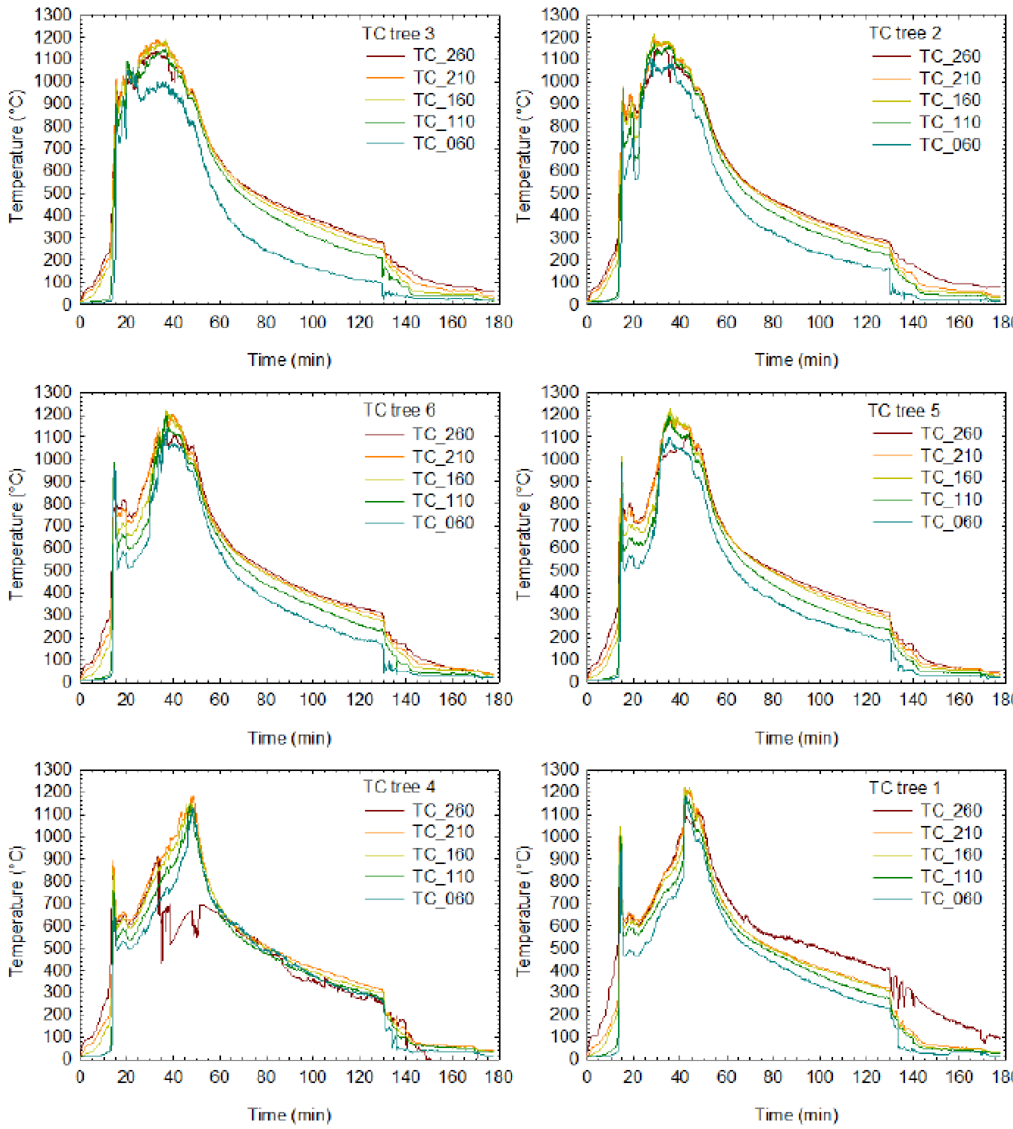


Figure 16. FPRF test 1-1 – Thermocouple tree readings [19]

Figure 17 shows heat fluxes calculated from plate thermometers in the ceiling at the centre of the compartment and above the bed compared to the heat flux measurements on the floor (at the back of the compartment) in test 1-1. The initial vertical spike at the floor corresponds to flashover. Heat fluxes above the bed peaked close to 250 kW/m^2; at the floor the peak was very briefly at 200 kW/m^2. The total heat flux at each location (based on the area under the curve) was significantly less at the floor. A similar trend was observed for tests 1-2 and 1-3, but higher heat fluxes for longer durations were measured at the floor in tests 1-4, 1-5, and 1-6. The heat flux plots for these other tests are presented in Appendix B. Due to the variability in the locations where heat flux was measured, it is difficult to make any correlations between the heat fluxes experienced at the floor and the ceiling.

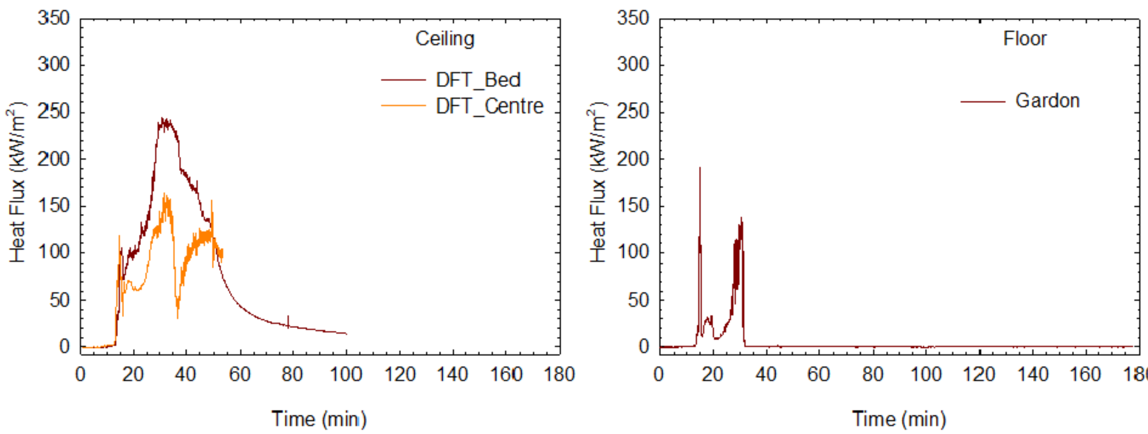


Figure 17. FPRF Heat flux at the ceiling and floor in test 1-1 [19]

6.5.3 Carleton University Compartment Fires

Three CLT compartment fire tests were conducted at Carleton University [20]. In these tests, the floor was constructed of wood studs, 12.7-mm plywood, 12.7-mm cement board and a finished hardwood floor. Thermocouple trees were installed to evaluate room temperatures, with thermocouples placed between 0.4 and 2.4 m (at the ceiling) above the floor. Throughout the 2-hour duration of the first test (test 1), all of the thermocouples in the middle and back of the room (location of ignition) read nearly identical temperatures except closest to the ceiling where temperatures were lower (which was also true for other thermocouple tree locations as well as in test 2); this was unexpected but may be related to the thermocouples being installed too close to the ceiling gypsum. A plot of temperatures in the back of the room is shown in Figure 18. By the door, lower temperatures were measured near the floor after 50 minutes into the test (Figure 19), which is associated with cool air entering the room [20]. In test 3, all of the thermocouple tree temperatures at the various heights were very consistent.

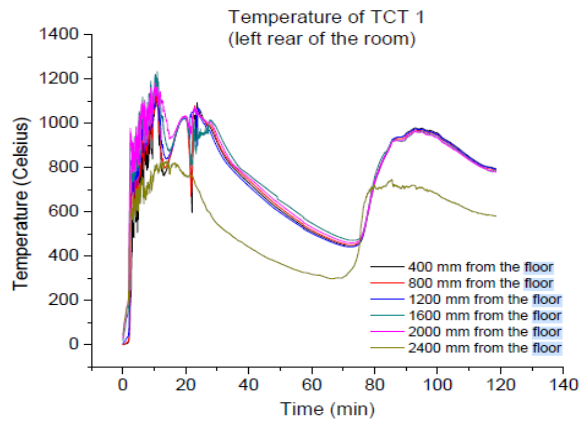


Figure 18. Carleton test – Temperature profile at back of room [20]

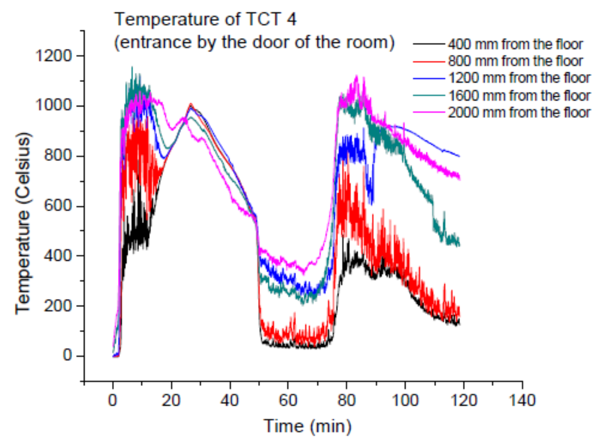


Figure 19. Carleton test – Temperature profile at opening [20]

6.5.4 Discussion

In real-scale compartment fire tests, the temperature at the floor and ceiling were generally consistent during flashover and the fully developed stage of the fire. In some tests, temperature stratification was more evident, with cooler temperatures at the floor, later in the tests, once the fire had started to decay. It was also apparent that, in some tests, temperatures near the floor were lower close to an opening where cool, fresh air was entering the compartment. It would be conservative to say that the floor was exposed to equivalent temperatures as the ceiling.

In most of the tests examined, heat flux was measured, but it was difficult to compare the results because heat flux gauges at the floor and ceiling were usually in different locations. In some cases, heat flux was significantly less at the floor, but in others they were similar. It depended on the location of ignition and progression of the fire.

Heat fluxes in real compartment tests of wood structures were consistently lower at the floor than at the ceiling. In standard fire tests, temperatures at the floor and ceiling were comparable, suggesting similar fire exposure. This would suggest that using standard fire exposure to evaluate both floor toppings would be conservative.

Based on this analysis, it would seem feasible that a modified CAN/ULC-S146 test could be conducted with an assembly on the floor of the furnace. The main reasons for this are:

1. Temperature within the furnace is generally uniform. The temperature at the floor level is equivalent to the temperature at the top of the furnace.
2. The furnace can be controlled with only four wall control thermocouples.
3. The dimensions of the furnace permit the required size of an assembly for the standard.
4. In compartment tests, heat fluxes at the floor were lower than at the ceiling. Standard fire exposure, typically used for ceiling exposures, would be conservative for a floor topping test.

7 TEST DESIGN & CONSTRUCTION

The final design of the assembly involved placing a 3,605 mm x 4,520 mm assembly on the floor in the furnace (referred to as Assembly F for floor). To capitalize on the opportunity, a 3,910 mm x 4,825 mm assembly was simultaneously tested on the top of the furnace (referred to as Assembly C for ceiling). See Figure 20 for an elevation view of the test setup. The detailed design drawings can be found in Appendix C.

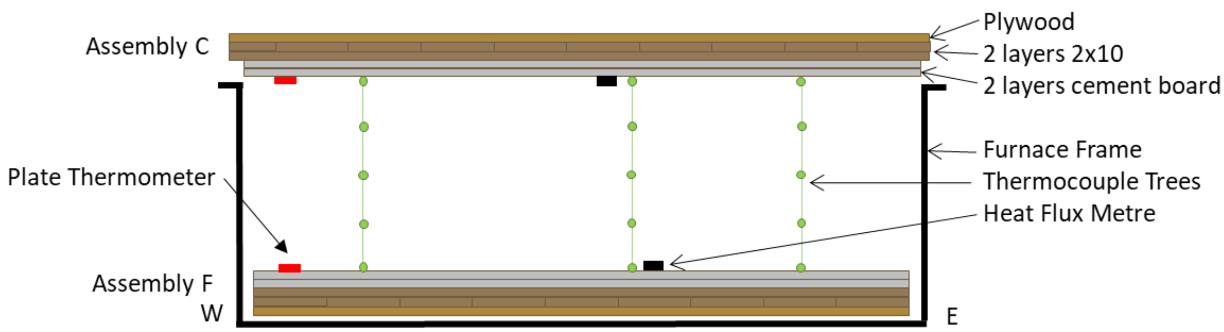


Figure 20. Elevation view of test setup

Fire exposure in non-standard compartment tests was generally lower at the floor. It would be conservative to subject the ceiling and floor to the same fire curve for evaluation. The literature also showed that temperature exposure should be equivalent at both surfaces within the furnace, so that the floor surface should be exposed to temperatures equivalent to at the ceiling.

7.1 Wood Substrate

The CAN/ULC-S146 standard requires that the substrate material that the encapsulation is attached to be at least 76-mm thick, which is equivalent to the depth of two 38 mm (standard 2 x) lumber boards laid flatwise. The assemblies were constructed of two layers of 2 x 10 lumber, with the boards of the face layer oriented perpendicular to the base layer. 63-mm (2 ½”) wood screws were used to connect the two layers. 1,220 mm x 2,440 mm (4’ x 8’) sheets of plywood were installed on the unexposed side of both assemblies to hold the assemblies together during installation and to potentially limit air leakage through any gaps. The wood surfaces before the installation of cement board are shown in Figure 21 and Figure 22, for the floor and ceiling assemblies, respectively.

Any exposed surface of the wood substrate around the outer edges of the assembly was protected from direct exposure, as per the standard, using ceramic fibre blankets.

Figure 21. Assembly F wood substrate

Figure 22. Assembly C wood substrate

7.2 Cement Board

Because two layers of 12.7 mm of cement board only reached an encapsulation time of 43 min, it was decided to use two layers of 15.9-mm cement board as the encapsulation material (15.9-mm cement board is less commonly available). The analysis of previous test data suggested that the additional thickness of the boards might be enough to increase the encapsulation time to 50 min. 1,220 mm x 2,440 mm (4' x 8') cement board sheets were attached to the wood surface; joints in the face layer were staggered from the base layer. CAN/ULC-S146 requires that the outer edges of the encapsulation material must not be supported by the walls and be at least 25 mm from the walls. The cement board surface was designed to accommodate these requirements. The cement board surface is shown in Figure 23 and Figure 24 for the floor and ceiling surfaces, respectively.

30-mm (1 ¼") cement board screws were used for the base layer on the floor, and 40-mm (1 ⅝") screws were used in the base layer of the ceiling. The face layer on the floor and ceiling used 57-mm (2 ¼") cement board screws. 200-mm o.c. screw spacing was used on the floor, with screws 25 mm from edges. 150-mm o.c. screw spacing, with screws 16 mm from edges, was used on the ceiling as per manufacturers specifications, with screws 50 mm away from any corners. A longer screw length was used for the ceiling to ensure adequate penetration depth into the wood substrate as well as closer screw spacing to mitigate potential fall-off on the ceiling.

Some small gaps, up to a maximum 3 mm (¼"), formed between some of the cement board panels on the floor after installation. These gaps, totaling roughly 1,200 mm linearly (4 ft.), were filled with Rescoset MD mortar. These gaps were not observed on the ceiling.

Figure 23. Assembly F Cement board

Figure 24. Assembly C Cement board

7.3 Instrumentation

According to CAN/ULC-S146, the temperature of the interface between the encapsulation material and the wood substrate shall be measured by 9 Type-K thermocouples located at the centre of the test specimen, at the centre of each quarter and at potentially critical locations such as joints. The locations of the Type-K thermocouples at the interface are shown in Figure 25.

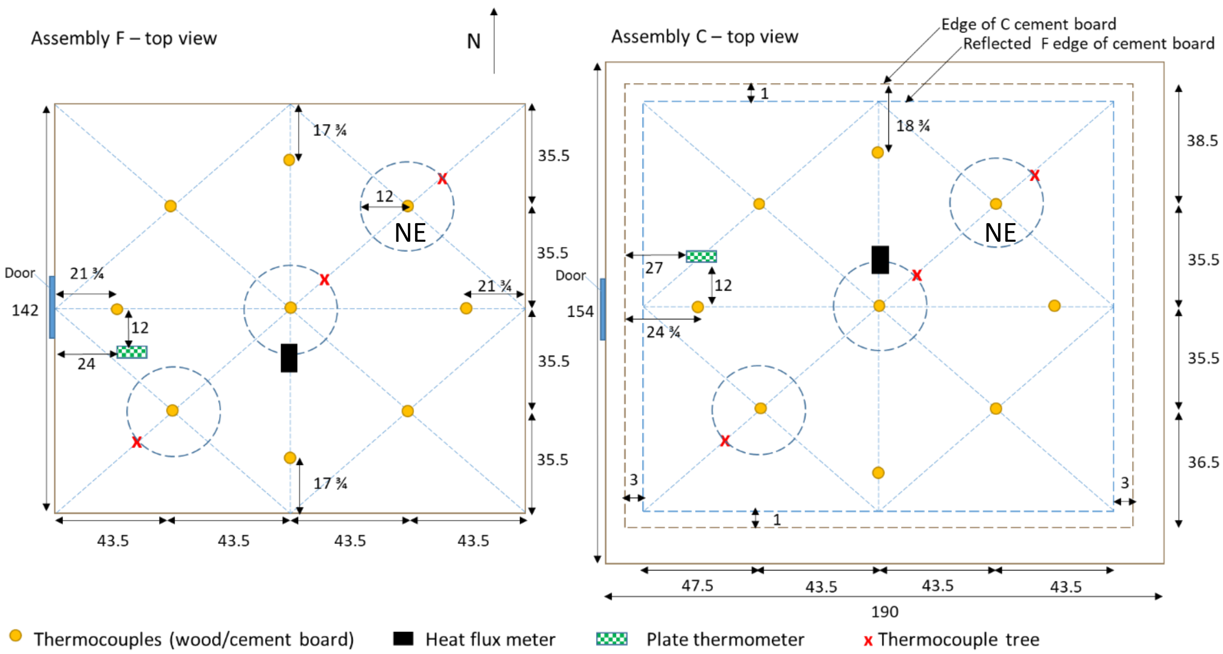


Figure 25. Instrumentation plan; not to scale (dimensions in in.)

7.3.1 Additional Instrumentation

Additional instrumentation was added to confirm that the temperature distribution along the height of the furnace was consistent, but most importantly that it was similar at the two cement board surfaces. Gardon gauges to measure heat flux (manufactured by Medtherm Model 64-20-18), and plate thermometers (manufactured by Pentronic Model 5928060) were also added at each surface to assess any differences in heat flux at the floor and ceiling surfaces. The locations of the additional instrumentation are shown in Figure 25.

Three thermocouple trees were installed in the furnace, each with six thermocouples. The locations of the trees are shown in Figure 25. The trees were placed in a row along one diagonal, spaced 300 mm (12") from the centre of the furnace and the centre of the two quadrants that fell along the diagonal. In Figure 25, both assemblies are shown from above so that the locations of the thermocouples are easily translatable. Thermocouples were placed at the floor surface (0 m), 0.53 mm, 1.06 m, 1.63 m, 2.16 m and 2.69 m (at the ceiling surface). The heights of the thermocouples are shown in Figure 26, and the thermocouple tree installation in the furnace is shown in Figure 27.

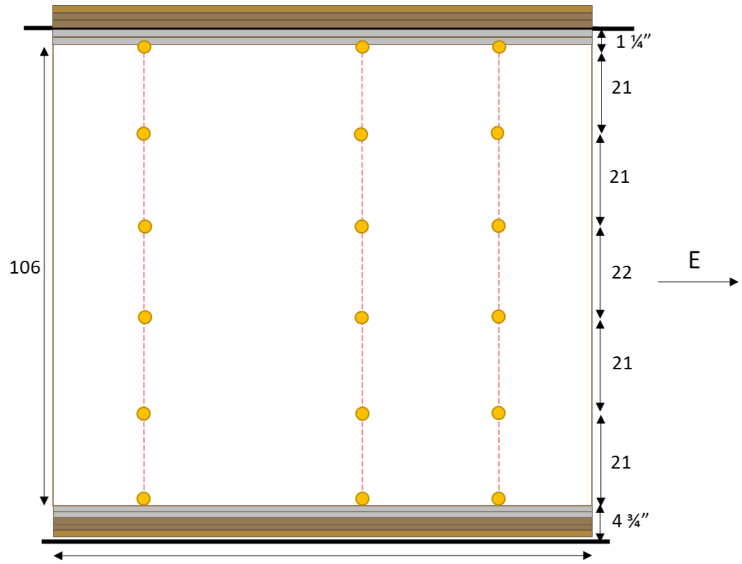


Figure 26. Thermocouple tree elevation drawing; not to scale (dimensions in in.)


Figure 27. Thermocouple tree installation

Plate thermometers were installed at both surfaces near the door, approximately 610 mm from the furnace wall, 305 mm from the centerline and approximately 150 mm above/below the surfaces. At the floor, the plate thermometer was to the south of the centerline, and at the ceiling it was to the north. The heat flux gauges were installed along the north-south centerline 305 mm away from the centre. On the floor the gauge was south of centre, and on the ceiling it was north of centre.

Two video cameras were used to film the ceiling during the test. Unfortunately, it was not possible to direct a camera to the floor surface.


Figure 28. Assembly F Plate Thermometer


Figure 29. Assembly C Heat flux gauge

8 RESULTS

The encapsulation test was conducted at the NRC Fire Research Laboratory on November 14, 2019. Both the ceiling and floor assemblies were simultaneously exposed to the CAN/ULC-S101 standard fire curve. The relative humidity of the wood substrate of the floor surface was 11.5% before the test, and the ceiling assembly was 10.3%. The encapsulation time of two layers of 15.9-mm cement board was the same for the ceiling and floor assembly at 38.9 minutes. Therefore, neither assembly achieved the desired 50-minute encapsulation time. The assigned encapsulation rating for both assemblies is 39 minutes. Both assemblies achieved their rating based on the single point increase of 270 °C criteria. The average time for temperatures to increase 250 °C was 42.3 minutes for the ceiling and 41.3 minutes for the floor. Figure 30 shows the average temperatures of the thermocouples between the wood surface and the cement board, as well as the two thermocouples that reached the single point criteria first in the ceiling (C-NE) and floor (F-SE). Ceiling measurements are denoted in blue and floor measurements in red. The plot of all of the interface thermocouples for both assemblies is given in Appendix D.

Ambient temperature at the beginning of the test for the thermocouples behind the ceiling was 18 °C and for the floor was 14 °C. The single point failure criteria were calculated individually for each thermocouple based on their initial temperature. The temperature criteria of 265 °C and 285 °C are plotted in Figure 30 to give an indication of when failure was reached. The average values are shown in dashed lines, and the single point values are shown as solid lines. A jump in temperatures was observed in several of the ceiling thermocouples between 10 to 15 minutes into the test and distinctly in the F-SE floor thermocouple at 10 minutes. The reason for this behaviour is not known but may be related to joint performance.

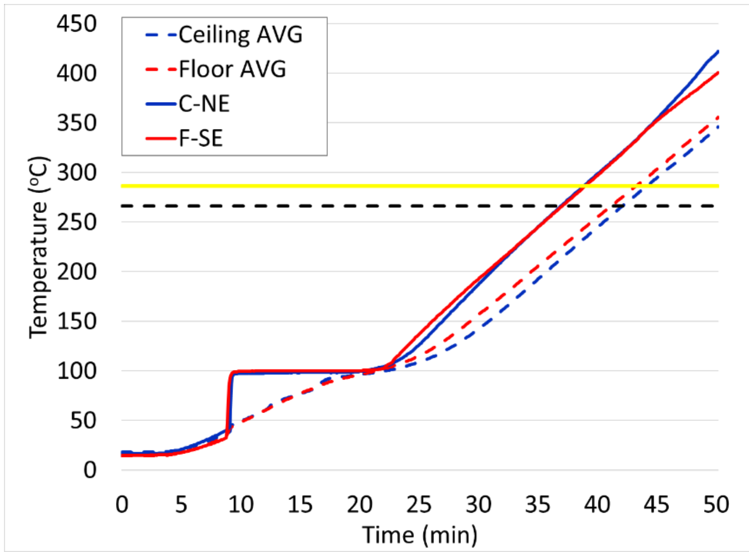


Figure 30. Temperatures behind base layer of cement board

Since the two assemblies were given an identical rating, this indicates that testing the assembly on the floor can adequately be used as an alternative to testing on the ceiling.

The cement board surfaces following the test are shown in Figure 35 and Figure 36 for the floor and ceiling, respectively. The ceiling surface picture was taken when the ceiling was removed from the furnace. Pictures of the floor surface were taken once the furnace had an opportunity to cool and was safe to open the door to the furnace, at which point there was no apparent flaming at the joints. Following the tests, the cement board was removed from the surface. The final wood substrate surfaces are shown in Figure 33 and Figure 34 for the floor and ceiling, respectively.


Figure 31. Assembly F: Cement board surface after test

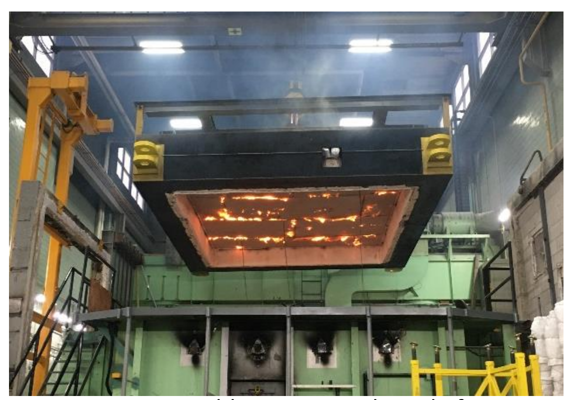


Figure 32. Assembly C: Cement board after test

Figure 33. Assembly F: Wood surface after test

Figure 34. Assembly C: Wood surface after test

8.1 Temperature Distribution in the Furnace

The furnace control thermocouples were in very close agreement with the standard fire curve. All of the four control thermocouples were within 1% of the control thermocouples average and the standard fire curve. The temperatures at each of the control thermocouples compared to the standard curve is shown in Figure 35. The removal of the five floor control thermocouples did not negatively affect the ability of the furnace to follow the standard curve.

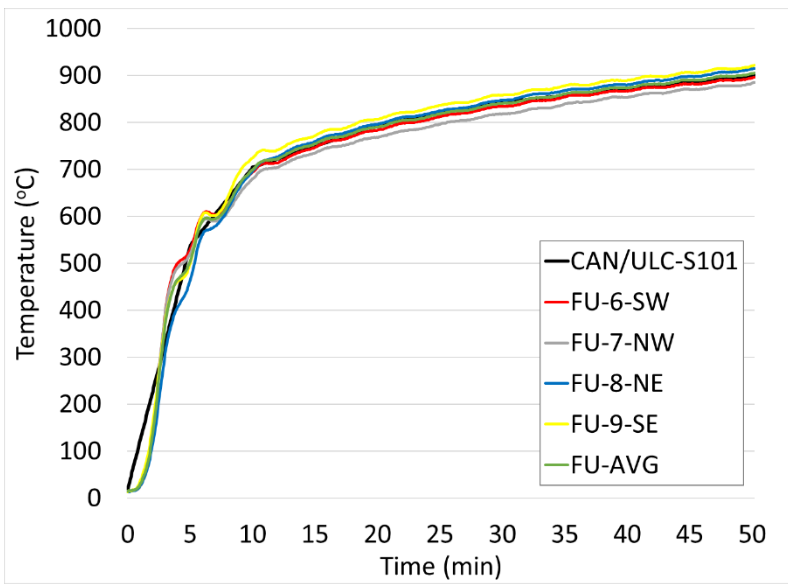


Figure 35. Furnace control thermocouple temperatures

The average of the temperatures at each of the thermocouple tree height locations is shown in Figure 36. At each measurement height the temperatures were very consistent. Generally, the average temperatures at the different heights were in close agreement within about 100 °C throughout the furnace, with the floor on the low end, except at the highest ceiling location which was roughly 200 °C lower than the floor temperatures for the first 20 minutes into the test, and then it was roughly 100 °C for the remainder of the test. The ceiling thermocouple may have been impacted by the surrounding cement board, since it was installed individually through the assembly and was not directly attached to the tree itself. A similar trend with the ceiling temperatures measuring lower was observed in the Carleton University CLT compartment tests [20]. The plate thermometer at the ceiling measured temperatures that were closer to the other thermocouples throughout the furnace. The plate thermometer temperatures are also shown in Figure 36, depicted by a dashed line. Their temperatures were nearly identical for the first 10 minutes, and then they maintained about a 50 °C temperature difference for the remainder of the test, with the ceiling temperature being higher.

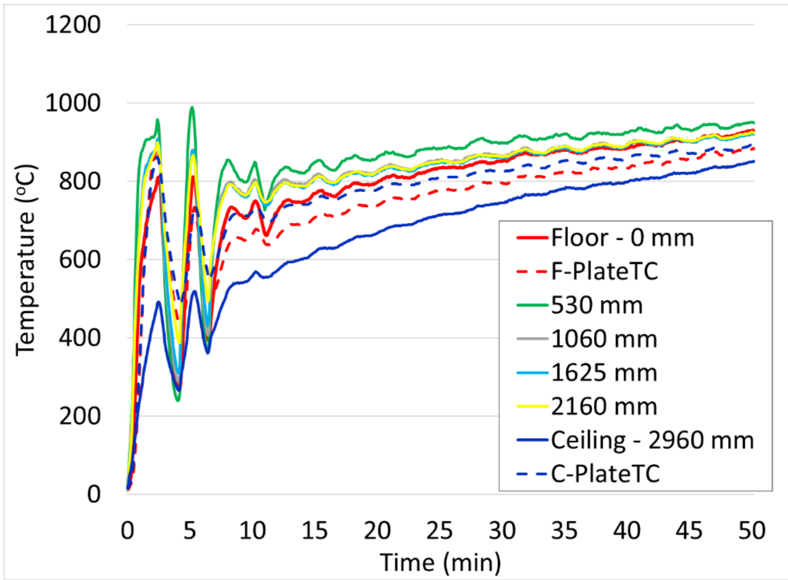


Figure 36. Average temperatures at thermocouple tree heights

8.2 Heat Flux Exposure

The heat flux at the floor and ceiling are shown in Figure 37. The heat fluxes were similar for the first 20 minutes, with some higher fluctuations at the floor, and then the heat flux at the ceiling stayed at approximately 20 kW/m^2 higher than at the floor for the rest of the test.

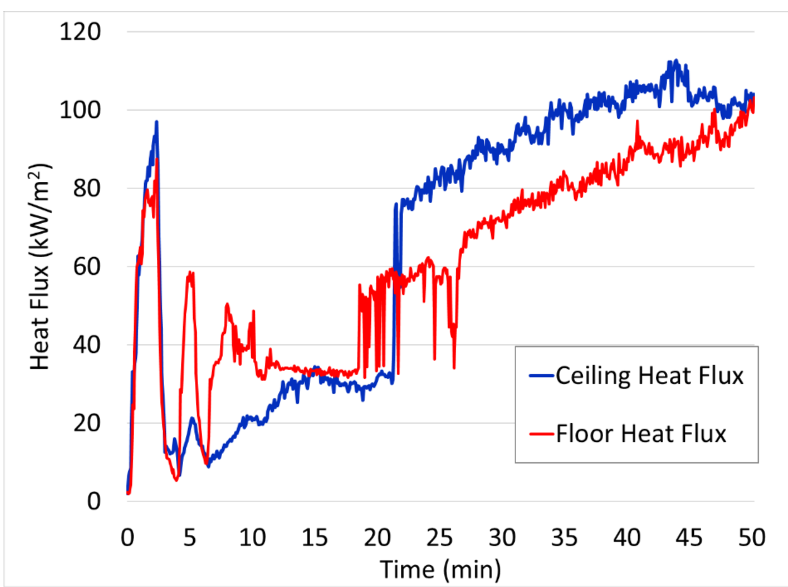


Figure 37. Heat flux measurements

8.3 Discussion

It was surprising that the two layers of 15.9-mm cement board in a full-scale test did not perform better than two layers of 12.7 mm, which achieved an encapsulation rating of 43 minutes in an intermediate-scale test. It was anticipated that the exposure in the full-scale furnace would be lower than in the intermediate-scale test, which would potentially result in a longer encapsulation rating. It was expected that the increased thickness of the cement board would provide better thermal protection. In revisiting the intermediate-scale test results, one major difference between the tests was that full sheets of cement board were used in the intermediate scale test without the inclusion of any joints. During the full-scale test, flaming was apparent at the joints in the ceiling 20 minutes into the test. Better protection at the joints would be needed to meet a 50 minutes encapsulation rating for cement board. Some of the interface thermocouples were located close to the joints in the base layer of cement board. Temperatures were very close between all of the interface thermocouples, temperatures beneath joints were not noticeably higher.

This was the first full-scale CAN/ULC-S146 test conducted in Canada. The design that was selected for the wood substrate to meet the requirements was two layers of 2 x 10s laid flat with a layer of plywood on the unexposed side. The 76-mm thickness ensured the substrate remained thermally thick throughout the test. It is possible that gaps between the wood boards may have permitted air flow through the assemblies which could have had an impact of the encapsulation time. The wood substrate assembly could be constructed more cost effectively by using simply plywood or alternatively having a mass timber substrate and using a sacrificial layer of plywood on the exposed side. The mass timber could be reused for subsequent tests since charring should be contained to the plywood layer. Using gas as the fuel for the fire within the furnace is also not indicative of a real fire scenario. In a compartment fire with contents burning there is likely to be a layer of ash forming on the floor which may further protect the floor surface.

During test design, there was concern that the cement board might prematurely fall-off the ceiling due to its weight. Longer screws and a tighter screw pattern was used on the ceiling to compensate. During the test, there was no evidence that any cement board fell-off. Other cement board encapsulation methods could simply be tested with the traditional exposure from beneath, so long as it is securely fastened. However, if there is an assembly where this may be more of an issue, e.g., a thin concrete topping that is not fastened with screws, this test has demonstrated that it is in fact possible to expose an assembly to the standard fire in a floor top orientation.

The floor furnace was able to successfully test the encapsulation performance of an assembly on the floor. The furnace was able to follow the standard fire curve, and the heat exposure (based on temperatures and heat flux) was similar at the floor and ceiling surfaces. One challenge with this test was extinguishing the fire at the floor following the test. Because the floor was so tightly fit into the furnace, it was not easy to remove it quickly following the test while the assembly and furnace were still hot. Small amounts of water were used to help cool the assembly, to avoid having water pool in the pit of the furnace and to not damage the fire brick beneath the floor.

8.4 Future Work

Because of the interest in an alternative to a 38-mm thick concrete topping in mass timber buildings, cement board should be further explored for its possible use as a floor encapsulation material. Preliminary tests using a radiant source (e.g., cone calorimeter) or an intermediate-scale furnace could be done to evaluate methods to protect the cement board joints to improve performance; these tests are more cost effective than full-scale tests. Once an appropriate method is found, a full-scale test could be done to confirm the results.

The results from this work should be shared with potential users of the CAN/ULC-S146 standard regarding the construction of the wood substrate so that the design can be used and improved upon. The current test procedure is impractical for many floor topping designs, such as concrete toppings or honeycomb sand solutions; updating the standard to provide provisions to allow testing floor assemblies from above is warranted. Alternatively, requirements for the protection of the top of wood floors in the NBCC should be revisited.

Some limited commentary was provided on the similarities of exposure between the full-scale wall and floor furnaces. It may be appropriate to review the requirements in the CAN/ULC-S146 standard to allow for evaluation of wall assemblies. It was also shown that the temperature distribution within the floor furnace was very consistent. The CAN/ULC-S146 standard (and potentially also the CAN/ULC-S101 standard) could be revised to require fewer control thermocouples. However, confirmation of uniform furnace temperature would be needed from other laboratories performing this test.

The results of this work should be shared with the fire testing community, as it is believed this was the first test of its kind. There are very few fire test standards that expose assemblies to standard fires from above. This test specifically looked at the encapsulation performance of a floor topping, but there may be other applications were this test method might be useful.

9 CONCLUSIONS

The objective of this project was to determine whether a cement board floor topping could meet the encapsulation requirements for use in a mass timber building in accordance with the proposed NBCC 2020 EMTC requirements. Available existing data showed that two layers of 12.7-mm cement board was insufficient to reach the 50 minutes rating required by the proposed EMTC provisions. There was evidence to suggest that using two layers of 15.9-mm cement board might meet the rating requirements.

A new standard test method has been developed, CAN/ULC-S146, to determine the encapsulation rating of materials. The standard is designed to expose assemblies to a standard fire in a horizontal orientation from underneath (as a ceiling). There was concern that installing an assembly intended for use as a floor topping might not perform in the same way as if it were installed on a ceiling. Installing the cement board, which is heavy, on a ceiling might lead to premature fall-off and a reduction in the encapsulation rating. If the assembly were tested on the floor, then there is no opportunity for the encapsulation material to fall-off. A secondary objective of this work was to develop and evaluate the feasibility of a test method to evaluate the encapsulation of a floor topping in its intended orientation (on the floor with exposure from above) in a full-scale floor furnace to achieve an accurate rating. Literature suggested that it would be possible to test an assembly in this orientation.

A test method was developed that involved installing a floor assembly at the bottom of furnace. When the test was conducted, there was also an opportunity to install an identical, but mirrored, assembly in the ceiling of the furnace. Additional instrumentation was installed in the furnace to confirm the temperatures and heat fluxes at the floor and ceiling surfaces and to evaluate the temperature distribution in the furnace.

This was the first time a full-scale test of the CAN/ULC-S146 standard was conducted, albeit modified. The method used to construct the wood substrate was effective and could be used for future tests. There is potential to further refine the wood substrate design to reduce the cost of construction. If multiple tests are to be run in sequence, it would make sense to construct a reusable substrate and install a sacrificial thin wood layer, such as plywood.

The method was tested and successfully put into practice. The temperatures at the two surfaces were very close as were the heat fluxes. The setup of installing an assembly on the floor of the full-scale floor furnace worked well. If another assembly would benefit from being tested in a floor top orientation, this research demonstrated that it can be done.

Two layers of 15.9-mm cement board reached an encapsulation time of 39 minutes in the ceiling and floor orientation, which is less than the 50-minute minimum requirement for use as a floor topping in EMTC buildings. It may be possible to achieve the 50-minute rating if some details are changed, such as including protection at the joints. The similarities in the results further confirm that the assemblies received similar heat exposure in the test. No fall-off of the cement board was observed; potential future cement board encapsulation tests could simply be run in the typical horizontal orientation with exposure from beneath. Protection at the joints would likely lead to an improved encapsulation rating. Further research is warranted into appropriate products and methods to protect cement board joints from fire exposure as well as other alternative floor topping methods for mass timber.

10 REFERENCES

[1] National Building Code of Canada, Ottawa, ON: National Research Council Canada, 2015.

[2] J. Z. Su and G. D. Lougheed, Fire Safety Summary: Fire Research Conducted for the Project on Midrise Wood Construction (Report to Research Consortium for Wood and Wood-Hybrid Mid-Rise Buildings), Ottawa, ON: National Research Council of Canada, 2014.

[3] "Tall Wood Building Demonstration Initiative (TWBDI)," Natural Resources Canada, 5 July 2019. [Online]. Available: https://www.nrcan.gc.ca/science-data/funding-partnerships/funding-opportunities/forest-sector-funding-programs/expanding-market-opportunities-p/tall-wood-building-demonstration-initiative-twbdi/20176.

[4] NFPA 13: Standard for the Installation of Sprinkler Systems, Quincy, MD: National Fire Protection Association, 2016.

[5] Proposed Change 1024. New Subsection for Encapsulated Mass Timber Construction. Fall 2019 Public Review of Changes to Codes Canada Publications, Ottawa, ON: Canadian Commission on Building and Fire Codes. National Research Council Canada., 2019.

[6] CAN/ULC-S146. Standard Method of Test For the Evaluation of Encapsulation Materials and Assemblies of Materials for the Protection of Structural Timber Elements, Toronto, ON: Underwriters' Laboratories of Canada, 2019.

[7] CAN/ULC-S102. Standard Method of Test for Surface Burning Characteristics of building Materials and Assemblies, Toronto: Underwriters' Laboraties of Canada (ULC), 2010.

[8] CAN/ULC-S101. Standard Methods of Fire Endurance Tests of Building Construction and Materials, Toronto, ON: Underwriters' Laboratories of Canada (ULC), 2014.

[9] M. Bijloos, G. Lougheed, J. Su and N. Bénichou, "Solutions for Mid-Rise Wood Construction: Cone Calorimeter Results for Encapsulation Materials: Report to Research Consortium for Wood and Wood-Hybrid Mid-Rise Buildings," National Research Council Canada, Ottawa, ON, 2014.

[10] R. Berzins, P.-S. Lafrance, P. Leroux, G. D. Lougheed, J. Z. Su and N. Bénichou, Solutions for Mid-rise Wood Construction: Intermediate-Scale Furnace Tests with Encapsulation Materials: Report to Research Consortium for Wood and Wood-Hybrid Mid-Rise Buildings, Ottawa, ON: National Research Council of Canada, 2014.

[11] M. A. Sultan, "Incident Heat Flux Measurements in Floor and Wall Furnaces of Different Sizes," *Fire and Materials,* vol. 30, no. 2, pp. 1-17, 2006.

[12] S. L. Zelinka, L. E. Hasburgh, K. J. Bourne, D. R. Tucholski and J. P. Ouellette, Compartment Fire Testing of Two-Story Mass Timber Building. General Technical Report FPL-GTR-247., Madison, WI: US Department of Agriculture, Forest Service, Forest Products Laboratory, 2018.

[13] A. Bwalya, E. Gibbs, G. Lougheed and A. Kashef, Characterization of Fires in Multi-suite Residential Dwellings: Summary, Ottawa, ON: National Research Council of Canada, 2014.

[14] A. Bwalya, E. Gibbs, G. Lougheed and A. Kashef, Characterization of Fires in Multi-suite Residential Dwellings: Final Project Report: Part 1-A Compilation of Post-Flashover Room Fire Test Data, Ottawa, ON: National Research Council Canada, 2014.

[15] CAN/ULC-S102.2. Standard Method Of Test For Surface Burning Characteristics Of Flooring, Floor Coverings, And Miscellaneous Materials And Assemblies, Toronto, ON: Underwriters' Laboratories of Canada (ULC), 2018.

[16] T. Harmathy, "Temperature Variations in the DBR Floor Furnace," National Research Council of Canada, Ottawa, ON, 1960.

[17] L. Ranger, C. Dagenais and N. Benichou, Evaluating Fire Performance of Nail-Laminated Timber, Ottawa, ON: FPInnovations, 2019.

[18] L. Ranger, C. Dagenais and N. Benichou, Fire-Resistance of Mass Timber Laminated Elements, Ottawa, On: FPInnovations, 2019.

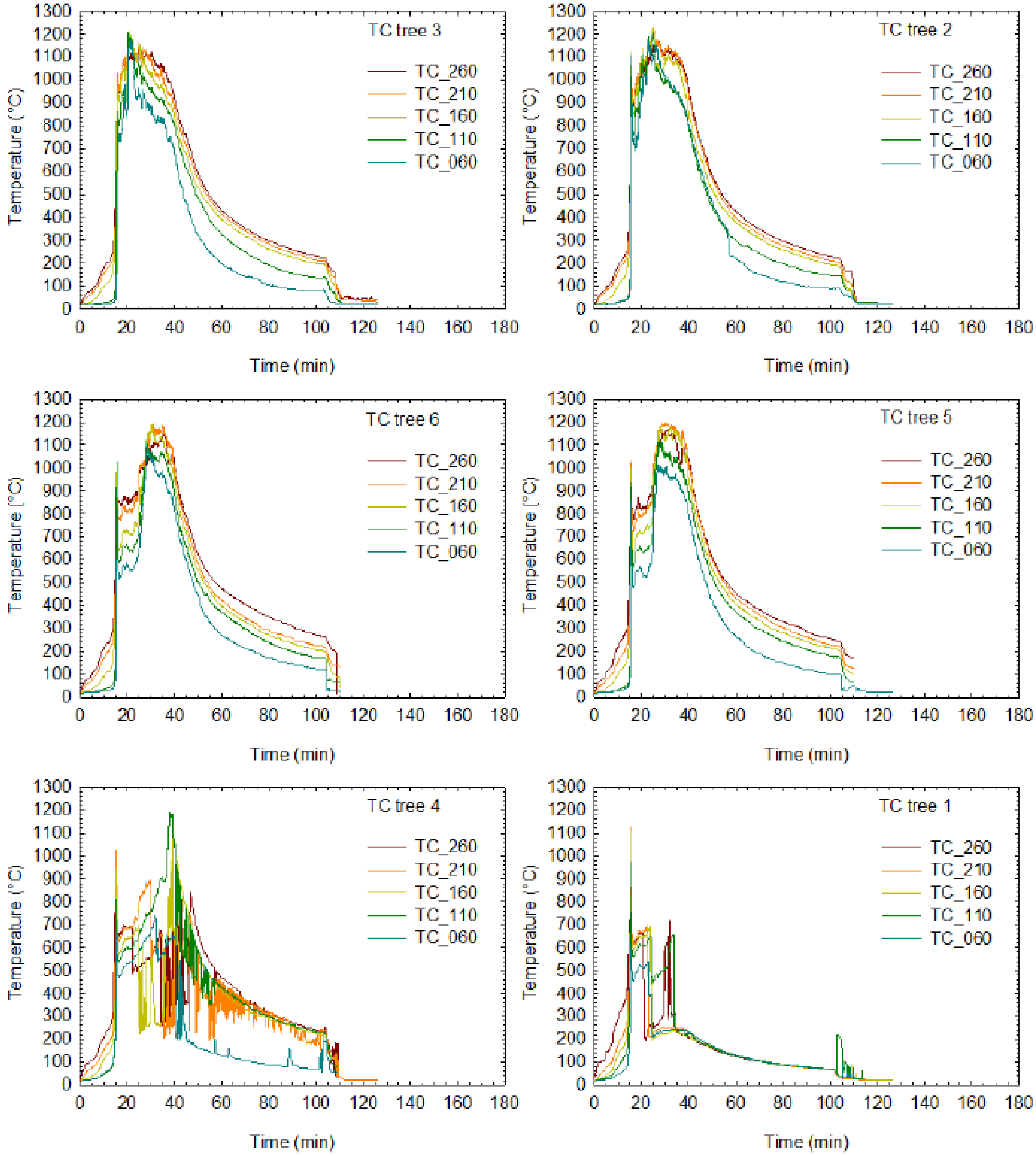
[19] J. Su, P.-S. L. M. Hoehler and M. Bundy, Fire Safety Challenges of Tall Wood Buildings - Phase 2: Task 2&3 - Cross Laminated Timber Compartment Fire Tests, Ottawa, ON: National Reserach Council of Canada, National Institute of Standards and Technology, 2018.

[20] A. R. M. Hevia, Fire Resistance of Partially Protected Cross-Laminated Timber Rooms. Master's Thesis., Ottawa, ON: Department of Civil and Environmental Engineering. Carleton University, 2014.

APPENDIX A - FPRF TEMPERATURE PROFILES

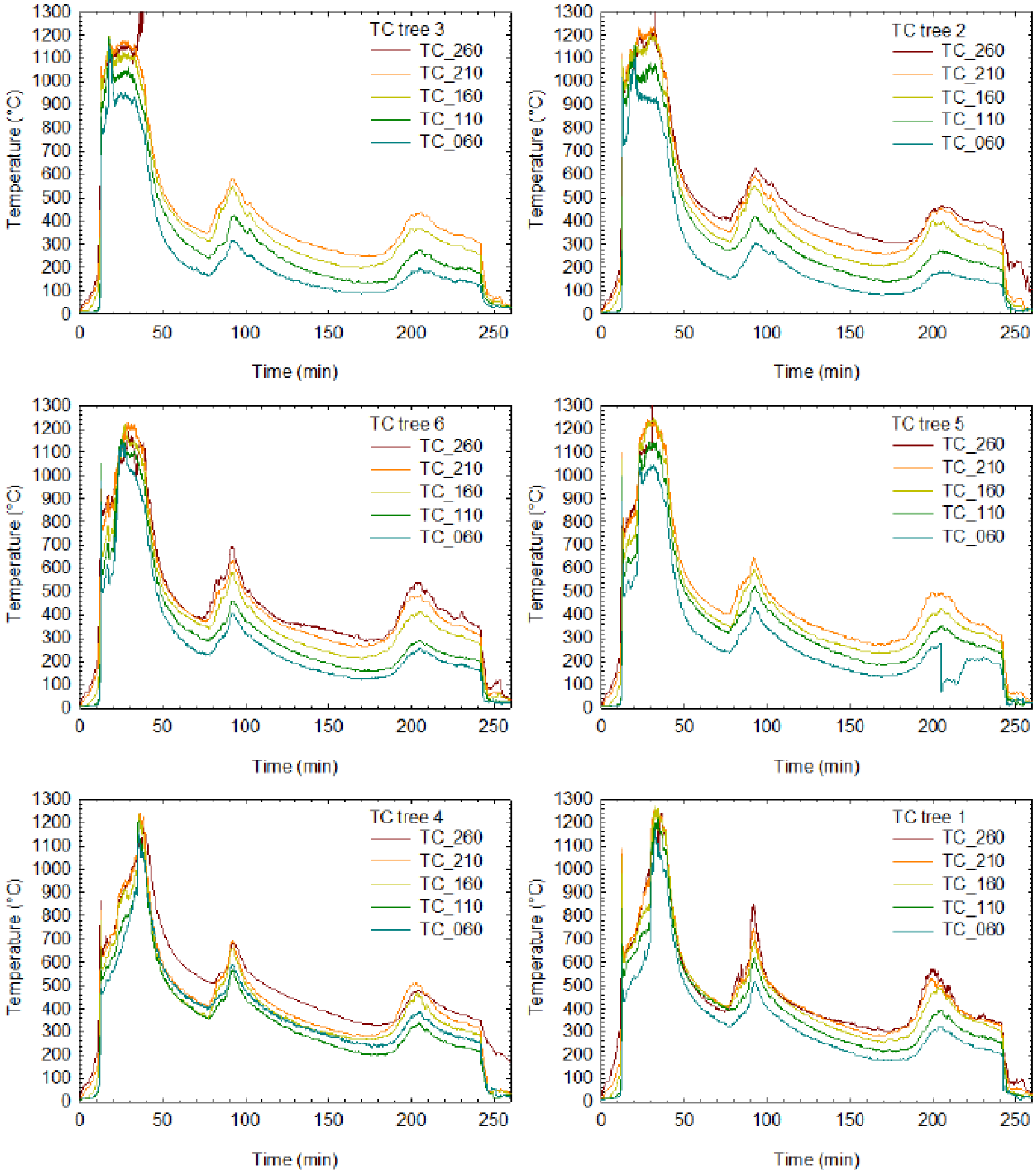
Temperature Profiles in FPRF Test 1-2 [19]

Height in cm



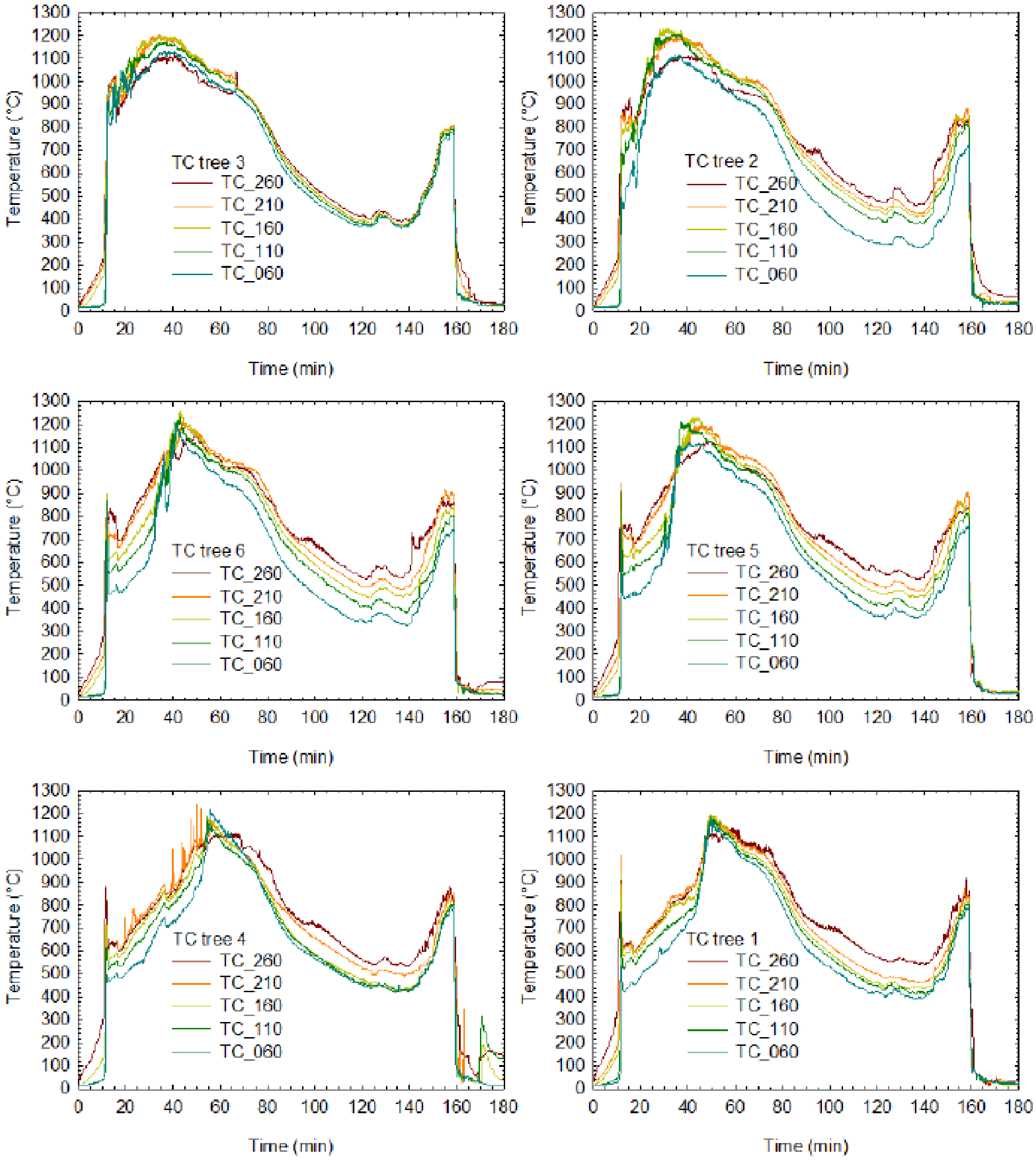
Temperature Profiles in FPRF Test 1-3 [19]

Height in cm



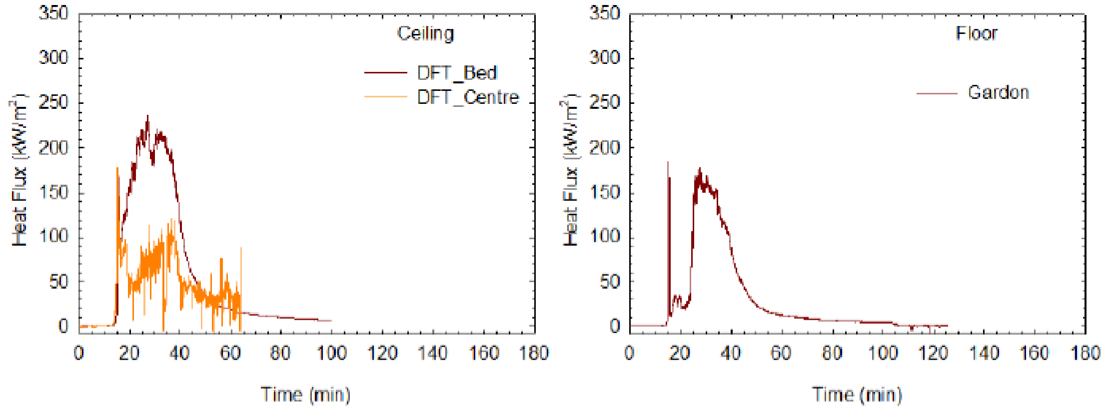
Temperature Profiles in FPRF Test 1-4 [19]

Height in cm

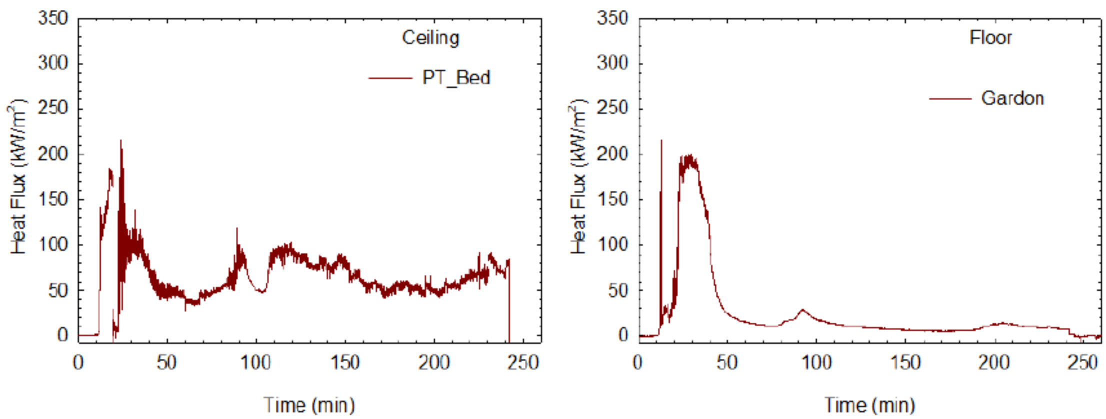


APPENDIX B - FPRF HEAT FLUX MEASUREMENTS

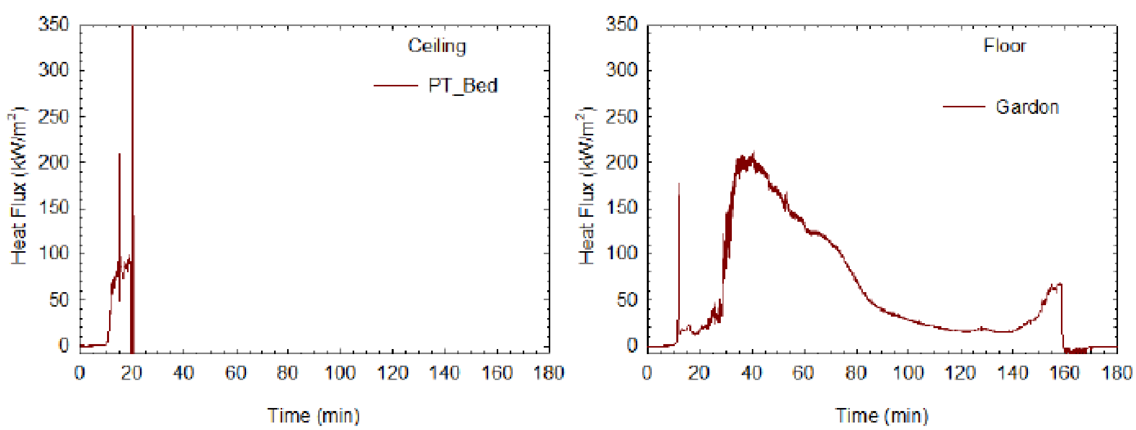
Heat Flux Measurements in FPRF Test 1-2 [19]



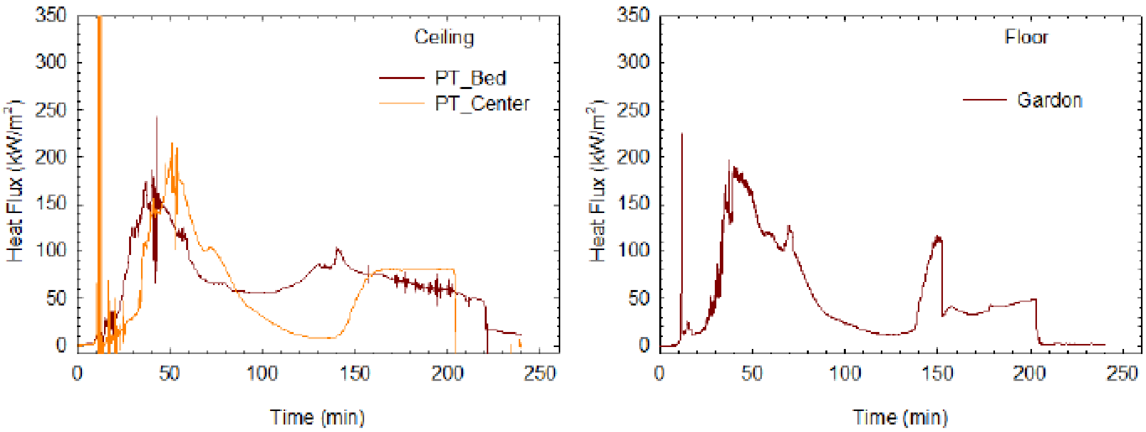
Heat Flux Measurements in FPRF Test 1-3 [19]



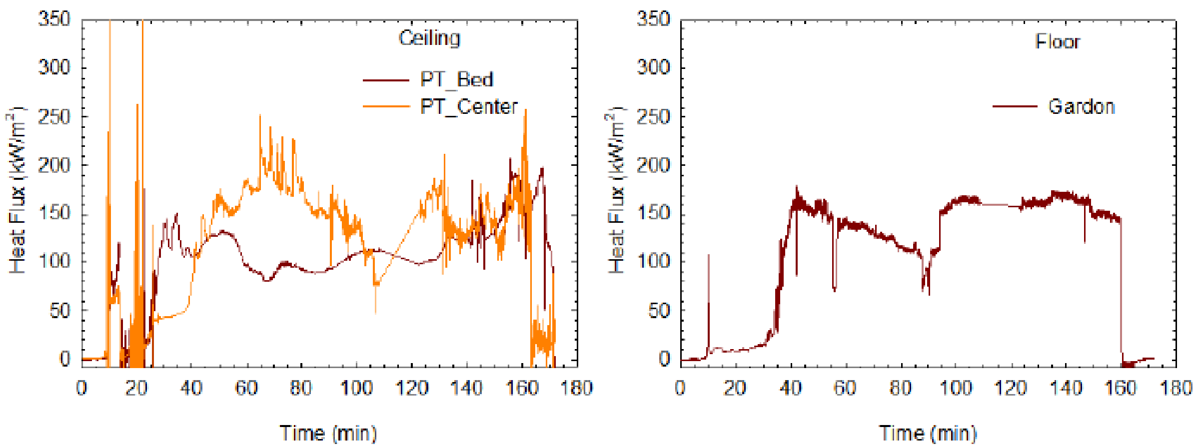
Heat Flux Measurements in FPRF Test 1-4 [19]



Heat Flux Measurements in FPRF Test 1-5 [19]

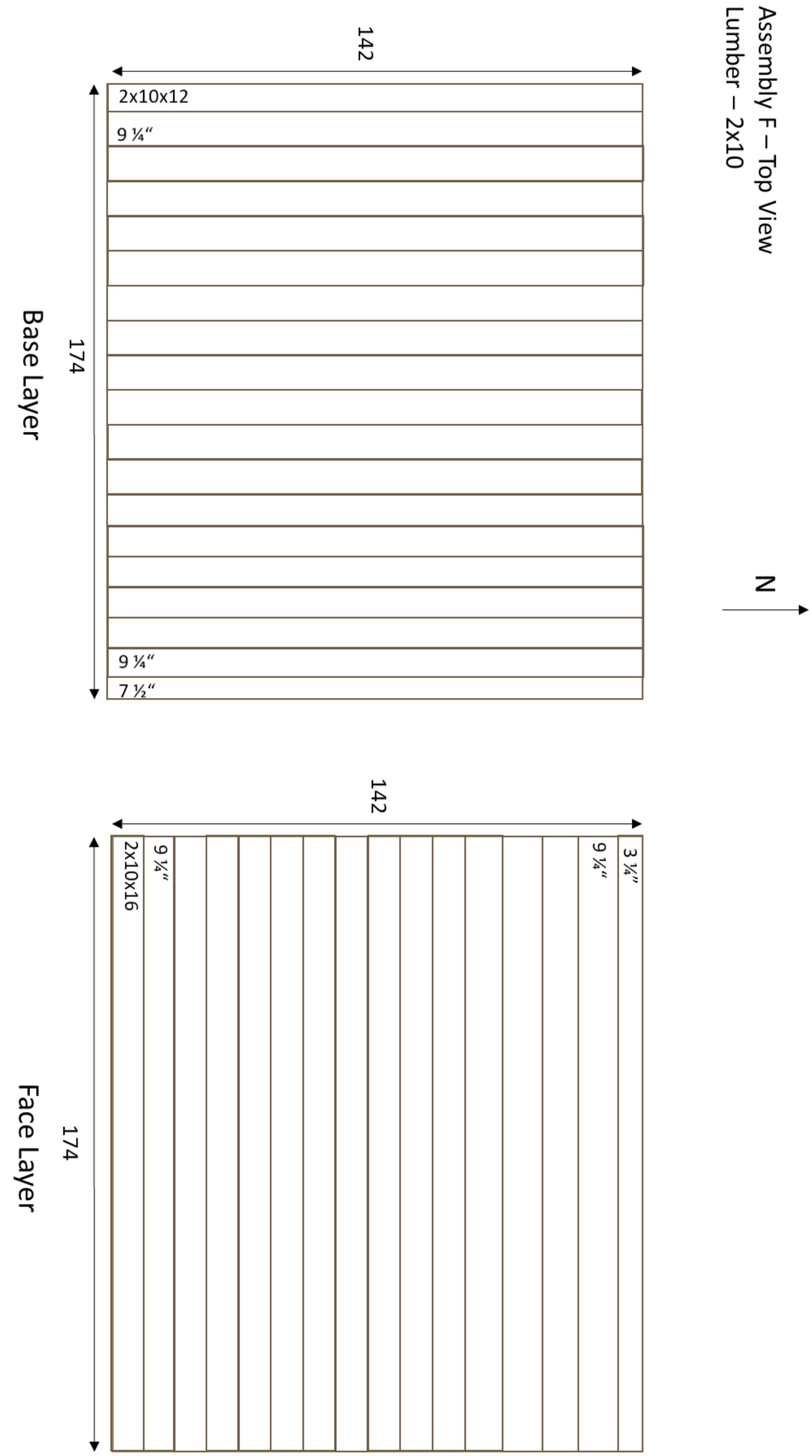


Heat Flux Measurements in FPRF Test 1-6 [19]

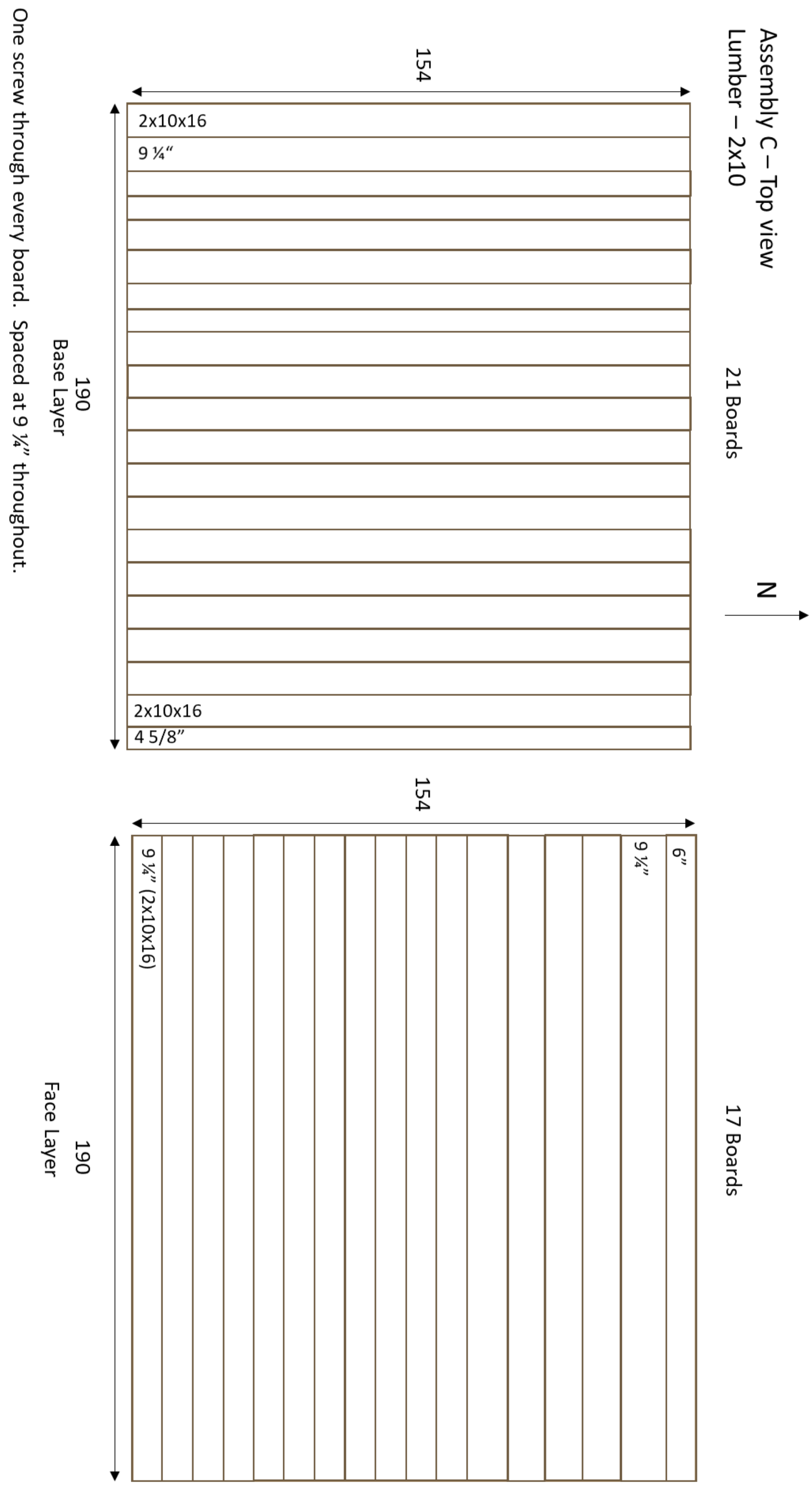


APPENDIX C - CONSTRUCTION DRAWINGS

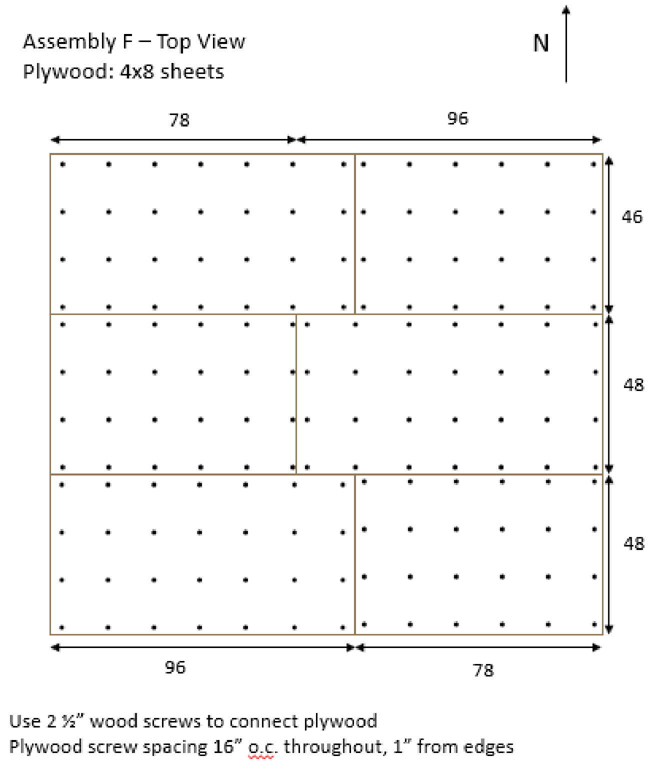
Wood Substrate – Assembly F (Not to scale. Dimensions in in.)



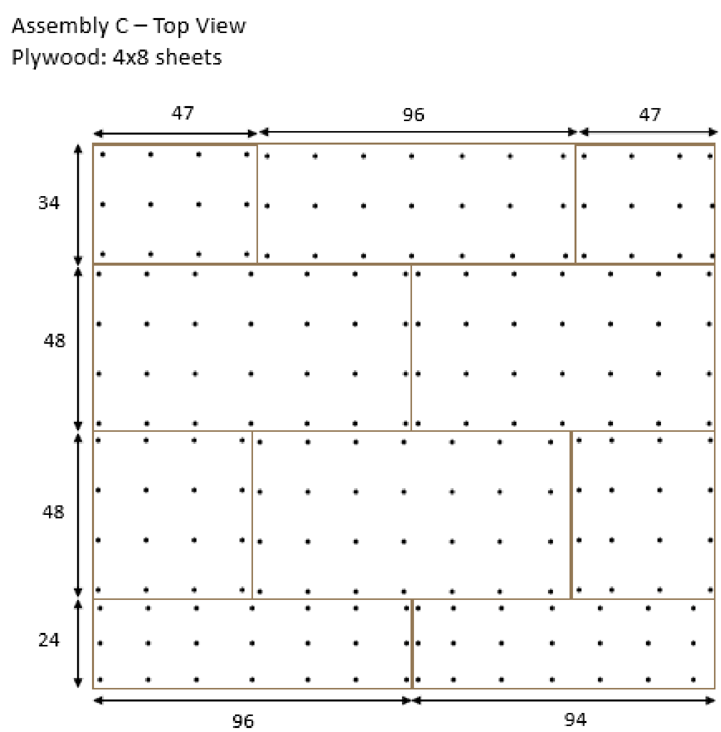
Wood Substrate – Assembly C (Not to scale. Dimensions in in.)



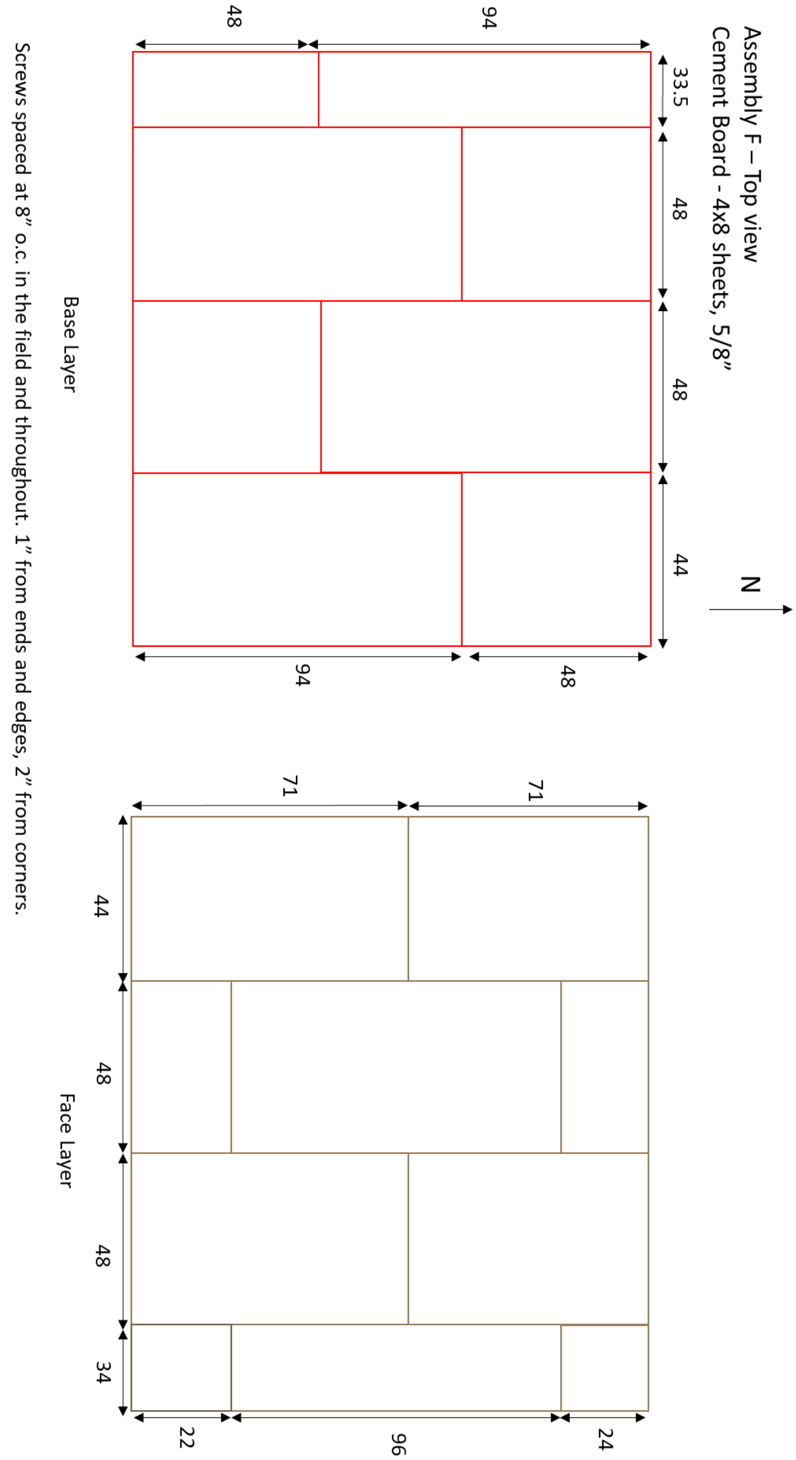
Wood Substrate – Assembly F – Plywood Layout (Not to scale. Dimensions in in.)



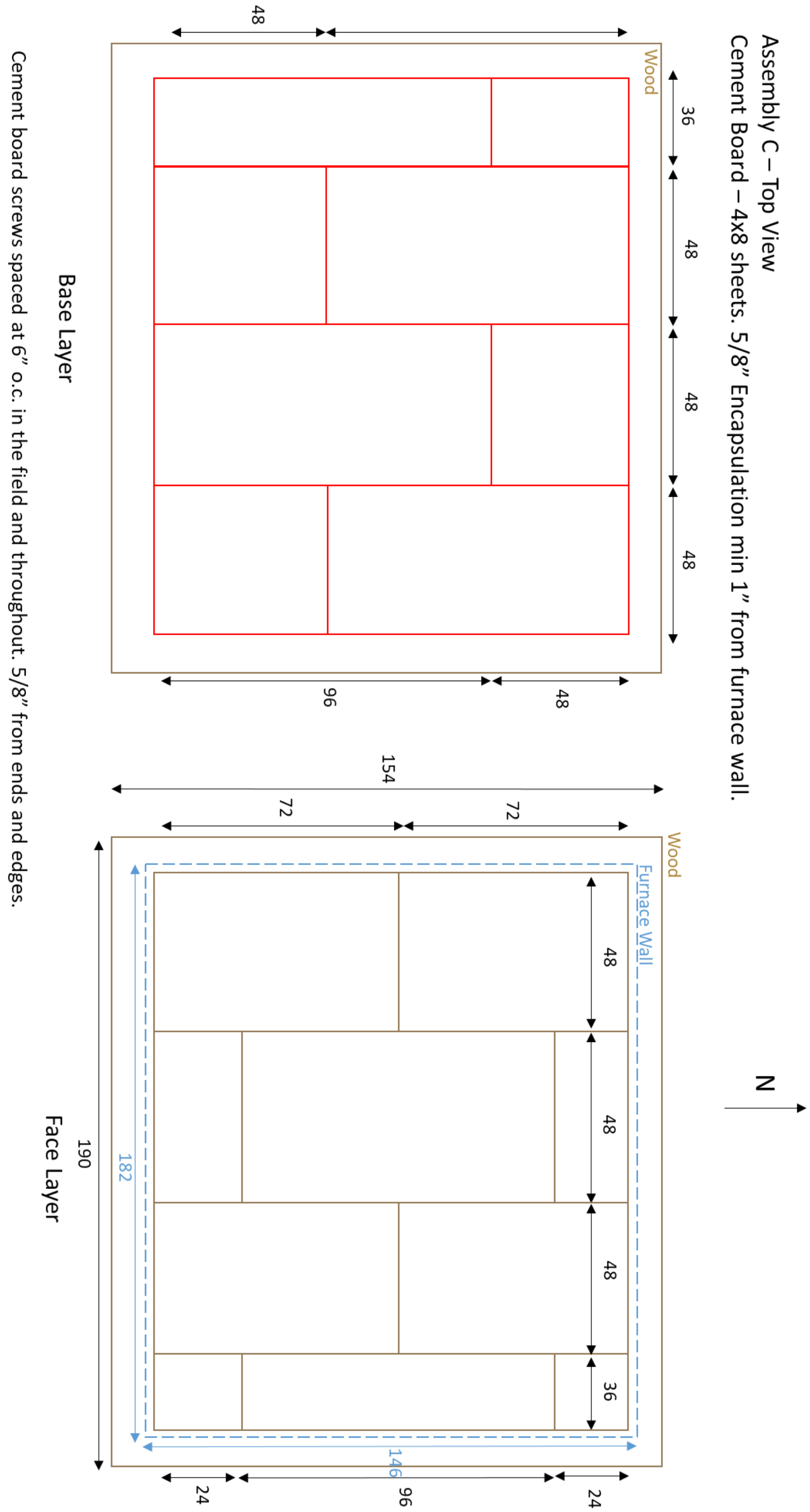
Wood Substrate – Assembly C – Plywood Layout (Not to scale. Dimensions in in.)



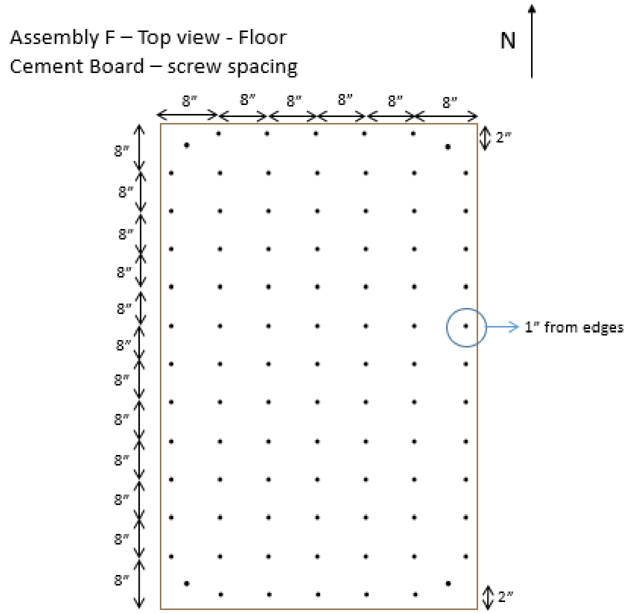
Cement Board Layout – Assembly F (Not to scale. Dimensions in in.)



Cement Board Layout – Assembly C (Not to scale. Dimensions in in.)

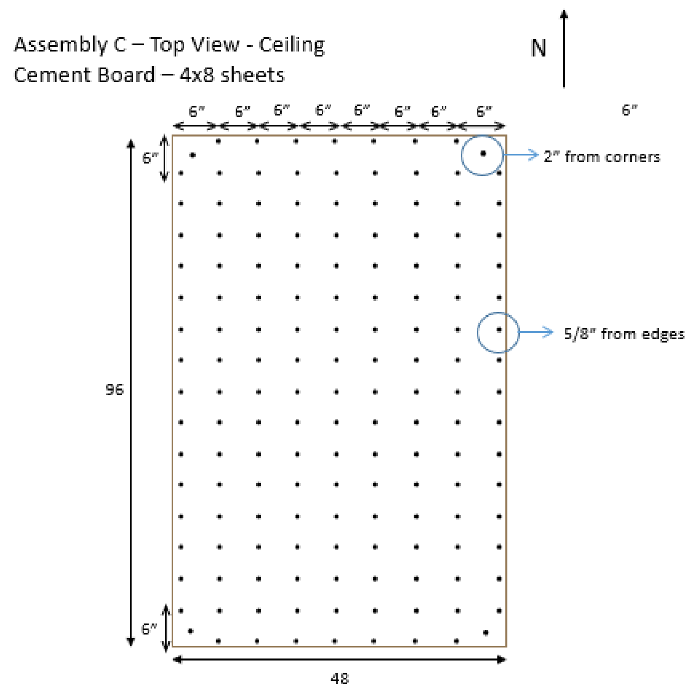


Cement Board Layout – Assembly F – Screw Spacing (Not to scale. Dimensions in in.)



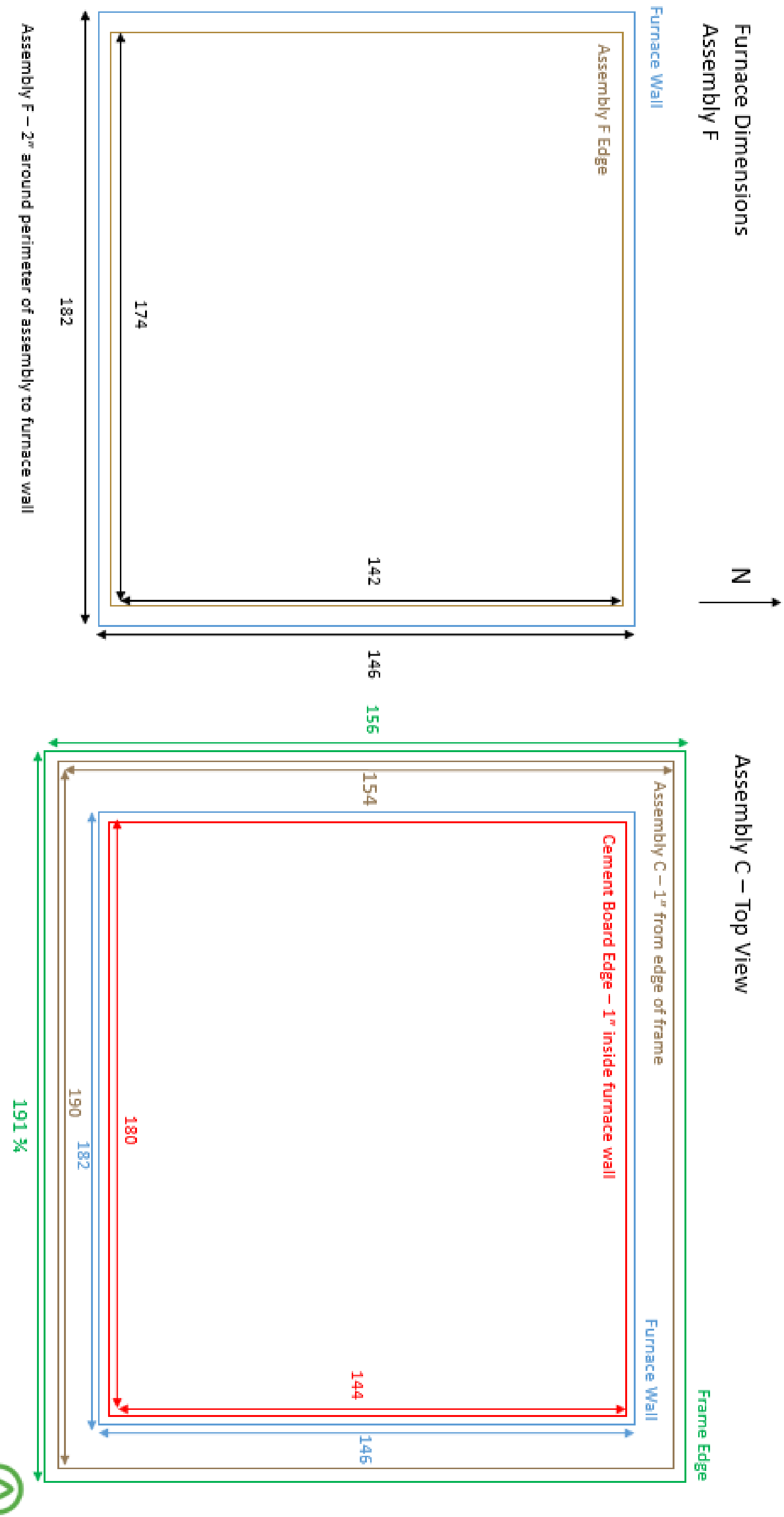
Screws spaced at 8" o.c. in the field and throughout. 1" from ends and edges, 2" from corners.

Cement Board Layout – Assembly C – Screw Spacing (Not to scale. Dimensions in in.)



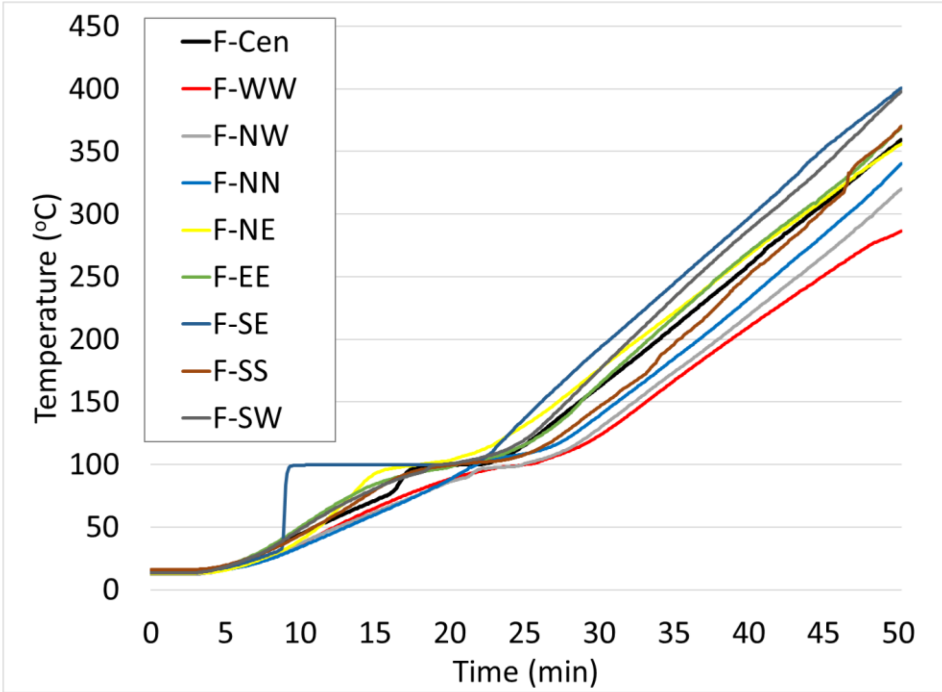
Cement board screws spaced at 6" o.c. in the field and throughout. 5/8" from ends and edges.
Use longer cement board screws for the ceiling.

Overall Assembly Sizes (Not to scale. Dimensions in in.)

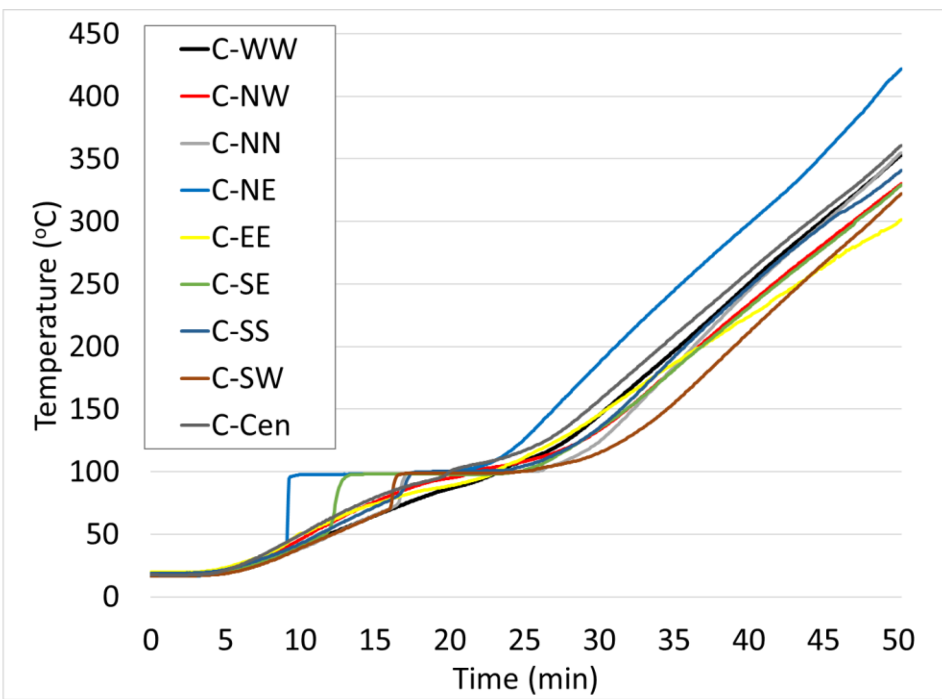


APPENDIX D - TEST RESULTS

Floor Interface Temperatures



Ceiling Interface Temperatures



FPInnovations

info@fpinnovations.ca
www.fpinnovations.ca

OUR OFFICES

Pointe-Claire
570 Saint-Jean Blvd.
Pointe-Claire, QC
Canada H9R 3J9
514 630-4100

Vancouver
2665 East Mall
Vancouver, BC
Canada V6T 1Z4
604 224-3221

Québec
1055 rue du P.E.P.S.
Québec, QC
Canada G1V 4C7
418 659-2647