Solutions for mid-rise wood construction: apartment fire test with encapsulated cross laminated timber construction: Test APT-CLT: report to Research Consortium for Wood and Wood-Hybrid Mid-Rise Buildings

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REPORT TO RESEARCH CONSORTIUM FOR WOOD AND WOOD-HYBRID MID-RISE BUILDINGS

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Solutions for Mid-Rise Wood Construction: Apartment Fire Test with Encapsulated Cross Laminated Timber Construction (Test APT-CLT)

B.C. Taber, G.D. Lougheed, J.Z. Su and N. Bénichou

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SOLUTIONS FOR MID-RISE WOOD CONSTRUCTION: APARTMENT FIRE TEST WITH ENCAPSULATED CROSS LAMINATED TIMBER CONSTRUCTION (TEST APT-CLT)

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1 INTRODUCTION

The acceptable solutions provided in the 2010 National Building Code (NBC) Division B [1] limits the use of combustible (wood) construction based on building height. For example, for Group C (Residential), Group D (Business and Personal Services) and Group E (Mercantile) occupancies, combustible construction can be used up to 4 storeys, and up to 2 storeys for Group A – Division 2 (Assembly) occupancies. In addition to the building height limitation, there are also building area limitations in the 2010 NBC for the use of combustible construction for these occupancies. For buildings that exceed the height and area requirements for combustible construction, the prescriptive requirements in the 2010 NBC require that noncombustible construction be used for the primary structural elements.

The prescriptive construction requirements for fire safety and protection of buildings, which are dependent upon the building size and occupancy type, are provided in Subsection 3.2.2 of the 2010 NBC. This includes the identification of the buildings for which noncombustible construction is required. The intent of the prescriptive requirements for noncombustible construction as they relate to the NBC fire safety/fire protection of building objectives is "*to limit the probability that combustible construction materials within a storey of a building will be involved in a fire, which could lead to the growth of fire, which could lead to the spread of fire within the storey during the time required to achieve occupant safety and for emergency responders to perform their duties, which could lead to harm to persons/damage to the building*".

The 2010 NBC defines noncombustible construction as "*that type of construction in which a degree of fire safety is attained by use of noncombustible construction materials for structural members and other building assemblies*" [1]. Article 3.1.5.1 requires that a building or part of a building required to be of noncombustible construction be constructed using noncombustible materials. The intent of this requirement, as it relates to the NBC fire safety/fire protection of building objectives, is "*to limit the probability that construction materials will contribute to the growth and spread of fire, which would lead to harm to persons/damage to the building*".

The NBC does permit, as exceptions, an extensive use of combustible materials in buildings otherwise required to have their primary structural elements to be of noncombustible construction. The allowed materials and associated limitations are primarily provided in Articles 3.1.5.2 to 3.1.5.21. Generally, the combustible elements permitted relate to interior finishes, gypsum board, combustible roofing materials, combustible plumbing fixtures, cabling, protected insulation, flooring, combustible glazing, combustible cladding systems, non-loadbearing framing elements in partitions, stairs in dwellings, and trim and millwork, among others.

Divisions B of the NBC (the "acceptable solutions" portion of the Code) generally does not permit combustible materials to be used for the primary structural elements in buildings required to be of noncombustible construction. In the Scoping Study [2] for mid-rise and hybrid buildings, it was suggested that an alternative solution using wood construction may be developed to meet the intent of the prescriptive "noncombustibility" requirement for mid-rise (and taller) buildings.

As one approach, encapsulation materials could be used to protect the combustible (wood) structural materials for a period of time in order to delay the effects of the fire on the combustible structural elements, including delay of ignition. In delaying ignition, any effects of the combustion of the combustible structural elements on the fire severity can be delayed. In some cases, and depending upon the amount of encapsulating material used (e.g. number of layers), ignition of the elements might be avoided completely. This scenario would primarily depend upon the fire event and the actual fire performance of the encapsulating materials used.

A research project, Wood and Wood-Hybrid Midrise Buildings, was undertaken to develop information to be used as the basis for alternative/acceptable solutions for mid-rise construction using wood structural elements. As part of this project, four large-scale fire experiments were conducted to evaluate the fire performance of two forms of encapsulated combustible structural wood systems, a lightweight wood-frame (LWF) system (2 experiments [3, 4]) and a cross-laminated timber (CLT) system (1 experiment). The fourth experiment [5] involved a test structure constructed using a steel frame system described below. Each experiment involved construction of a test set-up of an unsprinklered full-size apartment unit, intended to represent a portion of a mid-rise (e.g. six-storey) building.

The structural elements used in the LWF system (wood stud walls and wood I-joist floors) and CLT system (3-ply wall panels and 5-ply floor panels) were all chosen on the basis of the types of construction that were currently being used in 5- and 6-storey mid-rise residential construction being built in the province of British Columbia, where the building code had changed earlier, in 2009, to permit such mid-rise combustible construction.

The other full-scale experimental setup of an unsprinklered full-size apartment unit was built using a noncombustible lightweight steel-frame system (cold-formed steel). Other than there not being an automatic sprinkler system installed in the structure, this test setup was chosen to represent a code-conforming lightweight steel-frame system that is otherwise permitted to be used for 6-storey residential buildings having a building area not exceeding 6 000 m^2. This resulted in the steel-frame floor assemblies, loadbearing walls, and fire separations (suite-to-suite and corridor walls/partitions) being designed and constructed to provide a 1-h fire-resistance rating. In undertaking this test of a noncombustible system, it provided the opportunity for the fire performance of the encapsulated LWF and CLT systems to be compared with that of the lightweight steel-frame system, particularly in regards to assessing when and by how much (if at all) the ignition and burning of the wood structural elements contribute to the fire severity within the fire compartment.

This report provides the results of the experiment with an encapsulated CLT setup representing an apartment in a mid-rise (e.g. six-storey) building.

2 GENERAL TEST ARRANGEMENT

A test setup was constructed to represent a three-storey section of a building bounded on four sides (three internal walls and an exterior wall) within the lower storeys of a mid-rise (e.g. six-storey) building. The test arrangement was 8.51 m long by 6.55 m wide, which is comparable to the footprint of a one-bedroom apartment.

The test setup was located under a 10.67 m x 10.67 m hood (Figure 1), which was used to collect the hot gases and smoke produced by the fire. Instrumentation located in the ductwork, which connects the collection hood to an exhaust fan system, was used to measure the heat release and smoke production rates produced by the fire in a simulated apartment located in the test setup.

An elevation view of the test setup is shown in Figure 2. The test arrangement was 3 storeys in height. The lowest storey was bounded by three 2.0 m high concrete block walls and one partially framed-in wall. Figure 1 shows the 8.51 m long block wall on the north side of the test arrangement. The other two block walls were located on the south side and the east end of the test setup. A concrete block wall was not included in the west end (right side of the photograph) to allow for physical access to the space below the simulated apartment.

A metal beam was mounted in the notch shown in the west end of the concrete block walls (Figure 1) to provide structural support for the middle and highest storeys of the test setup. A wood column was used to support the beam at its mid-length. A metal beam was also located across the concrete block walls near the middle of this storey to support a loadbearing wall across the middle of the floor area of each of the upper storeys.

The design and the materials for CLT test arrangement were obtained from a Canadian CLT manufacturer. The design drawings for the CLT structure are provided in Appendix A.

The middle storey of the test structure simulated a one-bedroom apartment unit with CLT structural elements used to construct the walls and floor/ceiling assemblies. One wall (north) represented a typical loadbearing exterior wall, while the other three bounding walls were designed to represent typical interior loadbearing fire separations used to separate the dwelling unit from adjacent dwelling units and the public corridor. The ceiling/floor assemblies for the test sections were also typical fire-rated assemblies. The test arrangement was designed to provide a finished floor-to-ceiling height of 2.44 m on the middle storey.

A plan view of the simulated one-bedroom apartment used for the fire test is shown in Figure 3. The test area on the middle storey (fire floor) included:

1. A 3.6 m x 3.8 m bedroom plus a closet area. No doors were mounted on the closet. The bedroom was separated from the living room by a CLT wall containing a doorway having a hollow-core wood fibre door, which was closed at the start of the test.
2. A 6.2 m x 4.25 m living room / kitchen area with the kitchen area located on the south side of the test apartment, adjacent to the simulated entryway from a public corridor.
3. An entryway with a closet. No doors were mounted on the closet. A steel door with a 45 minute fire protection rating was located in the doorway in the simulated corridor (South) wall at the entryway.
4. A bathroom adjacent to the entryway. No fixtures were located in the bathroom. The bathroom was separated from the entryway by wood stud partition containing a doorway with a hollow-core wood fibre door, which was open at the beginning of the test.

The highest storey of the test structure had the same layout as the middle storey. However, the walls were 1.83 m in height. The shorter walls were used to provide clearance between the top of the test structure and the hood.

A detailed description of the structural assemblies and the test structure is provided in the following section.

Figure 1. Photograph showing lowest (first) storey concrete block walls and exhaust hood.

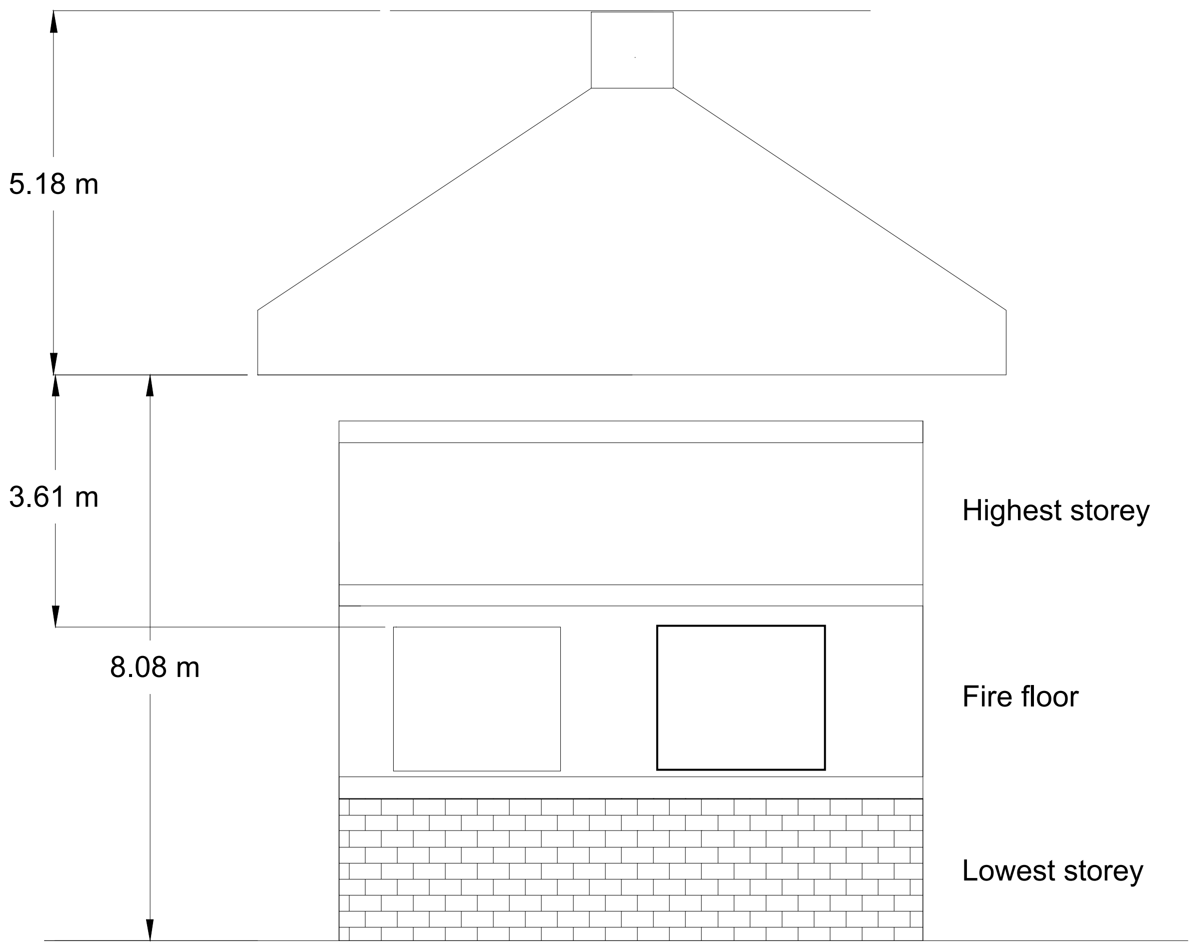


Figure 2. Test setup three storey elevation.

3 STRUCTURAL ASSEMBLIES (MIDDLE STOREY)

3.1 Wall Assemblies

All the CLT structural wall assemblies were loadbearing and were constructed using 105 mm thick 3-ply CLT panels with each ply 35 mm thick. However, the method used to attach the gypsum board encapsulation differed depending on the location of the wall. Four different wall assemblies, including wood stud non-loadbearing partitions enclosing the closets and bathroom, were used in the test arrangement, as shown in Figure 4. Detailed descriptions of these wall assemblies are provided in the following sections.

3.1.1 Wall Type A

Wall Type A simulated interior loadbearing walls, with the east and west walls simulating fire separations located between adjacent dwelling units, provided with encapsulation that would result in the assemblies having more than a 90-min fire-resistance rating and the south wall simulating a fire separation located between the apartment and corridor and provided with encapsulation that would result in the assembly having more than a 90-min fire-resistance rating (Figure 4).

Two layers of 12.7 mm thick Type X gypsum board, oriented vertically, were attached to the CLT panels using wood strapping on the interior (fire-exposed) side of the wall.

Vertical 41 mm x 41 mm wood strapping was attached to the interior side of the walls, spaced at 600 mm O.C. The cavities formed by the wood strapping were filled with glass fibre batt insulation. In actual practice, this lightweight wood-frame strapping would serve two purposes: 1) provide a space for electrical and plumbing services and 2) improve acoustical performance.

The base layer of gypsum board was attached to the strapping using 41 mm long Type S screws spaced at 600 mm O.C. in the vertical direction.

The face layer of gypsum board was attached over the base layer, with the joints between the panels staggered from those in the base layer. The face layer was fastened to the wood strapping along its edges and its centerline, using 50 mm long Type S screws spaced at 300 mm O.C. in the vertical direction.

In real applications, the same method of attaching the gypsum board to the CLT would be used on the unexposed (non-fire) side of the CLT. However, it was expected that the fire would have little to no effect on, and not spread through or beyond, the encapsulated CLT wall during the test. Therefore, to reduce construction time, only a single layer of 12.7 mm thick Type X gypsum board, oriented vertically, was directly attached to the unexposed side of the wall assembly.

The single layer of gypsum board was fastened to the CLT along its edges and in the field, using 41 mm long Type S screws spaced at 400 mm O.C. in both the vertical and horizontal directions. The joints of the gypsum board were staggered from the joints in the CLT panels.

3.1.2 Wall Type B

Wall Type B simulated an exterior loadbearing wall and was located on the north side of the test structure (Figure 4). Small CLT sections were used to connect the CLT panels on either side of the openings in the exterior wall (Figure 5).

Two layers of 12.7 mm thick Type X gypsum board, oriented vertically, were directly attached to the CLT panels on the interior side of the wall.

The base layer of gypsum board was attached using 41 mm long Type S screws spaced at 600 mm O.C. in both the vertical and horizontal directions. The joints between the panels for the base layer were staggered from the joints in the CLT panels.

The face layer of gypsum board was attached over the base layer, with the joints between the panels staggered from those in the base layer. The face layer of gypsum board was fastened using 50 mm long Type S screws spaced at 400 mm O.C. in both the vertical and horizontal directions.

A water resistant membrane (WRB) was applied to the exterior side of the CLT. Vertical wood strapping (41 mm x 41 mm) were attached over the WRB and fastened to the CLT. The strapping was spaced at 600 mm O.C. Top and bottom plates were included at each floor level. The cavity formed by the strapping was filled with glass fibre insulation.

A single layer of 12.7 mm regular gypsum sheathing was attached to the wood strapping using 41 mm long Type S screws spaced at 300 mm O.C. in the vertical direction. The gypsum sheathing material was combustible and had a flame spread rating of 20 and a smoke development of 0.

Other fire tests were conducted within this project involving CLT exterior walls using the standard CAN/ULC-S134 fire test method [6]. Those tests showed that ordinary gypsum sheathing was sufficient to limit upward exterior flame spread when used as part of the exterior cladding system for CLT wall assemblies that included a non-loadbearing wall system constructed on the outer face of the CLT wall using 38 mm x 144 mm studs, and having the stud cavities filled with extruded polystyrene insulation [7]. A non-combustible cladding was not used over the gypsum sheathing in the S-134 test.

The reasons for using a 41 mm x 41 mm stud wall insulated with glass fibre batt insulation, along with gypsum sheathing on the exterior face of the CLT test assembly are:

1. With the full-scale apartment testing, the objective was to investigate the impact of encapsulation of the wood structural members on fire spread within the storey of fire origin, not the potential for exterior flame spread from one storey to an upper storey in the test structure. The potential for exterior flame spread from one storey to another was examined using the CAN/ULC-S134 test method. Because no cladding was used in the simulated apartment fire test, there was the possibility of the external flames extending from the opening penetrating back through the exterior gypsum sheathing above the opening and eventually involving the wood studs and the insulation, thereby increasing the size of the fire outside the apartment, which could affect the measurements of the parameters for the fire within the apartment.
2. The non-loadbearing wood stud portion of the exterior wall was outboard of the CLT structural elements. The use of a different wall framing system with larger (deeper) studs and foam insulation was not expected to impact the test data with respect to the ability of the internal encapsulation of the CLT walls to protect the CLT from a fire originating inside the apartment.

3.1.3 Wall Type C

Non-loadbearing interior wood stud partitions were used at the south end of the bedroom to separate it from the closet in the entryway and from the bathroom (Figure 4). Similar walls were used for enclosing the bathroom. These walls were constructed using 38 mm x 89 mm wood studs, spaced 406 mm O.C. The partitions were not provided with encapsulation other than a single layer of 12.7 mm regular gypsum board, vertically oriented, which was installed on both sides of the wood stud framing, and fastened as required. The cavity spaces between the studs were filled with glass fibre batt insulation. These wall systems were identical to those used in the simulated apartment test with the lightweight wood frame test arrangement [3].

3.1.4 Wall Type D

Wall Type D was an interior loadbearing CLT wall that separated the bedroom from the living room/kitchen area. The interior loadbearing wall ran in the north-south direction for approximately three-quarters of the full width of the test arrangement, ending at the entryway. A door opening was included in the wall with a standard interior door. This door was closed at the start of the fire.

The interior CLT wall was provided with encapsulation on both faces that would result in the assembly having more than a 90-min fire-resistance rating.

Two layers of 12.7 mm thick Type X gypsum board, oriented vertically, were directly attached to the CLT panels on both sides of the wall.

The base layer of gypsum board was fastened to the CLT along its edges and its centerline, using 41 mm long Type S screws spaced at 600 mm O.C. in both the vertical and horizontal directions. The joints between the panels for the base layer were staggered from the joints in the CLT panels.

The face layer of gypsum board was attached over the base layer, with the joints between the panels staggered from those in the base layer. The face layer of gypsum board was fastened to the CLT along its edges and in the field, using 50 mm long Type S screws spaced at 400 mm O.C. in both the vertical and horizontal directions.

3.2 Floor/ceiling Assemblies

The two floor-ceiling assemblies within the test structure were constructed using 175 mm thick 5-ply CLT panels, with each ply 35 mm thick. Each floor assembly consisted of 3 panels that ran the full-length of the test arrangement in the east-west direction (see Figure 5).

For the ceiling/floor assembly between the lowest and middle storeys, a single layer of 12.7 mm thick Type X gypsum board was directly attached to the underside of the CLT floor assembly, as the ceiling of the lowest storey. The gypsum board was fastened to the CLT along its edges and in the field, using 41 mm long Type S screws spaced at 300 mm O.C. in both directions. The gypsum board joints were not taped and they were staggered from the joints in the CLT panels.

Two layers of 12.7 mm thick cement board were located on top of the CLT with limited fastening. These two layers of cement board were used as an alternative to a concrete topping as an encapsulation material for the floor in the fire floor. This was done to speed up construction. The joints of the base layer of cement board were staggered with the joints in the CLT panels and the joints of the face layer were staggered with the joints in the base layer. A floating hardwood floor using 17.5 mm thick hardwood flooring (nominal 19 mm) was located throughout the apartment area except the bathroom, where no finished floor was installed.

Acoustic membranes were located between the CLT floor assembly and the cement board, as well as between the face layer of cement board and the hardwood floor. The acoustic membranes used in the test assembly are identified as AM-5 and AM-6 in Reference [8]. The two products were selected based on cone calorimeter tests that indicated these products produced the highest total heat output of the acoustic membranes tested.

For the ceiling/floor assembly between the middle and highest storey, two layers of 12.7 mm thick Type X gypsum board were directly attached to the underside of the CLT floor assembly, as the ceiling of the fire floor. The base layer of gypsum board was fastened to the CLT along its edges and its centerline, using 41 mm long Type S screws spaced at 600 mm O.C. in both directions. The joints between the panels for the base layer were staggered from the joints in the CLT panels.

The face layer of gypsum board was attached over the base layer, with the joints between the panels staggered from those in the base layer. The face layer of gypsum board was fastened to the CLT along its edges and in the field, using 50 mm long Type S screws spaced at 300 mm O.C. in both directions.

The two gypsum board layers were attached to the ceiling before the vertical wood strapping and gypsum board were attached to the wall assemblies.

On the highest storey, the top of the CLT floor panels was covered with two layers of 12.7 mm cement board with limited fastening. The joints of the base layer of cement board were staggered with the joints in the CLT panels and the joints of the face layer were staggered with the joints in the base layer. Unlike in the fire floor, acoustic membranes and hardwood flooring were not used.

For all wall and ceiling surfaces inside the apartment on the middle storey (the fire floor), the gypsum board joints were taped and finished with joint compound.

4 LOWEST STOREY

The lowest storey of the test structure consisted of 2.0 m high concrete block walls. These walls were used to raise the test structure off the floor of the NRC research facility. This allowed access to the ceiling (underside) of the ceiling/floor assembly between the lowest and middle storeys, for construction purposes. It also provided a more representative arrangement for heat transfer through the ceiling/floor assembly with the underside of the ceiling interfacing with air rather than the concrete floor of the research facility.

The concrete block walls on the south and north sides of the test arrangement were 8.51 m long and the wall on the east end was 6.55 m long. The west end was partially framed-in and partially left open to allow access to the space beneath the test structure.

Steel beams supported by the north and south concrete block walls were located at approximately the mid-length of the test assembly and at its west end. The beam at the mid-length of the test arrangement was used to support the CLT panels in the ceiling/floor assembly between the lowest and middle storeys. The two steel beams were supported at their mid-length by wood posts.

At the top of the concrete blocks walls, 38 mm x 184 mm lumber was attached to the blocks to allow the CLT wood structural elements to be fastened to the top course in the concrete block walls.

The ceiling was a single layer of 12.7 mm thick Type X gypsum board, which was directly attached to the underside of the CLT panels. The joints were not taped.

In real applications, the two layers of 12.7 mm thick gypsum board would be used on the unexposed (non-fire) side of the CLT. However, it was expected that the fire would have little to no effect on, and not spread through or beyond, the encapsulated CLT floor during the test. Therefore, to reduce construction time, only a single layer of 12.7 mm Type X gypsum board was directly attached to the unexposed side of the floor/ceiling assembly.

5 HIGHEST STOREY

The highest storey had a similar layout as the middle storey. However, the walls were 1.8 m in height. The shorter walls were used to provide clearance between the top of the test structure and the hood.

The wall assemblies were lined with a single layer of 12.7 mm Type X gypsum board directly attached to both sides of the CLT.

The wood stud partition walls separating the bedroom from the bathroom and entryway were not included in the third storey. Also, a door was not provided at the corridor entryway. An opening was located in the west wall to provide access to the third storey during construction (Figure 5). A CLT section was used to close this opening prior to the fire test.

The floor included the two layers of 12.7 mm thick cement board. The acoustic membranes and the hardwood floor were not included in the floor.

Wood I-joists were used for the ceiling assembly on the third storey. The joists spanned the width of the test arrangement. The ceiling was lined with a single layer of 12.7 mm thick Type X gypsum board, which was directly attached to the joists. The joints were not taped. A subfloor was not attached to the wood I-joists and no insulation was included in the ceiling assembly.

6 STRUCTURAL LOADING

For other than some smaller low-rise buildings, the prescriptive provisions of the NBC generally include two requirements for major structural load-bearing elements (floors, walls, roofs, etc.):

1. The elements must have sufficient structural fire resistance to limit the probability of failure or collapse during the time required for occupants to evacuate safely and emergency responders to perform their duties.
2. For larger and taller buildings, the NBC also requires the use of noncombustible construction.

Whenever the first requirement applies, and a particular level of fire-resistance rating is prescribed (e.g. 45 min, 1 h, 2 h), the level of structural fire performance (fire resistance) of a building element is addressed in the NBC by requiring testing in accordance with CAN/ULC-S101 [9]. The design methods and loadings used are those required by the NBC and the superimposed load applied during the fire test must represent a full specified load condition or a restricted load use condition. However, these standard fire-resistance tests do not evaluate the effect or performance expected or intended by the second requirement, that is, use of noncombustible structural elements.

The (primary) objective of the simulated apartment fire tests was to determine the fire performance capability of the gypsum board and cement board to effectively encapsulate the combustible structural elements (and thus provide an equivalent level of fire safety to that provided by the application of the noncombustible construction requirements). In this regard, critical observations include the ability of the encapsulation to both delay (or prevent) ignition of the combustible structural elements and also limit their subsequent contribution (due to burning of the elements) to the fire severity within the fire compartment.

Given the primary objectives of the research, the standard fire resistance test, CAN/ULC-S101 was not suitable for this portion of the project. The loadbearing 3-ply CLT wall assemblies used in the test structure, with the level of encapsulation used, would be expected to demonstrate performance in the standard (CAN/ULC-S101) fire test of more than 90 min. The 5-ply CLT floor assembly, with the level of encapsulation used, would be expected to have a fire endurance period of more than 2 h.

For this simulated apartment fire test, the floor assembly of the middle storey (fire floor) was subjected to a superimposed live load arising from the presence of actual (typical) furnishings, fixtures and other contents. On the highest storey, concrete blocks were used to simulate live loads that were the same weight as the furniture and contents on the middle storey and also simulated larger items, such as the bed, in point loading. The loadbearing walls bounding the four sides and within the apartment structure (between bedroom and living room/kitchen) were subjected to the combination of the live loads on the middle and highest floors, along with the loads imposed by the self-weight (dead load) of the structure on the middle and highest storeys.

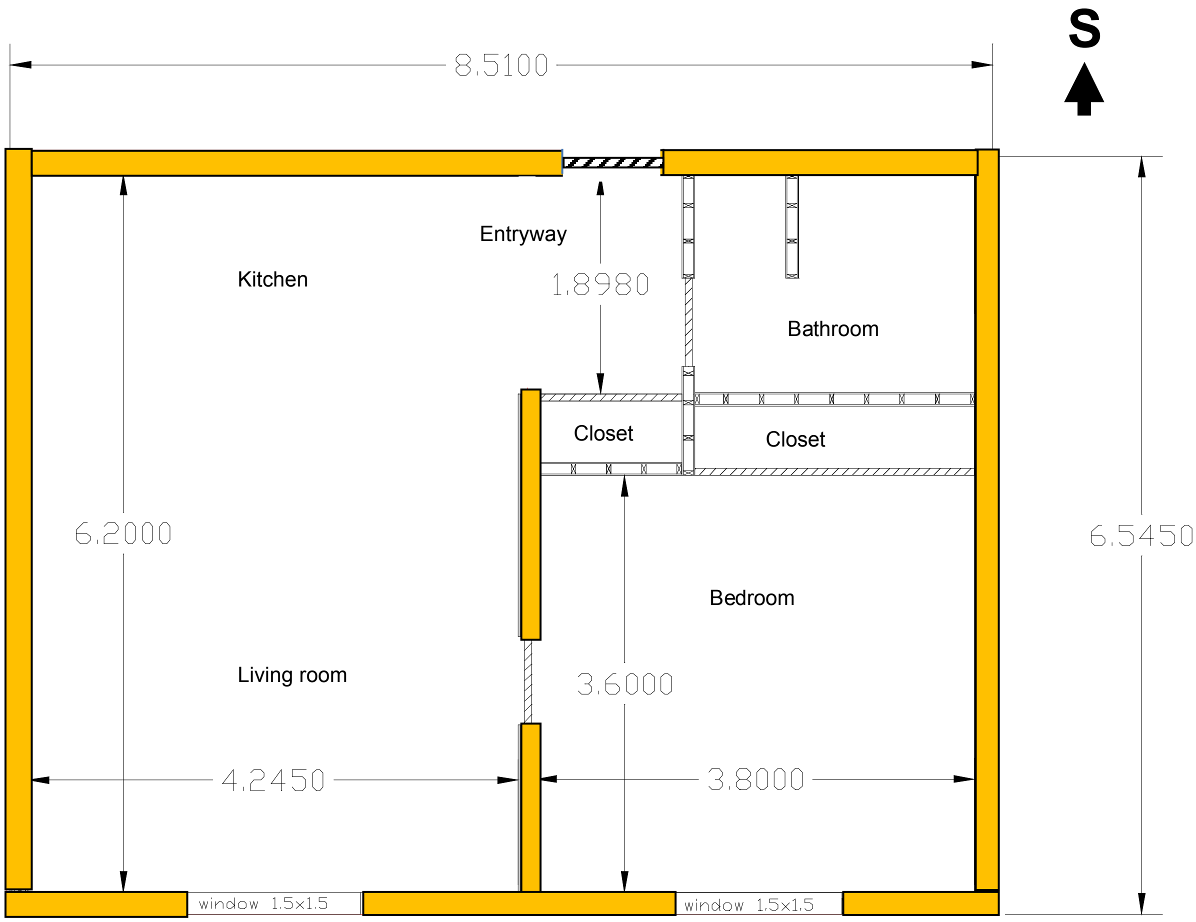
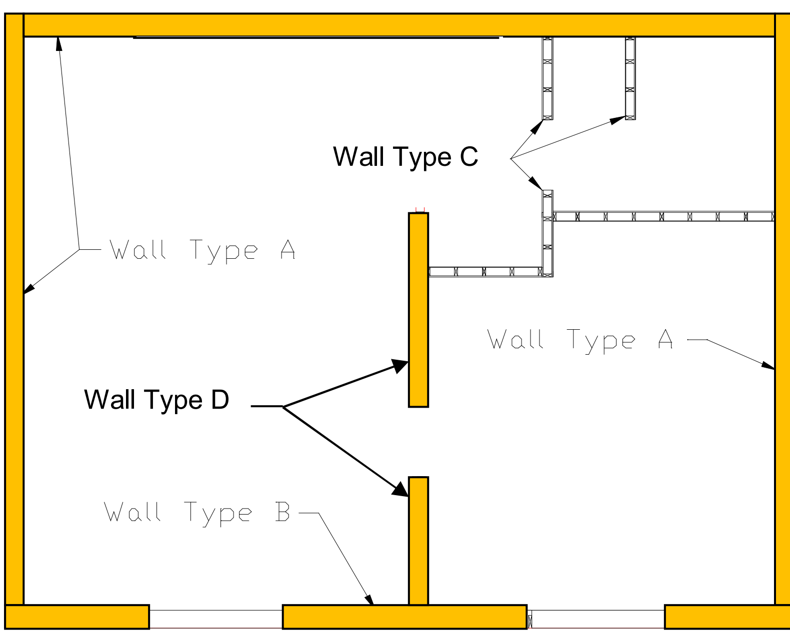


Figure 3. Apartment (fire floor) layout (all measurements in m).



Wall Type A. 3-ply CLT structural elements with 41 mm x 41 mm wood strapping on the fire-exposed side, glass fiber batt insulation and 2 layers of 12.7 mm thick Type X board. Single layer 12.7 mm thick Type X gypsum board on unexposed (outer) side.

Wall Type B. 3-ply CLT structural elements with 2 layers of 12.7 mm thick Type X gypsum board directly attached on the fire-exposed side. WRB used on unexposed side with a non-loadbearing 41 mm x 41 mm (2 in. x 2 in.) outboard wood stud wall with glass fibre batt insulation and 12.7 mm thick regular gypsum sheathing.

Wall Type C. 38 mm x 89 mm (2 in. x 4 in.) wood studs at 406 mm O.C.. One layer 12.7 mm thick regular gypsum board each side. Glass fibre batt insulation.

Wall Type D. 3-ply CLT structural elements with 2 layers of 12.7 mm thick Type X gypsum board directly attached on both sides.

Figure 4. Wall assemblies.

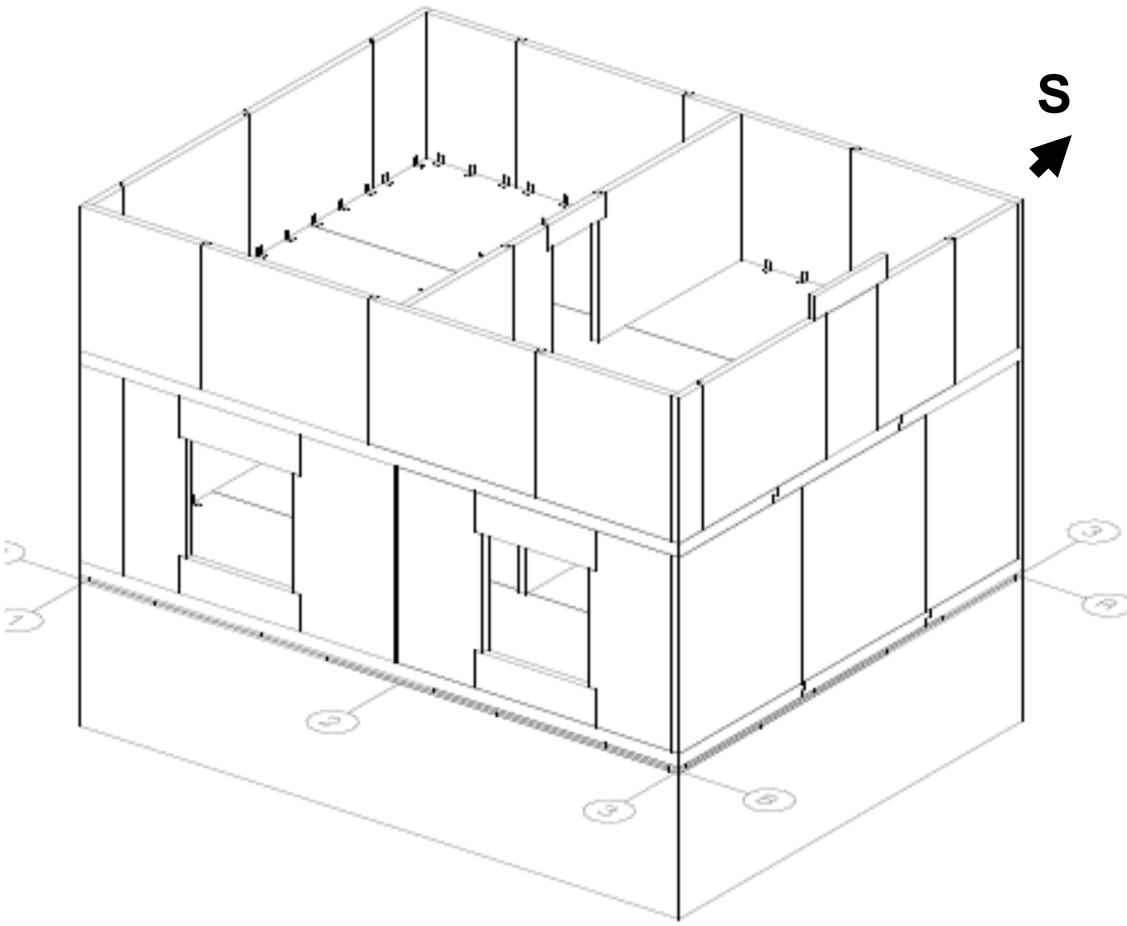


Figure 5. Isometric view of CLT structural assembly.

7 FUEL LOAD

The primary fuel load present within the fire floor (middle storey) was made up of typical furniture and contents found in residential occupancies. The items used in the apartment fire tests were based on previous fire tests conducted as part of a project to develop information to be used as a basis for establishing ‘design fires’ for multi-family occupancies [10]. These fuel loads were based on actual field surveys conducted to determine fuel loads in multi-family dwelling units [11]. The layout of the fuel load in the test area is shown in Figure 6.The labels (e.g. SI-13) on the items used in the bedroom refer to single item tests conducted on the fuel item [12].

In addition to the furniture and contents, fuel was also provided by the hardwood flooring used throughout the test area except the bathroom, the kitchen cabinets and island including counter tops and by the wood framing used for the partition wall between the bedroom and the bathroom/entrance.

Figure 6. Fuel load layout.

8 INSTRUMENTATION

Various measurement devices were used in the apartment fire test. This included thermocouples, heat flux meters, video cameras and gas analyzers. The devices used and their location are described in the following sections.

8.1 Thermocouple Trees in the Middle Storey (Fire Floor)

Thermocouple trees were located in the bedroom, the living room/kitchen area and the entryway. For each thermocouple tree, thermocouples were located at the 0.4 m, 1.4 m and 2.4 m (25 mm below the ceiling) heights. The temperatures measured using these thermocouples provided data on the temperature rise within the apartment.

Four thermocouple trees were located in the bedroom at the center of the room quadrants (Figure 7).

Three thermocouple trees were located in the living room and kitchen area. The trees were located along the north-south centerline of the area, with the trees located at the ¼, ½ and ¾ length of living room and kitchen area (Figure 7). A thermocouple tree was located at the center of the apartment entryway (Figure 7).

8.2 Thermocouples in Wall Assemblies

In the three simulated interior walls (Wall Type A) on the fire floor, thermocouples were located in the cavities formed by the 41 mm x 41 mm strapping used to attach the two layers of gypsum board on the exposed (fire) side of the three walls. The thermocouples were installed in the cavity space prior to the insulation and they measured the temperatures at the interface between the insulation and CLT panels.

The approximate location of thermocouples in each wall cavity area is shown in the sketch in Figure 8. The temperatures measured using these thermocouples provided data on the temperatures in the wall assemblies, which can be used to help determine the time required for the fire to penetrate the encapsulation materials. The following lists the number and locations of the TCs in the Type A and Type C walls on the fire floor:

1. Nine thermocouples were located in the west wall (Wall Type A) of the bedroom. The thermocouples were located at the 0.6, 1.2 and 1.8 m heights at three locations along the length of the room (¼ and mid-lengths of the main bedroom area excluding the closet).
2. Three thermocouples were located in the partition wall (Wall Type C) between the bedroom and the bathroom. The thermocouples were at the 1.8 m height and were located at the ¼ and mid-widths of the bedroom. The thermocouples were located at the interface between the gypsum board and the insulation on the bedroom side of the wall.
3. Nine thermocouples were located in the east wall (Wall Type A) of the living room and kitchen area. The thermocouples were located at the 0.6, 1.2 and 1.8 m heights at three locations along the length of the room (¼ and mid-lengths).
4. Nine thermocouples were located in the south wall (Wall Type A). The thermocouples were located at the 0.6, 1.2 and 1.8 m heights at three locations along the length of the wall (¼ and mid-lengths).

In the loadbearing CLT wall (Wall Type D) between the bedroom and living room/kitchen, the two layers of gypsum board were directly attached to the CLT and the thermocouples were located between the base layer of gypsum board and the CLT panels. Six thermocouples were located on both the bedroom and living room/kitchen sides of the wall at the 0.6, 1.2 and 1.8 m heights. The thermocouples were located at the quarter-points along the length of the bedroom wall (Figure 8).

Twelve thermocouples were located in the north wall (Wall Type B) with the two openings, which represented an exterior loadbearing CLT wall. For this wall, the two layers of gypsum board were directly attached to the interior side of the CLT panels and the thermocouples were located between the base layer of gypsum board and the CLT panels. The 12 thermocouples were located at the 0.6, 1.2 and 1.8 m heights. The thermocouples were located at the center of the wall sections on either side of the ventilation openings in the bedroom and living room (Figure 8).

8.3 Thermocouples in Ceiling/Floor Assemblies

On the underside of the ceiling/floor assembly between the lowest and middle storeys, a single layer of gypsum board was directly attached to the CLT and thermocouples were located between the gypsum board and the CLT panels in the ceiling located below both the bedroom and the living room/kitchen areas on the fire floor.

On the underside of the ceiling/floor assembly between the middle and highest storeys, two layers of gypsum board were directly attached to the CLT and thermocouples were located between the gypsum board base layer and the CLT panels in the ceiling for the bedroom and in the living room and kitchen areas. Thermocouples were also installed between the CLT panels and the layer of acoustic membrane installed under the two layers of cement board and hardwood flooring in the floor in the bedroom on the fire floor.

The approximate location of thermocouples in the ceiling/floor assemblies on both storeys (levels) are shown in the sketch in Figure9. The temperatures measured using these thermocouples provided data on the temperatures in the ceiling/floor assemblies, which can be used to determine the time required for the fire to penetrate the encapsulation materials within the different rooms.

1. Nine thermocouples were located between the base layer of gypsum board and the CLT panels in the ceiling/floor assembly above the bedroom. The thermocouples were located at the quarter- and mid-widths and lengths of the bedroom area, excluding the closet.
2. Nine thermocouples were located between the single layer of gypsum board (ceiling) in the lowest storey and the CLT panels in the floor assembly below the bedroom. The thermocouples were located at the quarter- and mid-widths and lengths of the bedroom area, excluding the closet. The thermocouples were installed from the top of the floor through holes drilled in the CLT panels.
3. Nine thermocouples were located between the base layer of gypsum board and the CLT panels in the ceiling/floor assembly above the living room and kitchen. The thermocouples were located at the quarter- and mid-widths and lengths of the kitchen and living room area.
4. Nine thermocouples were located between the single layer of gypsum board (ceiling) in the lowest (first) storey and the CLT panels in the floor assembly below the living room and kitchen. The thermocouples were located at the quarter- and mid-widths and lengths of the living room/kitchen area. The thermocouples were installed from the top of the floor through holes drilled in the CLT panels.

8.4 Surface and Interface Temperatures

There were ten thermocouples located at the mid-length of the West bedroom wall to measure the temperatures either on the surface of or at the interface between the various materials used in the construction of the CLT wall assembly. The temperatures measured using these thermocouples provided data on the temperature profiles within the wall assembly and the time required for heat transfer through the wall assembly. These ten thermocouples were at the same location as the thermocouples located in the cavity space of the west wall of the bedroom at the mid-length of the wall, with five TCs located at both the 1.2 and 1.8 m heights (Figure 8). The locations of the thermocouples, starting in the fire area (bedroom), were as follows.

1. Exposed surface of the face layer of gypsum board.
2. Interface between the face and base gypsum board layers on the exposed (fire) side of the CLT wall assembly.
3. Interface between the base layer gypsum board and the 41 mm x 41 mm wood strapping.
4. Interface between the 41 mm x 41 mm wood strapping and the CLT panel.
5. Interface between the CLT panel and the gypsum board on the unexposed (outer) side of the wall assembly.

There were five thermocouples located at the center of the bedroom to measure the temperature either on the surface of or at the interface between the various materials used in the construction of the CLT ceiling/floor assembly separating the middle and highest storeys. The temperatures measured using these thermocouples provided data on the temperature profiles within the ceiling/floor assembly and the time required for heat transfer through the assembly. The locations of the five thermocouples, starting in the fire area (bedroom) were as follows:

1. Exposed surface of the face layer of gypsum board.
2. Interface between the face and base gypsum board layers on the exposed (fire) side of the CLT ceiling/floor assembly.
3. Interface between the base layer of gypsum board and CLT panel.
4. Interface between the CLT panel and base layer of cement board on the unexposed (upper) side of the ceiling/floor assembly.
5. Interface between the base and face layers of cement board on the unexposed (upper) side of the CLT ceiling/floor assembly.

Thermocouples were located at the center of the bedroom to measure the temperature either on the surface of or at the interface between the various materials used in the construction of the floor/ceiling assembly separating the middle and lowest storeys. The temperatures measured using these thermocouples provided data on the temperature profiles at various locations in the floor/ceiling assembly and the time required for heat transfer through the assembly. The locations of the thermocouples, starting in the fire area (bedroom) were as follows:

1. On the exposed side (top) of the hardwood flooring.
2. Interface between the acoustic membrane and the hardwood flooring.
3. Interface between the face layer of cement board and acoustic membrane.
4. Interface between the base and face layers of cement board.
5. Interface between the acoustic membrane and the base layer of cement board.
6. Interface between the single layer of gypsum board (ceiling) in the lowest (first) storey and CLT panels.
7. Unexposed face of single layer of gypsum board (ceiling) on the unexposed side of the CLT floor assembly.

Nine thermocouples were installed between the CLT panels and the layer of acoustic membrane installed under the two layers of cement board and wood flooring in the floor below the bedroom. The thermocouples were located at the quarter- and mid-widths and lengths of the bedroom area, excluding the closet. In plan view, these thermocouples were at the same location as the thermocouples in the ceiling/floor assembly shown in Figure 9.

8.5 Thermocouples in the Highest Storey

Thermocouple trees were located in the bedroom and living room and kitchen area on the highest storey. Each tree was located at the center of the respective area. The thermocouples were located at the 0.4, 1.4 m heights and 1.8 m (25 mm below the ceiling).

Nine thermocouples covered with the pads used in standard fire resistance tests [9] were located on the exposed surface (top) of the face layer of cement board in the bedroom area on the highest storey. The thermocouples were located at the quarter- and mid-widths and lengths of the bedroom area, excluding the closet. In plan view, these thermocouples were at the same location as the thermocouples in the ceiling above the bedroom area on the fire floor, as shown in Figure 9.

8.6 Additional Thermocouples

Nine thermocouples covered with pads used in standard fire resistance tests [9] were located on the surface of the gypsum board on the unexposed (outer) side of the West bedroom wall. The thermocouples are located at the 0.6, 1.2 and 1.8 m heights at three locations along the length of the bedroom (¼ and mid-lengths of the main bedroom area excluding the closet), which represents the same elevation and location as the thermocouples in the cavity of the West bedroom wall (Figure 8).

Two thermocouples were located on both the bedroom and corridor entryway doors approximately 50 mm below the top of the door. The thermocouples on the bedroom door were located on the living room side and the thermocouples on the entryway door were located on the unexposed (corridor) side of the door.

Thermocouples were located in the joint between CLT panels 21_15 and 21_16 in the west bedroom wall (see Figures A-5 and A-7). The two panels were at the north end and the center of the wall, respectively. The joint was approximately 2.1 m from the northwest corner of the structure. The thermocouples were located in the section of the joint that was parallel with the wall and were 0.6, 1.2 and 1.8 m above the floor.

Thermocouples were located in the joint between CLT panels 11_02 and 11_03 in the bedroom ceiling/floor assembly (see Figure A-7) just above the bedroom. The two panels were at the center and north end of the floor assembly, respectively. The joint was approximately 1.8 m from the North end of the structure. The thermocouples were located in the section of the joint that was parallel with the ceiling/floor and were at the quarter and mid-widths of the bedroom.

8.7 Heat Flux Meters.

Heat fluxes were measured at various locations exterior to the fire area. This included:

1. Two heat flux meters facing the bedroom opening with both meters centered on the opening. The heat flux meters were located 2.4 and 4.8 m from the opening.
2. Two heat flux meters facing the living room opening with both meters centered on the opening. The heat flux meters were located 2.4 and 4.8 m from the opening.
3. Heat fluxes to the exterior wall façade were measured using heat flux meters located 3.5 m above the top of the openings in the bedroom and living room. The meters were centered on the openings. This location is consistent with the location used for measuring heat fluxes in exterior wall fire testing in accordance with CAN/ULC S134 [6].

The heat flux meters in Items 1 and 2 were used to provide data on potential exposures from the fire to adjacent buildings. The heat flux meters located in the exterior wall façade provided data on the fire exposure to the upper storey(s) and exterior cladding from the fire plumes extending from the openings on the fire floor.

8.8 Duct Measurements

The smoke and hot gases produced by the fire was collected using a 10.67 by 10.67 m hood system mounted above the test setup (Figure 2). The hood system was connected through a duct system to an exhaust fan system.

A measuring station was setup in the duct system at which a thermocouple was used to measure the smoke temperature and a pitot tube was used to measure the pressure difference produced by the flow in the duct. These measurements were used to estimate the equivalent volumetric flow rate at standard atmospheric conditions.

In addition, smoke samples were taken from the center of the duct and were analyzed to determine the concentrations of O_2, CO and CO_2. These measurements, along with the volumetric flow rate of exhaust gases, were used to determine the heat release rate using the oxygen depletion method [13].

8.9 Video

Video cameras were mounted at various locations to provide video records for the test. This included:

1. A disposable camera was located in the bedroom, viewing the ignition area on the bed.
2. A disposable camera was mounted on the east wall of the living room, viewing the loadbearing wall between the bedroom and living room and the hollow core door mounted in this wall.
3. A disposable camera was located in the kitchen area, viewing the entryway and bathroom area.
4. A disposable camera was located in the highest storey bedroom area.
5. Two cameras were located exterior to the test setup, viewing the fire within the apartment through the bedroom and living room openings.

In addition to the cameras installed by the laboratory, video and photographic records were also taken by the NRC videographer. Additional photographs were also taken by the project participants and NRC staff.

8.10 Smoke Alarm

A smoke alarm was located at the center of the bedroom ceiling. Its response time was determined using video records.

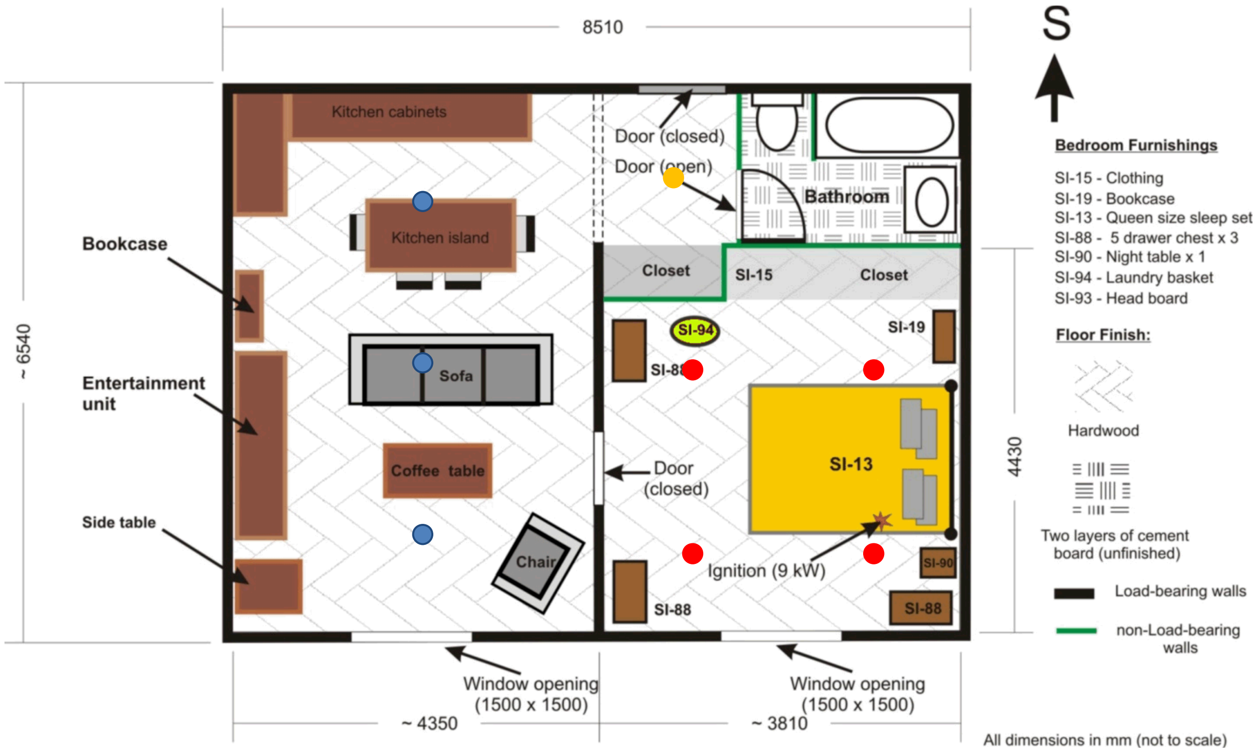


Figure 7. Location of thermocouple trees in the bedroom (●), living room/kitchen (●) and entryway (●).

Figure 8. Sketch showing locations of thermocouples in wall assemblies. (The locations indicated by ▲ had thermocouples located at the 0.6, 1.2 and 1.8 m heights. The locations indicated by ▲ had a single thermocouple at the 1.8 m height.)

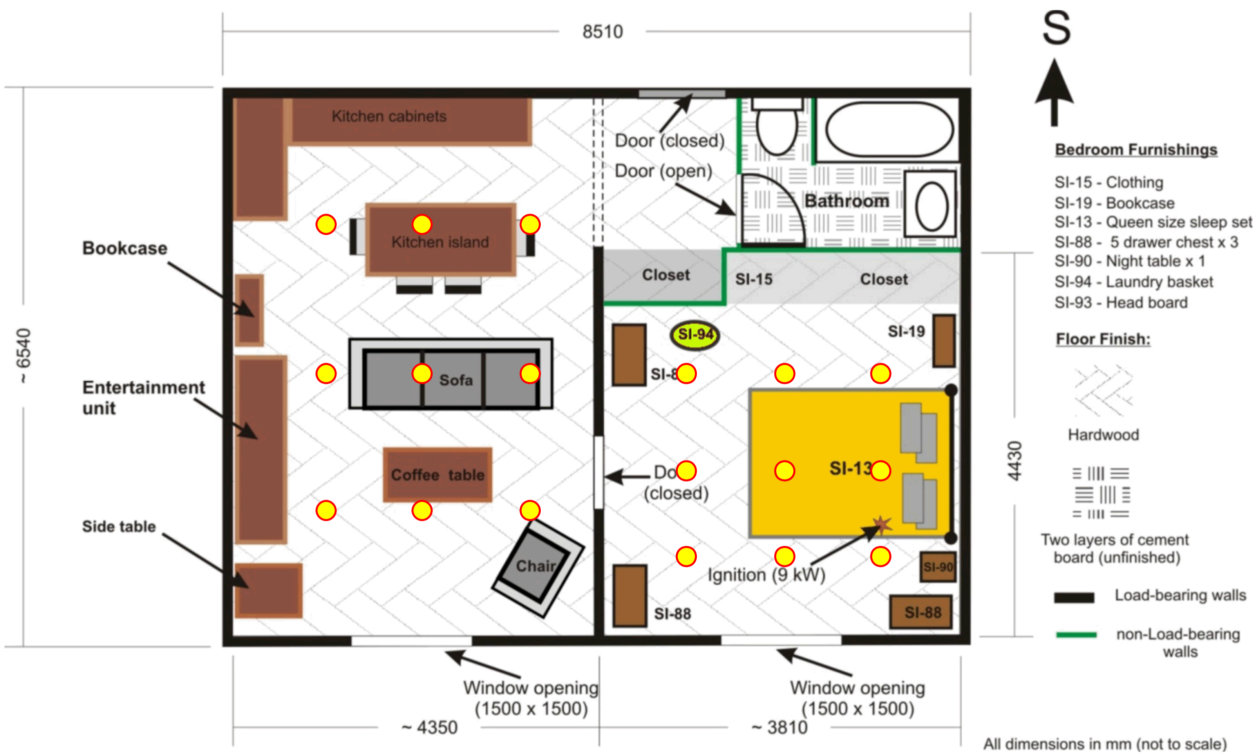


Figure 9. Sketch showing the locations of the thermocouples in the ceiling assemblies in the bedroom and living room and kitchen (○).

9 VENTILATION

Rough openings were used in the exterior wall to provide ventilation air for the fire. One opening was in the bedroom and the second in the living room (Figure 6). Both openings were 1.5 m x 1.5 m in size.

The edges of the openings were protected using steel sheet to limit direct attack of the fire on the framing elements. The objective of the simulated apartment fire test was to investigate the performance of the encapsulation materials for the structural elements and not the attack of the fire on the structural elements at the openings. In actual applications, the structural elements would be protected by the window frame.

The size of the openings was based on previous tests conducted as part of a fire research project to develop information to be used as a basis for establishing 'design fires' for multi-family residential occupancies [10]. In these tests, it was determined that this size of openings would maximize the amount of combustion and thus the fire temperatures inside the building. As a result, the fire severity and its exposure to the encapsulation materials are maximized.

Within the apartment, the hollow-core (wood fibre) door between the bedroom and living room was closed at the beginning of the test (Figure 6). A similar door used for the bathroom doorway was left open at the beginning of the test.

The 45-min fire rated steel door in the south (corridor) wall was closed throughout the test (Figure 6).

10 IGNITION SCENARIO

The bedding on the bed assembly was the first item ignited. It was ignited using a 9 kW T-burner that was positioned at a distance of 470 mm from the head of the bed (Figure 6). The same ignition scenario was used in the full-scale bedroom fire tests discussed in Reference [10].

11 RESULTS

Various measurement devices were used in the fire test. This included thermocouples, heat flux meters, video cameras and gas analyzers. The results of these measurements are provided in the following sections.

The ambient temperature at the start of the test was approximately 0°C. The fire floor was heated prior to the test. However, after the heaters were removed, there was cooling within the fire area. The temperatures measured within the wall and floor assemblies at the beginning of the test varied depending on the location.

A smoke alarm was located on ceiling at the center of the bedroom. It responded to the fire at 19 s.

11.1 Temperatures in Simulated Apartment

Thermocouple trees were located in the bedroom, the living room/kitchen area and the entryway. For each thermocouple tree, thermocouples were located at the 0.4 m, 1.4 m and 2.4 m (25 mm below the ceiling) heights.

11.1.1 Bedroom Temperatures

Four thermocouple trees were located in the bedroom at the southeast, southwest, northeast and northwest quarter points of the primary room area excluding the closet (Figure 7). The results measured at these locations are provided in Figure 10, Figure 11, Figure 12 and Figure 13, respectively.

There was an initial rapid increase in temperature at all heights in the bedroom with the temperature exceeding 600°C near the ceiling and at the 1.4 m height within 3.0 min. The temperature increase at the 0.4 m height for the two thermocouple trees located near the ventilation opening (Figures 12 and 13) was faster than at the two locations near the partition wall, with the temperatures exceeding 600°C within 3 and 5 min, respectively. These results indicate that flashover in the bedroom occurred within 3 min. The initial fire growth was consistent with a fast t-squared fire.

General observations regarding the temperatures measured at the thermocouple tree locations in the bedroom are (Note: since the total time duration for the test with the CLT structure was longer than for the tests with the lightweight frame structural assemblies, there was more variations in the temperatures measured within the bedroom and more detailed observations are provided in this report than in the reports for the other three tests):

1. **Southeast thermocouple tree.**
    a. Initial temperature peak at 3 min with peak temperature 777°C at the 1.4 m height.
    b. Temperature decrease to <700°C between 3 and 4 min.
    c. Increase in temperature at all levels between 4 and 12 min with a maximum temperatures of approximately 1200ºC at 12 min.
    d. Temperatures > 1150°C until approximately 22 min.
    e. Decrease in temperature between 22 and 30 min followed by temperature plateau until 40 min. There was also a temperature dip at the ceiling between 26 and 33 min.

f. Temperatures at the 1.4 m and ceiling heights comparable to approximately 40 min
g. After 40 min, temperatures gradually decreased as the fire decayed due to consumption of the combustibles in the apartment/bedroom area. Temperatures were > 800°C at 1.4 m and ceiling height until 54 and 56 min, respectively.
h. Dip in temperatures at 1.4 m and ceiling heights at approximately 128 min with the failure of the steel door in the corridor wall.
i. Temperatures increased after 170 min with partial burning of CLT ceiling.

2. **Southwest thermocouple tree.**
    a. Initial temperature peak at 3 min with peak temperature 783°C at the 1.4 m height.
    b. Temperature decrease to <700°C at 4 min.
    c. Increase in temperature at 1.4 and 2.4 m heights between 4 and 22 min.
    d. Increase in temperature at the 0.4 m height at approximately 15 min to temperatures comparable to those measured at the 1.4 m and ceiling height.
    e. Maximum temperatures of approximately 1200ºC at the 0.4 m and 1.4 m heights between 20 and 22 min.
    f. Decrease in temperature between 22 and 30 min followed by temperature plateau until 40 min.
    g. Temperatures at the 1.4 m and ceiling heights comparable to approximately 40 min. Temperatures were > 800°C at 1.4 m and ceiling height until 53 and 55 min, respectively.
    h. After 40 min, temperatures gradually decreased as the fire decayed due to consumption of the combustibles in the apartment/bedroom area.
    i. Increase in temperature at ceiling height at approximately 96 min.
    j. Dip in temperatures at 1.4 m and ceiling heights at approximately 128 min with the failure of the steel door in the corridor wall.
    k. Temperatures increased after 170 min with partial burning of CLT ceiling.
3. **Northeast thermocouple tree.**
    a. No initial temperature peak/dip.
    b. Temperatures at all heights > 950°C within 5 min.
    c. After 5 min, temperatures increased to 1100 - 1150°C between 18 and 23 min.
    d. Decrease in temperature between 23 and 30 min followed by temperature plateau until 40 min. There was also a temperature dip at the ceiling height between 26 and 33 min.
    e. Temperatures at the 1.4 m and ceiling heights comparable to approximately 40 min
    f. After 40 min, temperatures decreased as the fire decayed due to consumption of the combustibles in the apartment/bedroom area. Temperatures were > 800°C at 1.4 m and ceiling height until 51 and 58 min, respectively.
    g. Dip in temperatures at 1.4 m and ceiling heights at approximately 128 min with the failure of the steel door in the corridor wall.
    h. Temperatures increased after 170 min with partial burning of CLT ceiling.
4. **Northwest thermocouple tree.**
    a. Initial temperature peak just after 3 min, with peak temperature 948°C at the 1.4 m height.
    b. Temperature decrease to 803°C at 4.1 min followed by increase in temperatures at all levels.
    c. Temperatures at all heights exceeded 950°C after 6 min with highest temperatures at 1.4 m height reaching approximately 1150°C at 19 min.

d. Decrease in temperature between 24 and 30 min followed by temperature plateau until 40 min.
e. Temperatures at the 1.4 m and ceiling heights comparable to approximately 40 min. Temperatures were > 800°C at 1.4 m and ceiling height until 52 and 54 min, respectively.
f. After 40 min, temperatures decreased as the fire decayed due to consumption of the combustibles in the apartment/bedroom area.
g. Rapid increase in temperature at 0.4 m height at approximately 65 min. The temperature at this height remained higher than at the other heights until approximately 144 min. (The reason for this difference in temperature at the 0.4 m height is not known. One possibility is that an object was burning near the thermocouple resulting in direct flame impingement.)
h. Dip in temperatures at 1.4 m and ceiling heights at approximately 128 min with the failure of the steel door in the corridor wall. There was a further decrease in temperatures at 144 min.
i. Temperatures increased after 170 min with partial burning of CLT ceiling.

11.1.2 Living Room/Kitchen and Entryway Temperatures

Four thermocouple trees were located in the living room/kitchen area and entryway. The trees in the living room and kitchen were located along the north-south centerline of the area with the trees located at the ¼, ½ and ¾ length of living room and kitchen area (Figure 7). The results measured at South thermocouple tree, in the entryway and the mid-length and North living room trees are provided in Figure 14, Figure 15, Figure 16 and Figure 17, respectively.

Initial temperature increases were measured at the ceiling between 2 and 3 min after the fire was ignited in the bedroom. There was a faster growth in the living room area with temperatures > 600°C at 4 min near the ventilation opening and at 5 min at the center of the living room. The temperatures in the kitchen and entryway were > 600°C at 7 min and 14 min, respectively. These results suggest that there was localized flashover in the living room between 4 and 5 min after the fire was ignited in the bedroom. Flashover in the kitchen and entryway was at 7 and 14 min, respectively.

General observations regarding the temperatures measured at the thermocouple tree locations are (Note since the total time duration for the test with the CLT structure was longer than for the tests with the lightweight frame structural assemblies, there was more variations in the temperatures measured within the living room/kitchen and entryway areas and more detailed observations are provided in this report than in the reports for the other three tests)::

1. **North living room thermocouple tree.**
   a. Initial temperature increase at 3 min at ceiling.
   b. Temperatures exceeded 600°C at the ceiling, 1.4 and 0.4 m heights at 4, 7 and 8 min, respectively.
   c. After 8 min, the temperatures measured at the ceiling and 1.4 m heights increased with a peak temperature of 1178°C at 30 min at the 1.4 min height.
   d. General decrease in temperatures after 32 min as the fire decayed due to consumption of the combustibles in the living room/kitchen area.
   e. Temperatures at the 1.4 m and ceiling heights comparable to approximately 40 min. Temperatures were > 800°C at 1.4 m and ceiling height until 57 and 63 min, respectively.

   f. Dip in temperatures at all heights at approximately 128 min with the failure of the steel door in the corridor wall.
   g. Temperatures increased after 170 min with partial burning of CLT panels in the ceiling.
2. **Center living room thermocouple tree.**
   a. Initial temperature increase at 2.0 min at ceiling.
   b. Temperatures exceeded 600°C at the ceiling, 1.4 and 0.4 m heights at 5.0, 8 and 20.0 min, respectively.
   c. After 8 min, the temperatures measured at all heights increased with approximately 1240°C peak temperatures at the 1.4 m and 0.4 m heights at 30 min. The maximum temperature at the ceiling height was 1115°C. (The higher temperatures measured at lower heights may be due to direct flame impingement on the thermocouples.)
   d. After 32 min, there was decrease in temperature at the two lower heights. The temperature at the ceiling remained relatively steady until approximately 44 min.
   e. After 44 min, there was a general decrease in temperature at all heights as the fire decayed, due to consumption of the combustibles in the living room/kitchen area. Temperatures were > 800°C at 1.4 m and ceiling height until 59 and 65 min, respectively.
   f. Dip in temperatures at all heights at approximately 128 min with the failure of the steel door in the corridor wall.
   g. Temperatures increased after 170 min with partial burning of CLT ceiling.
3. **South kitchen thermocouple tree.**
   a. Initial temperature increase at 2.5 min at ceiling.
   b. Temperatures exceeded 600°C at the ceiling, 1.4 and 0.4 m heights at 7, 11 and 25 min, respectively.
   c. After 8.0 min, the temperatures measured at all heights continued to increase with peak temperatures > 1200°C at the 1.4 m and 0.4 m heights at 34 and 39 min, respectively. The maximum temperature at the ceiling was 1150°C. (The higher temperatures measured at lower heights may be due to direct flame impingement on the thermocouples.)
   d. After 39 min, there was decrease in temperature at the two lower heights. The temperature at the ceiling remained relatively steady until approximately 45 min.
   e. After 45 min, there was a general decrease in temperature at all heights as the fire decayed, due to consumption of the combustibles in the living room/kitchen area. Temperatures were > 800°C at 1.4 m and ceiling height until 59 and 68 min, respectively.
   f. Dip in temperatures at all heights at approximately 128 min with the failure of the steel door in the corridor wall.
   g. Temperatures increased after 170 min with partial burning of CLT ceiling panels.
4. **Entryway thermocouple tree.**
   a. Initial temperature increase at 3.0 min at ceiling.
   b. Temperatures exceeded 600°C at the ceiling, 1.4 and 0.4 m heights at 14, 16 and 24 min, respectively.
   c. After 8.0 min, the temperatures measured at all heights increased with a peak temperature of 1205°C at the 1.4 m height at 34 min. The maximum temperatures at the 0.4 m height and at the ceiling were 1100 - 1150°C.
   d. After 35 min, there was a gradual decrease in temperatures at all heights as the fire decayed, due to consumption of the combustibles in the living room/kitchen area. Comparable temperatures were measured at all heights until 53 min.

e. After 53 min, the highest temperatures were measured at the ceiling. Temperatures were > 800°C at 1.4 m and ceiling height until 54 and 55 min, respectively.
f. Dip in temperatures at all heights at approximately 128 min with the failure of the steel door in the corridor wall.
g. Temperatures increased after 170 min with partial burning of CLT ceiling.

11.1.3 Summary Temperatures in Simulated Apartment

Overall, the temperatures measured at the four thermocouple tree locations in the bedroom had similar profiles with some variations depending on the fire dynamics at the particular location. The general trend was as follows:

1. An initial rapid increase in temperature to an initial peak temperature followed by a short dip in temperature with flashover occurring within 3 min.
2. A period with sustained high temperatures between 6 and 23 min.
3. An initial decrease in temperature between 23 and 28 min followed by a temperature plateau until approximately 40 min.
4. Temperatures at the 1.4 m and ceiling height above 800°C until after 50 min.
5. A gradual temperature decrease until 170 min at which time there was an increase in temperature with the ignition of some of the CLT panels in the ceiling assembly.

Based on the temperatures measured at the four thermocouple tree locations in the living room/kitchen and entryway, the following general observations can be made regarding the fire development in the kitchen/living room and entryway areas:

1. Initial temperature increases were measured at the ceiling between 2 and 3.0 min after the fire was ignited in the bedroom.
2. The fire developed faster in the living room area with temperatures > 600°C at 4 min near the ventilation opening and at 5 min at the center of the living room. The temperatures in the kitchen and entryway were > 600°C at 7 min and 14 min, respectively
3. The maximum temperatures in the living room area were measured between 29 and 30 min. The maximum temperatures in the kitchen and entryway were between 34 and 39 min.
4. After 45 min, there was a general decrease in temperatures at all heights and locations.
5. The temperatures exceeded 800°C at the 1.4 m and ceiling heights until 54 min in the entryway and until 57 to 69 min in the living room/kitchen area.
6. There was a temperature decrease at approximately 128 min with the failure of the steel door in the corridor wall.
7. The temperatures increased after 170 min with the ignition of some of the CLT in the ceiling assembly.

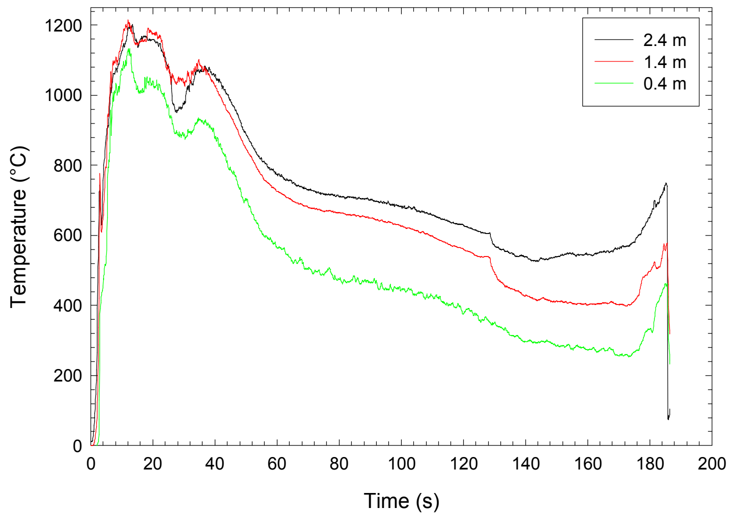


Figure 10. Temperatures southeast bedroom thermocouple tree.

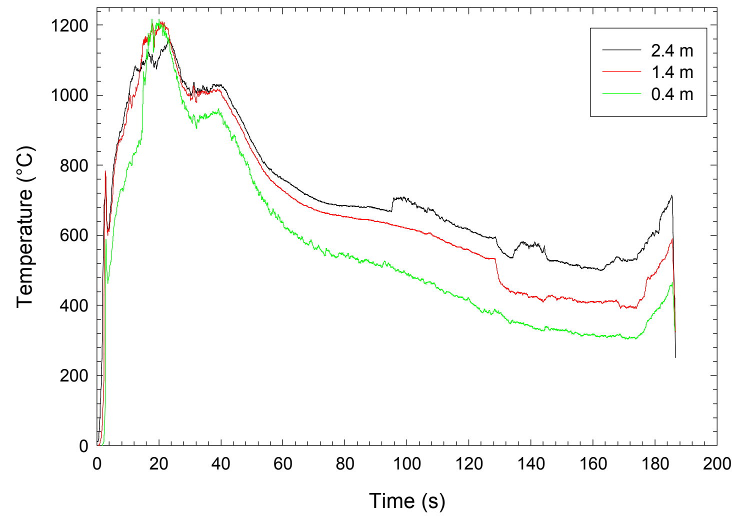


Figure 11. Temperatures southwest bedroom thermocouple tree.

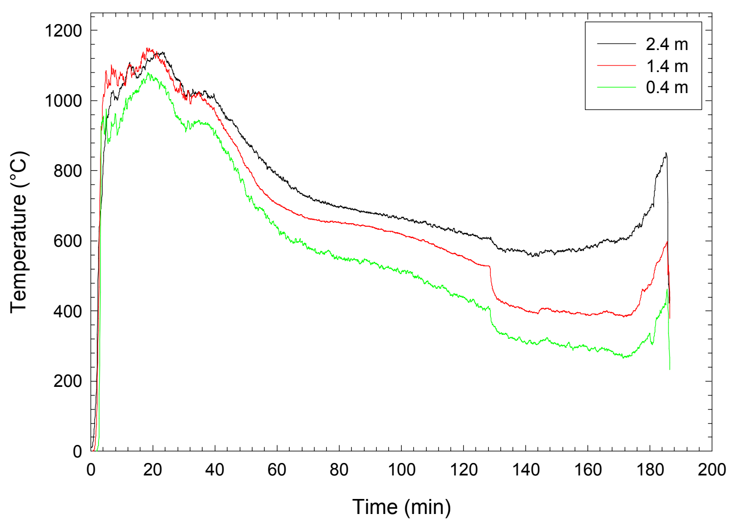


Figure 12. Temperatures northeast bedroom thermocouple tree.

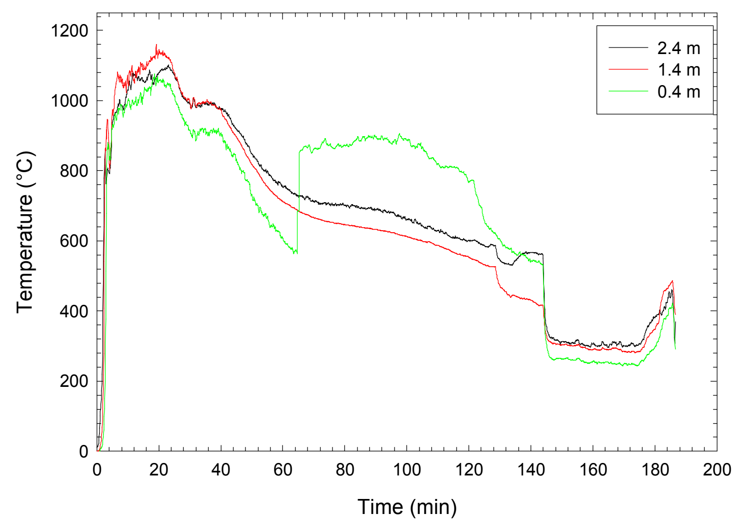


Figure 13. Temperatures northwest bedroom thermocouple tree.

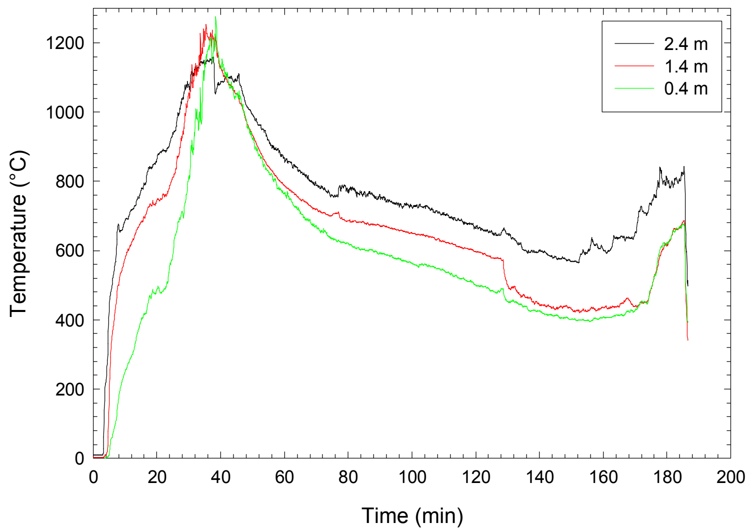


Figure 14. Temperatures south kitchen thermocouple tree.

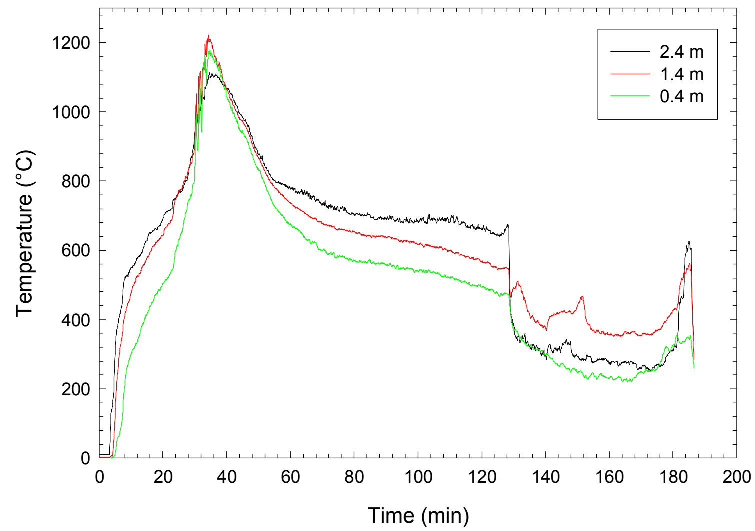


Figure 15. Temperatures entryway thermocouple tree.

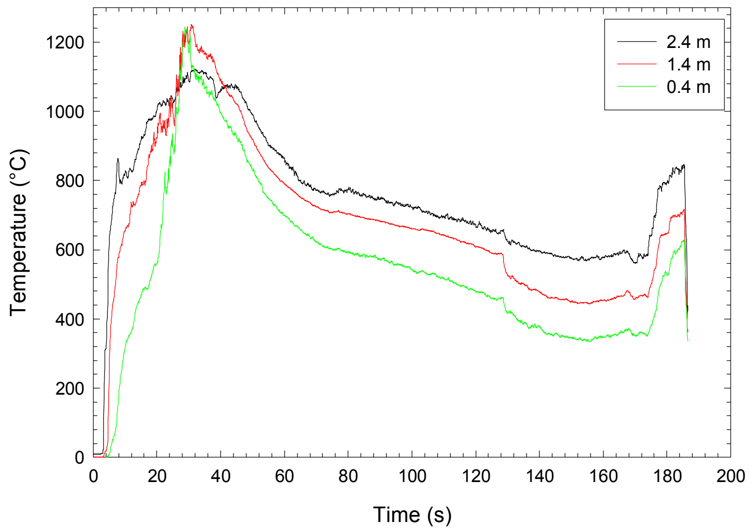


Figure 16. Temperatures center living room thermocouple tree.

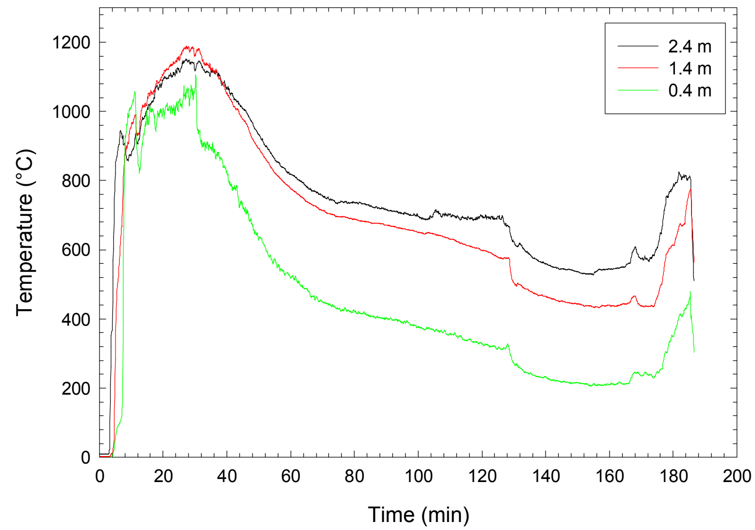


Figure 17. Temperatures north living room thermocouple tree.

11.2 Temperatures in Wall Assemblies

Thermocouples were located in all the CLT wall assemblies on the middle storey. The approximate location of thermocouples in each wall assembly is shown in the sketch in Figure 8. At each location, the thermocouples were located at three heights: 0.6, 1.2 and 1.8 m, except in the case of the partition between the bedroom and bathroom, where the thermocouples were located only at the 1.8 m height. The thermocouples in the wall assemblies with the gypsum board attached to 41 mm x 41 mm strapping (Wall Type A) were located on the unexposed side of the glass fibre insulation in the cavities formed by the wood strapping.

11.2.1 West Bedroom Wall

The temperatures were measured by the nine thermocouples located in the west bedroom wall (Figure 8).Two layers of gypsum board were attached to 41 mm x 41 mm strapping (Wall Type A) attached to the interior (fire) side of the CLT panels. The thermocouples were at the 0.6, 1.2 and 1.8 m heights and were located at three locations along the length of the room at the ¼ and mid-widths of the wall.

The temperatures measured in the cavity formed by strapping are shown in Figure 18, Figure 19 and Figure 20. The temperatures measured in the cavity formed by strapping followed the typical pattern for heat transfer through two layers of gypsum board:

1. There was an initial temperature rise to approximately 90°C. The time required to reach this temperature was 17 - 21 min depending on the height and location in the room. The fastest temperature increases were at the 1.8 m height and the slowest at the 0.6 m height.
2. There was a second phase during which the temperatures remained < 100°C during the calcination of the gypsum board. This phase lasted until 38 – 47 min depending on the height and location in the room.
3. Once the gypsum board was calcined, there was a more rapid temperature increase within the cavity. The times at which the temperature reached 300°C are listed in Table 1.There was considerable variation in the times with the earliest time (62 min) at the 1.2 m height at the mid-length of the wall. The longest time was 107 min at the 1.8 m height at the North end of the wall. Since 300°C is the temperature at which wood and wood-based materials begin to char [14], the temperatures measured in the cavities indicate that there was limited or no charring of the CLT in the panel areas until after 60 min at the mid-length of the wall and until after 80 min in other areas.
4. The encapsulation time for the two layers of gypsum board attached to the 41 mm x 41 mm strapping was 57 min based on a single point temperature increase of 270°C. The single point criterion was first exceeded at the 1.2 m height at the mid-length of the wall assembly. Based on the average temperature increase for the nine thermocouples, the 250°C average temperature increase criterion was exceeded at 68 min. (The three criteria for determining the effectiveness of an encapsulation material or system in protecting the combustible structural elements were assessed using intermediate scale furnace tests [15]. The criteria, which uses an average temperature increase of 250°C and a single point temperature increase of 270°C, is used in Europe for the classification of encapsulation materials and is based on the temperature at which wood begins to char (300°C). The encapsulation time is earlier than the time to reach 300°C noted in Table 1, since the temperature in the wall cavity at the start of the test was < 4.5°C. As

a result the single point temperature increase criteria were exceeded at temperatures of 274.5°C or less.)

5. The temperatures remained < 450°C until 135 – 145 min, at which time there was a rapid increase in temperatures to > 600°C at the mid-length and North end of the wall indicating there was burning within the cavity space. Similar temperatures were not measured at the South end of the wall until the end of the test.

11.2.2 Bedroom/Bathroom Partition with Regular Gypsum Board

Three thermocouples were located in the stud cavities of the partition (Wall Type C) that separated the bedroom and the bathroom/entryway (Figure 8). A single layer of regular gypsum board was directly attached to both sides of the wood stud framing. The thermocouples were at the 1.8 m height and were located at the ¼ and mid-widths of the bedroom.

The temperatures measured by the thermocouples in the partition are shown in Figure 21. The temperatures measured in the cavity follow the typical pattern for heat transfer through gypsum board:

1. There was an initial temperature rise to > 80°C within 5 min.
2. There was a second phase during which the temperatures remained < 100°C during the calcination of the gypsum board. This phase lasted until 13 – 15 min depending on the location in the room. The earliest temperature increase was at the east end of the partition wall.
3. Once the gypsum board was calcined, there was a rapid temperature increase within the cavity. The times at which the temperature reached 300°C are listed in Table 1. The temperatures were > 1000°C within 14 min and 18 min at the East and West end of the partition wall, respectively indicating the fire had penetrated into the stud cavity.
4. The encapsulation time for the single layer of regular gypsum board was 13 min The encapsulation time for the two layers of gypsum board attached to the wood framing was 57 min and 65 min in the living room and bedroom, respectively, based on the single point temperature increase criterion (270°C). Based on the average temperature increase for the six thermocouples in the bedroom and living room exterior walls, the 250°C average temperature increase criterion was not exceeded..
5. The temperatures were also measured at the intersection between the header (top plate) of the partition and the CLT floor assembly and at the mid-width of the header/CLT interface at the West end of the partition. There was a rapid increase in temperature starting at 16 min and within 1 min, the temperatures at these locations exceeded 1000°C.
6. There was a temperature drop in the stud cavity starting at approximately 23 min. This may indicate the fall-off of the gypsum board on the corridor/bathroom side of the partition.

11.2.3 Interior Bedroom/Living room Wall

Twelve thermocouples were located in the loadbearing interior wall that separated the bedroom and living room/kitchen area (Figure 8). Two layers of gypsum board were directly attached to both sides of the CLT panels (Wall Type D). The thermocouples were at the 0.6, 1.2 and 1.8 m heights and were located at the quarter-points along the length of the wall. Six thermocouples were located between the base layer of gypsum board and the CLT panels on both the bedroom and living room/kitchen side of the wall. The thermocouples were located at quarter-points along the length of the bedroom wall.

The temperatures measured on the bedroom side of the wall are shown Figure 22, and Figure 23. Figure 24 and Figure 25 show the temperatures measured on the living room side of the wall.

Overall, the temperature profiles were similar on the bedroom and living room side of the wall except for differences in the time required to reach various temperatures. The temperature profiles were also similar to those measured in the loadbearing exterior (north) wall with the two openings.

1. There was an initial temperature rise to approximately 90°C. The time required to reach this temperature on the bedroom side of the wall was 6 – 11 min and 16 – 21 min on the living room side. The fastest temperature increases was at the 1.2 m height on the north end of the wall in the bedroom. The slowest increase was at the 0.6 m height at the south end of the wall in the living room.
2. There was a second phase during which the temperatures remained < 100°C during the calcination of the gypsum board. This phase lasted until 18 – 34 min on the bedroom side of the wall and until 25 – 36 min on the living room side.
3. Once the gypsum board was calcined, there was a more rapid temperature increase at the interface. The times at which the temperature reached 300°C are listed in Table 1 and Table 2. The time at which the temperature reached 300°C depended on the location of the wall section. The earliest time was at the 1.8 m height at the south end on the bedroom side of the wall (37 min). The longest time was at the 0.6 m height at the South end on the living room side of the wall (54min). Overall, the times to reach 300°C were comparable to those for the exterior (north) wall.
4. The encapsulation time for the two layers of gypsum board directly attached to the CLT was 36 min on the bedroom side of the wall, based on a single point temperature increase of 270°C. The single point criterion was first exceeded at the 1.8 m height at the south end of the wall assembly. Based on the average temperature increase for the six thermocouples located on the bedroom side of the wall, the 250°C average temperature increase criterion was exceeded at 39 min. The encapsulation time for the two layers of gypsum board on the living room side of the wall was 43 min, based on a single point temperature increase of 270°C. The single point criterion was first exceeded at the 1.8 m height at the North end of the wall assembly. Based on the average temperature increase for the six thermocouples located on the living room side of the wall, the 250°C average temperature increase criterion was exceeded at 47 min. (The three criteria for determining the effectiveness of an encapsulation material or system in protecting the combustible structural elements were assessed using intermediate scale furnace tests. [15] The criteria, which uses an average temperature increase of 250°C and a single point temperature increase of 270°C, is used in Europe for the classification of encapsulation materials and is based on the temperature at which wood begins to char (300°). The encapsulation time is earlier than the time to reach 300°C noted in Table 1 and Table 2, since the temperature in the wall at the start of the test was < 17°C. As a result the single point temperature increase criteria were exceeded at temperatures of 287°C or less.)
5. There was a secondary temperature plateau with temperatures between 500 and 600°C. The time at which the temperature exceeded 500°C ranged from 49 min at the 1.8 m height at the south end on the bedroom side of the wall to 86 min at the 1.2 m height at

the south end on the living room side of the wall. This temperature plateau continued until the end of the test and is an indication that there were no flames at the thermocouple locations. The steady temperatures also indicated there was limited heat transfer through the gypsum board after 60 min.

11.2.4 North Exterior Wall

The north wall included the two openings and represented an exterior loadbearing CLT wall (Wall Type B). The two layers of gypsum board were directly attached to the interior side of the CLT panels. The temperatures were measured by twelve thermocouples located between the base layer of gypsum board and the CLT panels. The twelve different thermocouples were located at the 0.6, 1.2 and 1.8 m heights. The thermocouples were located at the center of the four wall sections on either side of the ventilation openings in the bedroom and living room (Figure 8). The temperatures measured in the bedroom section of the wall are shown Figure 26 and Figure 27. Figure 28 and Figure 29 show the temperatures measured in the living room section of the wall.

Overall, the temperature profiles were similar in the bedroom and living room sections of the north exterior wall except for differences in the time required to reach various temperatures. The temperature profiles were also similar to those measured in the loadbearing interior CLT wall between the bedroom and living room.

1. There was an initial temperature rise to approximately 90°C. The time required to reach this temperature in the bedroom section of the wall was 9 – 13 min and 11 – 17 min on the living room side. The fastest temperature increase was at the 1.2 m height in the wall section on the west side of the opening in the bedroom. The slowest increase was at the 0.6 m height in the east section of the wall in the living room.
2. There was a second phase during which the temperatures remained < 100°C during the calcination of the gypsum board. This phase lasted until 20 – 33 min in the bedroom section of the wall and until 21 – 32 min in the living room section.
3. Once the gypsum board was calcined, there was a more rapid temperature increase at the interface. The times at which the temperature reached 300°C are listed in Table 1 and Table 2. The time at which the temperature reached 300°C depended on the location of the wall section. The earliest time was at the 0.6 m height in the east section of the bedroom exterior wall (40 min). The longest time was at the 1.2 m height in the in the west wall section in the bedroom (56 min). Overall, the time to reach 300°C was comparable in the living room and bedroom section of the exterior wall. The times were also comparable to those for the loadbearing wall between the bedroom and the living room/kitchen.
4. The encapsulation time for the two layers of gypsum board directly attached to the CLT was 38 min in the bedroom section of the wall, based on a single point temperature increase of 270°C. The single point criterion was first exceeded at the 0.6 m height in the east section of the wall assembly. Based on the average temperature increase for the six thermocouples located in the bedroom section of the wall, the 250°C average temperature increase criterion was exceeded at 45 min. The encapsulation time for the two layers of gypsum board in the living room section of the wall was 40 min, based on a single point temperature increase of 270°C. The single point criterion was first exceeded at the 0.6 m height in the east section of the wall assembly. Based on the average temperature increase for the six thermocouples located on the living room side of the wall, the 250°C average temperature increase criterion was exceeded at 42 min. (The

three criteria for determining the effectiveness of an encapsulation material or system in protecting the combustible structural elements were assessed using intermediate scale furnace tests. [15] The criteria which uses an average temperature increase of 250°C and a single point temperature increase of 270°C is used in Europe for the classification of encapsulation materials and is based on the temperature at which wood begins to char (300°C). The encapsulation time is earlier than the time to reach 300°C noted in Table 1 and Table 2 since the temperature in the wall at the start of the test was < 14.2°C. As a result the single point temperature increase criteria were exceeded at temperatures of 284.2°C or less.)

5. There was a secondary temperature plateau with temperatures between 500 and 600°C. The time at which the temperature exceeded 500°C ranged from 58 min at the 0.6 m height in the east section of the living room wall to 131 min at the 1.2 m height in the west section of the bedroom wall. This temperature plateau continued until the end of the test and is an indication that there were no flames at the thermocouple locations. The steady temperatures also indicated there was limited heat transfer through the gypsum board after 60 min.

11.2.5 East Living Room/Kitchen Wall

The temperatures were measured by the nine thermocouples located in the east living room/kitchen wall (Figure 8). Two layers of gypsum board were attached to 41 mm x 41 mm strapping (Wall Type A) attached to the interior (fire) side of the CLT panels. The thermocouples were at the 0.6, 1.2 and 1.8 m heights and were located at three locations along the length of the room at the ¼ and mid-widths of the wall.

The temperatures measured in the cavity formed by strapping are shown in Figure 30, Figure 31 and Figure 32.The temperatures followed the same general trend as those measured in the west bedroom wall:

1. There was an initial temperature rise to approximately 90°C. The time required to reach this temperature varied depending on the height and location in the room. The fastest temperature increases were at the north end of the living room wall, with temperatures reaching 90°C between 20 and 23 min. This temperature was reached at the mid-length of the wall at 23 – 28 min and at the south end of the wall in the kitchen area at 34 – 43 min. The slowest time was for the thermocouple at the 0.6 m height in the kitchen area. This thermocouple was located behind the kitchen cabinets.
2. There was a second phase during which the temperatures remained < 100°C during the calcination of the gypsum board. This phase lasted until 35, 48 and 58 min at the north end, mid-length and south end of the wall assembly, respectively.
3. Once the gypsum board was calcined, there was a more rapid temperature increase within the cavity. The times at which the temperature reached 300°C are listed in Table 2. There was considerable variation in the times with the earliest time (39 min) at the 0.6 m height at the north end of the wall. The temperature at the 0.6 m height at the south end of the wall in the kitchen area did not reach this temperature. Since 300°C is the temperature at which wood and wood-based materials begin to char [14], the temperatures measured in the cavities indicate that there was limited or no charring of the CLT in the panel areas until after 39, 65 and 115 min at the north end, center and south end of the wall, respectively. (Note: After calcination, the temperature increase at the 0.6 m height at the north end of the wall was more rapid than at other locations. The temperature rise at this location was consistent with a thermocouple that was not

protected by the insulation in the cavity resulting in faster temperature increases a the thermocouple location.)

4. The encapsulation time for the two layers of gypsum board attached to the 41 mm x 41 mm strapping was 38 min based on a single point temperature increase of 270°C. The single point criterion was first exceeded at the 0.6 m height at the north end of the wall assembly (Note: as indicated in Item 3, the temperature increase at this location was more rapid than at other locations.) Based on the average temperature increase for the 9 thermocouples, the 250°C average temperature increase criterion was exceeded at 65 min.
5. After 90 min, there was an increase in temperatures measured in the cavity at the north end of the wall to > 600°C, indicating there was burning within the cavity space. A similar temperature increase occurred at the mid-length of the wall assembly starting at approximately 160 min. The temperatures in the cavity at the south end of the wall remained under 400°C until the end of the test.

11.2.6 South Corridor Wall

The temperatures were measured by the nine thermocouples located in the south corridor wall (Figure 8). Two layers of gypsum board were attached to 41 mm x 41 mm strapping (Wall Type A) attached to the interior (fire) side of the CLT panels. The thermocouples were at the 0.6, 1.2 and 1.8 m heights and were located at three locations along the length of the room at the ¼ and mid-widths of the wall.

The measured temperatures measured in the south corridor wall are shown in Figure 33, Figure 34 and Figure 35. Observations regarding the temperatures measured in the south corridor wall are as follows:

1. Unlike the east living room/kitchen wall and the west bedroom wall, there were two distinct steps in the initial temperature increase within the wall cavity of the south corridor wall. Initially, the temperature increased to approximately 50°C followed by a short temperature plateau. The temperature subsequently increased to approximately 90°C. The time required to reach this temperature varied depending on the height and location in the room and was slower than in the east living room/kitchen wall. The fastest temperature increases were at the center of the wall with temperatures reaching 90°C between 34 and 35 min. There was considerable variation in the initial temperature increase at the east end of the wall. The earliest time to reach 90°C was 34 min at the 1.2 m height. A longer time was required at the other two heights, as the thermocouples were located behind the kitchen cabinets. This temperature was reached at the west end of the wall at 40 – 42 min. The slower temperature increases within the wall cavities in the south corridor walls is consistent with the slower temperature increases within the apartment space in this area.
2. There was a second phase during which the temperatures remained < 100°C during the calcination of the gypsum board. This phase lasted until 48, 52 and 63 min at the center, 1.2 m height at the east end and west end of the wall assembly, respectively. The kitchen cabinets delayed the end of the steady temperature plateau at the 1.8 and 0.6 m heights in the kitchen area until 60 and 78 min, respectively.
3. Once the gypsum board was calcined, there was a more rapid temperature increase within the cavity. The times at which the temperature reached 300°C are listed in Table 2. There was considerable variation in the times with the earliest time (75 min) at the 1.2 m height at the east end of the wall. The temperature at the 0.6 and 1.8 m

heights at the west end of the wall in the bathroom area did not reach this temperature. Since 300°C is the temperature at which wood and wood-based materials begin to char [14], the temperatures measured in the cavities indicate that there was limited or no charring of the CLT panels until after 75, 79 and 119 min at the east end, center and west end of the wall, respectively.

4. The encapsulation time for the two layers of gypsum board attached to the 41 mm x 41 mm strapping was 66 min based on a single point temperature increase of 270°C. The single point criterion was first exceeded at the 1.8 m height at the center of the wall assembly. Based on the average temperature increase for the nine thermocouples, the 250°C average temperature increase criterion was exceeded at 87 min.
5. After 120 min, there was an increase in temperatures measured in the cavity at the center of the wall to > 600°C, indicating there was burning within the cavity space. The temperatures in the cavity at the east and west ends of the wall remained under 450°C until the end of the test.

11.2.7 Interface Temperature Profiles in West Bedroom Wall

There were ten thermocouples located at the mid-length of the west bedroom wall to measure the temperatures at each interface between the various materials used in the construction of the CLT wall assembly. These ten thermocouples were near the locations at which the temperatures were measured in the cavity space formed by the 41 mm x 41 mm strapping at the mid-length of the wall, with five thermocouples located at both the 1.2 and 1.8 m heights (Figure 8). The locations of the thermocouples, starting in the fire area (bedroom), were as follows.

1. Exposed surface of the face layer of gypsum board.
2. Interface between the face and base gypsum board layers on the exposed (fire) side of the CLT wall assembly.
3. Interface between the base layer gypsum board and the 41 mm x 41 mm wood strapping.
4. Interface between the 41 mm x 41 mm wood strapping and the CLT panel.
5. Interface between the CLT panel and the gypsum board on the unexposed (outer) side of the assembly.

The temperatures measured at the 1.2 and 1.8 m heights are shown in Figure 36 and Figure 37, respectively.

The temperatures at the exposed surface of the face layer of gypsum board reached an initial peak > 900°C in 2 min. The temperature subsequently decreased to approximately 550°C at 3 min. After the initial drop in temperature, the temperature increased to above 800°C at 6 min and remained higher than this temperature until 45 min. The maximum temperature was approximately 1060°C at 17 min.

The temperature at the interface between the two layers of gypsum board exceeded 100°C within 7 min, indicating that the face layer of gypsum board was calcined in the early stages of the fire exposure. The temperatures measured between the two layers exceeded 300°C within 16 min. These results indicate that wood materials would begin to char in the early stages of the fire exposure if protected with a single layer of 12.7 mm Type X gypsum board.

Based on the average temperature increase for the two thermocouples located at the interface between the base and face gypsum board layers, the average temperature increase at the interface between the two layers of gypsum board exceeded 250°C at 16 min and the temperature increase at the 1.8 m height exceeded 270°C at 16 min. This indicates that the face layer of gypsum board provided an encapsulation time of 16 min.

The temperatures at the interface between the face and base layers of gypsum board were lower than the temperature at the exposed surface of the face layer until approximately 48 min. This indicates that the face layer of gypsum board probably remained in place until this time.

The temperature at the interface between the base layer of gypsum board and the 41 mm x 41 mm wood strapping reached 100°C at approximately 20 min indicating the gypsum board was reaching the end of the calcination stage. The temperature at this location reached 300°C at approximately 35 min. After this, the wood strapping would begin to char.

Based on the average temperature increase for the two thermocouples located at the interface between the base gypsum board layer and the strapping, the he average temperature increase at the interface between the base layer of gypsum board and the 41 mm x 41 mm wood strapping exceeded 250°C at 33 min and the temperature increase at the 1.8 m height exceeded 270°C at 33 min. This indicates that the two layers of gypsum board provided an encapsulation time of 33 min for the wood strapping elements.

The temperature at the interface between the base layer of gypsum board and the wood strapping exceeded 500°C at 46 min and subsequently remained relatively steady until 145 min, at which time there was flaming combustion within the cavity formed by the 41 mm x 41 mm wood strapping.

The temperature profile at the interface between the gypsum board and the 41 mm x 41 mm wood strapping was similar to the temperature profiles for the walls with two layers of gypsum board attached directly to the CLT.

There was a slow temperature increase at the interface between the 41 mm x 41 mm wood strapping and the CLT. The temperature exceeded 300°C at 115 min at the 1.8 m height and at 132 min at the 1.2 m height. Subsequently, there was a rapid increase in temperature at approximately 145 min, indicating flaming combustion within the cavity area.

Based on the average temperature increase for the two thermocouples located at the interface between the strapping and the CLT panel, the average temperature increase at the interface between the 41 mm x 41 mm wood strapping and the CLT panel exceeded 250°C at 99 min and the temperature increase at the 1.8 m height exceeded 270°C at 100 min. This indicates that the two layers of gypsum board combined with the wood strapping provided an encapsulation time of 99 min for the CLT structural elements.

There was minimal heat transfer through the CLT 3-ply panel. The temperature increase at the CLT interface with the single layer of gypsum board on the unexposed (outer) side of the assembly was < 22°C.

11.2.8 Temperatures Measured on Unexposed Side of West Bedroom Wall

Nine thermocouples covered with pads used in standard fire resistance tests [9] were located on the unexposed (outer) face of the single layer of gypsum board on the unexposed (outer) side of the west bedroom wall. These thermocouples were at the same elevation and location as the thermocouples located in the cavity formed by the 41 mm x 41 mm wood strapping in the west bedroom wall (Figure 8).

The temperatures measured at the different locations are shown in Figure 38, Figure 39 and Figure 40. There was a very slow increase in the temperatures measured on the unexposed side of the wall assembly throughout the test. There was limited variation in the temperature with height. The temperatures varied with the location on the wall with the highest temperatures measured at the center of the wall. The average and single point temperature increase at the end of the test was 17.3°C and 21.0°C, respectively. These temperature increases are well below the requirements in CAN/ULC-S101 [9] (140°C average and 180°C single point temperature increase).

11.2.9 Temperatures Measured on Bedroom and Corridor Entryway Doors

Two thermocouples were located on both the bedroom and corridor entryway doors approximately 50 mm below the top of the door. The thermocouples on the bedroom door were located on the living room side, while the thermocouples on the entryway door were located on the corridor side of the door. The temperatures measured on the bedroom and corridor entryway doors are shown in Figure 41 and Figure 42, respectively.

After 2 min, there was a rapid increase in temperature on the living room side of the door between the bedroom and the living room. At 4 min, the temperature exceeded 600ºC indicating the living room side of the door was burning. After the initial peak temperature, the temperature decreased to < 600ºC as the door burned out and the thermocouples started to measure the temperature in the doorway. The minimum temperature was at 9 min. Subsequently, the thermocouples likely measured the air temperature. However, the exact location of the thermocouples is not known.

The temperature measured on the unexposed side of the entryway door started to increase at 4 min as the temperature increased in the entryway. The temperature continued to increase to a peak temperature of 740ºC at 39 min. Subsequently, the temperature decreased until 127 min at which time there was an increase in temperature after the door fell into the apartment. There was subsequent variation in temperatures. However, after the failure of the door, the exact location of the thermocouples is not known.

The temperatures measured on the unexposed side of the corridor entryway door had the same general profile as the temperatures measured at the thermocouple tree in the entryway (Figure 15). However, the peak temperature on the door was approximately 460ºC lower than the peak temperature measured in the entryway. This indicates there was substantial temperature loss from the door.

11.2.10 Temperatures in Joint between CLT Panels in West Bedroom Wall

Thermocouples were located in the joint between CLT panels 21_15 and 21_16 in the west bedroom wall (see Figures A-5 and A-7). The two panels were at the north end and the center of the wall, respectively. The joint was approximately 2.1 m from the northwest corner of the structure.

Thermocouples were located in the section of the joint at mid-depth of the 105 mm thick CLT panel that was parallel with the wall. The thermocouples were 0.6, 1.2 and 1.8 m above the floor. The temperatures measured in the CLT joint are shown in Figure 43.

The temperature in the joint remained at ambient until approximately 16 min. After 16 min, there was a rapid increase in temperature to initial peak temperatures of approximately 90°C. The time at which the peak temperatures occurred varied depending on the height but was between 20 and 25 min. This initial temperature increase corresponded to the initial temperature increase in the cavity formed by the 41 mm x 41 mm strapping (see 'Strpng/CLT' curve in Figure 37).

After the initial peak, the temperature decreased reaching minimum temperatures between 65 and 75 min depending on the height of the thermocouples. The temperatures subsequently increased but never exceed 100ºC. The temperatures in the joint were likely due to air leakage through the joint.

11.2.11 Summary of Temperatures in Wall Assemblies

The times at which the temperatures in the wall assemblies reached 300°C are summarized in Table 1 and Table 2 for the bedroom and the living room/kitchen walls, respectively.

The temperatures exceeded 300ºC at the interface between the base layer of gypsum board and the CLT on the bedroom side of the interior loadbearing wall between 37 and 44 min depending on the thermocouple location. For the north exterior bedroom wall, the 300ºC temperature was exceeded between 40 and 56 min. For the west bedroom wall with the two layers of 12.7 mm Type X gypsum board attached to 41 mm x 41 mm wood strapping, the temperatures exceeded 300ºC on the unexposed side of the insulation in the cavities formed by the wood strapping between 62 and 107 min depending on the thermocouple location.

The temperature reached 300ºC at the interface between the base layer of gypsum board and the CLT between 44 and 54 min and between 40 and 50 min on the living room side of the interior loadbearing wall and in the north exterior wall, respectively.

There were large variations in the time for the temperatures to exceed 300ºC on the east living room kitchen wall (39 -139 min). This wall assembly had 2 layers of 12.7 mm Type X gypsum board attached to 41 mm x 41 mm wood strapping and the thermocouples located on the unexposed side of the insulation in the cavity formed by the strapping. However, the times at the north end of the living room were comparable to those measured in the wall assemblies with the gypsum board directly attached to the CLT indicating that there were likely openings in the insulation at the thermocouple location resulting in earlier than expected temperature increases at these locations.

For the south corridor wall with gypsum board attached to 41 mm x 41 mm wood strapping, the earliest time for the temperature to exceed 300ºC was 75 min and for two thermocouples in the bathroom area, the temperature did not reach 300ºC by the end of the test.

The encapsulation times for the wall assemblies are summarized in Table 3. Some general observations based on the results are:

1. A single layer of gypsum board (12.7 mm thick regular and Type X) provides limited encapsulation time 13 min).
2. The two layers of 12.7 mm thick Type X gypsum board directly applied to the CLT (Wall Type B and Wall Type D) provided an encapsulation time of 36 – 43 min, depending on the wall assembly. The shortest time observed in this test was for the location where the two layers of gypsum board were directly attached on the bedroom side of the interior loadbearing CLT wall, which was between the bedroom and living room/kitchen.
3. The lowest encapsulation time for the two layers of 12.7 mm thick Type X gypsum board attached to the 41 mm x 41 mm wood strapping, based on both single point and average temperature increase measurements at the interface between the wood strapping and the gypsum board, was 33 min in the west bedroom wall. This encapsulation time is comparable to the 36 min encapsulation time determined for the two layers of 12.7 mm thick Type X gypsum board on the bedroom side of the interior loadbearing wall.
4. The encapsulation time for the two layers of Type X gypsum board attached to the 41 mm x 41 mm wood strapping plus the insulation in the strapping cavities varied considerably depending on the wall assembly. The encapsulation time was particularly short (38 min) for the east living room/kitchen wall. This encapsulation time was comparable to the times determined for the assemblies measured at the interface between the base layer of gypsum board and the CLT or the wood strapping. These results indicate that at some locations there was minimal delay in heat transfer to the thermocouple located on the unexposed side of the insulation. In other assemblies such as the west bedroom wall, the insulation delayed the heat transfer to the thermocouple location resulting in increased encapsulation times (57 min) The effectiveness of insulation in cavity spaces for increasing encapsulation times should be further investigated.
5. The encapsulation time at the interface between the 41 mm x 41 mm wood strapping and the CLT in the west bedroom wall was 99 - 100 min.

For the walls with the two layers of gypsum board directly attached to the CLT panels, the temperatures measured between the gypsum board and the CLT eventually reached a plateau with the temperature remaining < 600°C. This indicates that flaming combustion did not occur in the areas of the CLT protected by the gypsum board.

It was noted after the test that the loadbearing interior wall between the bedroom and the living room was no longer in place, indicating that the CLT panels had completely charred/pyrolyzed during the test.

Tests with encapsulation materials conducted with a cone calorimeter indicated that once the interface temperature between the encapsulation material and the wood substrate exceeded the ignition temperature for the wood, flaming combustion would occur on the exposed surface of the encapsulation material [16]. This phenomenon may also have occurred in the full-scale apartment test. However, it is not possible to ascertain, based on the results of this test, the extent and effect of this process. The results from other projects need to be reviewed to determine if this process needs to be further investigated and the potential impacts quantified.

For the walls with the two layers of gypsum board attached to 41 mm x 41 mm wood strapping, the time at which the strapping material began to be affected by the heat conducted through the gypsum board was comparable to the time required for the CLT panels to be affected in the walls with the gypsum board directly attached to the CLT. However, the temperatures in the cavity space were reduced and, consequently, there would be less effect of the fire on the CLT panels in those (Type A) walls.

There was flaming combustion within the wall cavities for the wall assemblies with the gypsum board attached to the wood strapping. However, this occurred late in the test (> 130 min). The performance of encapsulation systems attached to strapping needs further investigation.

Table 1. Time to reach 300°C in the bedroom wall assemblies.

Wall Assembly	Location	TC Height (m)	Time (min)
Interior loadbearing wall between bedroom and living room with two layers of 12.7 mm Type X gypsum board directly attached to the CLT panels.	South	1.8 1.2 0.6	37 38 45
	North	1.8 1.2 0.6	44 39 39
Exterior (north) wall with two layers of 12.7 mm Type X gypsum board directly attached to the CLT panels.	East	1.8 1.2 0.6	46 44 40
	West	1.8 1.2 0.6	49 56 52
West wall with two layers of 12.7 mm Type X gypsum board attached to 41 mm x 41 mm wood strapping on the CLT panels.	South	1.8 1.2 0.6	87 84 83
	Center	1.8 1.2 0.6	91 62 68
	North	1.8 1.2 0.6	107 100 84
Partition between bedroom and bathroom with a single layer of regular gypsum board.	East Center West	1.8 1.8 1.8	13 15 16

Table 2. Time to reach 300°C in the living room/kitchen wall assemblies.

Wall Assembly	Location	TC Height (m)	Time (min)
Interior loadbearing wall between bedroom and living room with two layers of 12.7 mm Type X gypsum board directly attached to the CLT panels.	South	1.8 1.2 0.6	51 52 54
	North	1.8 1.2 0.6	46 45 44
Exterior (north) wall with two layers of 12.7 mm Type X gypsum board directly attached to the CLT panels.	East	1.8 1.2 0.6	46 48 40
	West	1.8 1.2 0.6	50 44 43
East wall with two layers of 12.7 mm Type X gypsum board attached to 41 mm x 41 mm wood strapping on the CLT panels.	South	1.8 1.2 0.6	115 139 DNR
	Center	1.8 1.2 0.6	102 86 65
	North	1.8 1.2 0.6	52 47 39
Corridor (south) wall with two layers of 12.7 mm Type X gypsum board attached to 41 mm x 41 mm wood strapping on. the CLT panels	East	1.8 1.2 0.6	99 75 140
	Center	1.8 1.2 0.6	79 83 86
	West	1.8 1.2 0.6	DNR 120 DNR

DNR – Did not reach 300ºC.

Table 3. Encapsulation times based on measurements in wall assemblies.

Wall Assembly	Encapsulation	Number and location thermocouples	Average ΔT 250°C	Single Point ΔT 270°C
West Bedroom	2 layers 12.7 mm thick Type X GB + strapping cavity insulation	9 thermocouples strapping cavity	68	57
	1 layer 12.7 mm thick Type X GB	2 thermocouples GB_f/GB_b interface	16	16
	2 layers 12.7 mm thick Type X GB	2 thermocouples GB_b/strapping interface	33	34
	2 layers 12.7 mm thick Type X GB + 41 mm x 41 mm strapping	2 thermocouples strapping CLT interface	99	100
Interior Loadbearing Wall Bedroom	2 layers 12.7 mm thick Type X GB	6 thermocouples GB_b/CLT	39	36
Interior Loadbearing Wall Living Room	2 layers 12.7 mm thick Type X GB	6 thermocouples GB_b/CLT	47	43
North Exterior Wall Bedroom	2 layers 12.7 mm thick Type X GB	6 thermocouples GB_b/CLT	44	38
North Exterior Wall Living room	2 layers 12.7 mm thick Type X GB n	6 thermocouples GB_b/CLT	42	40
East Living room/Kitchen	2 layers 12.7 mm thick Type X GB + strapping cavity insulation	9 thermocouples strapping cavity	65	38*
South Corridor	2 layers 12.7 mm thick Type X GB + strapping cavity insulation	9 thermocouples strapping cavity	87	66
Partition Bedroom/Bathroom	1 layer regular GB + stud cavity insulation	3 thermocouples wall cavity	14	13

*Time comparable to the encapsulation times for loadbearing interior wall between bedroom and living room/kitchen, indicating limited reduction in heat transfer by cavity insulation.
GB – Gypsum Board DNR – Did not reach temperature criteria
GB_f – Gypsum board face layer. GB_b – Gypsum board base layer.

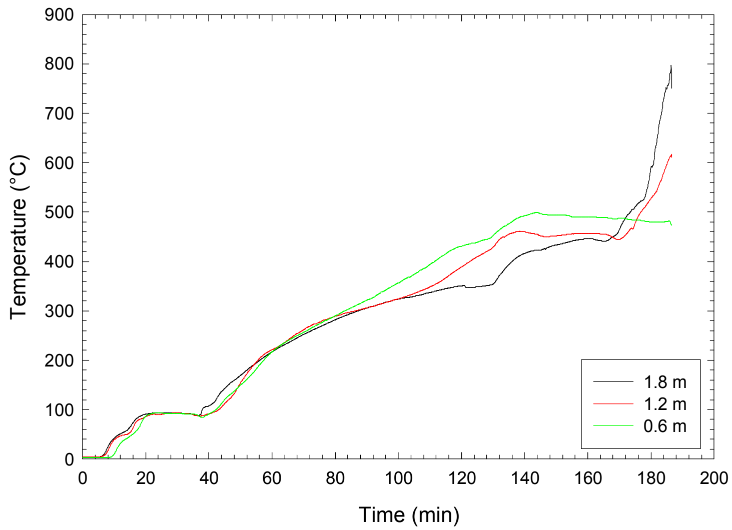


Figure 18. Temperatures west bedroom wall cavity (south).

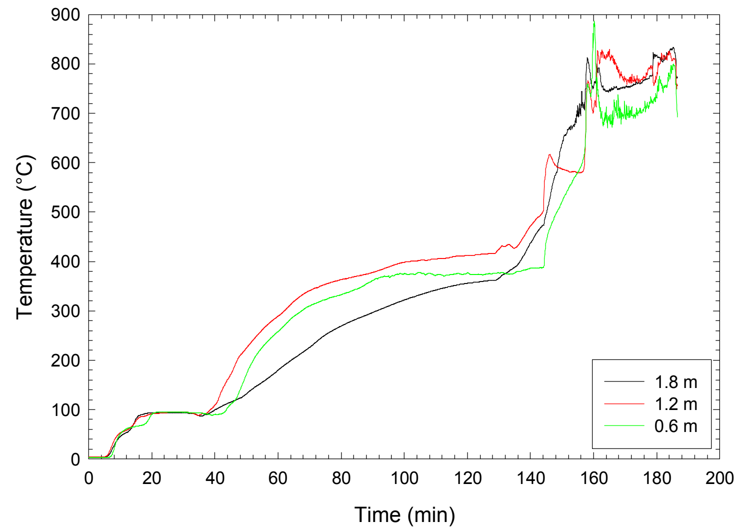


Figure 19. Temperatures west bedroom wall cavity (center).

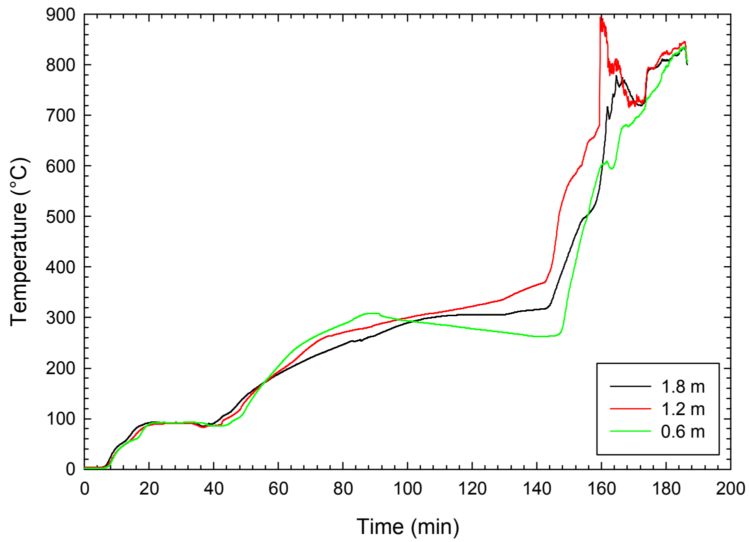


Figure 20. Temperatures west bedroom wall cavity (north).

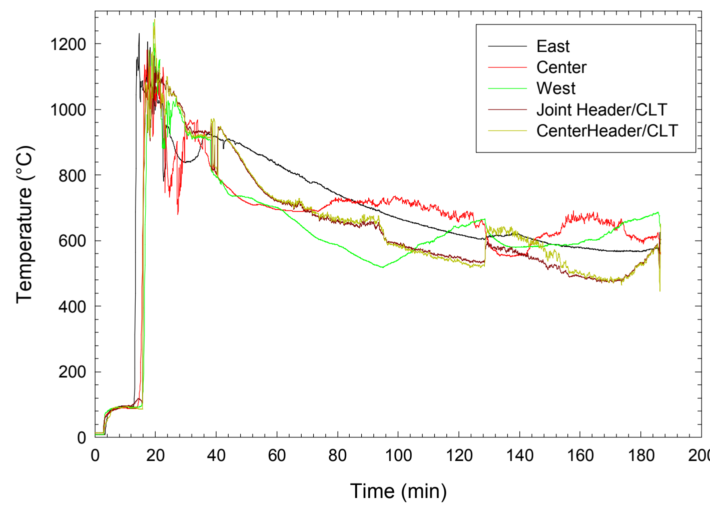


Figure 21. Temperatures in bedroom/bathroom partition cavity.

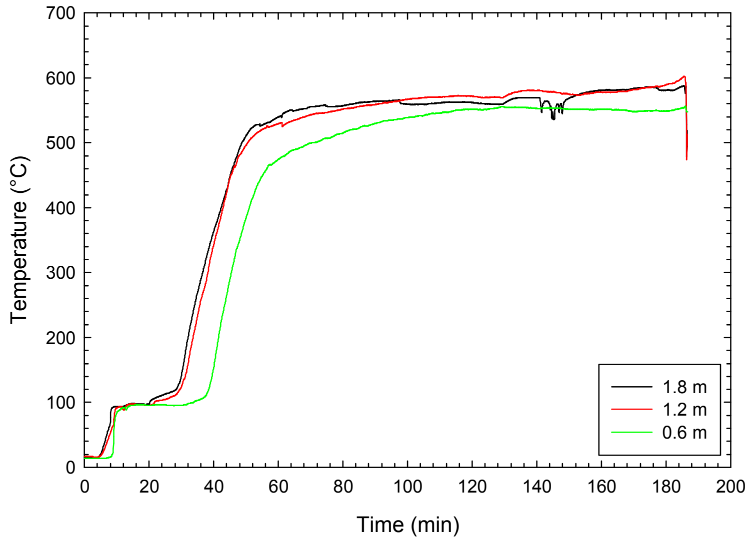


Figure 22. Temperatures interface CLT and gypsum board interior loadbearing wall (bedroom south).

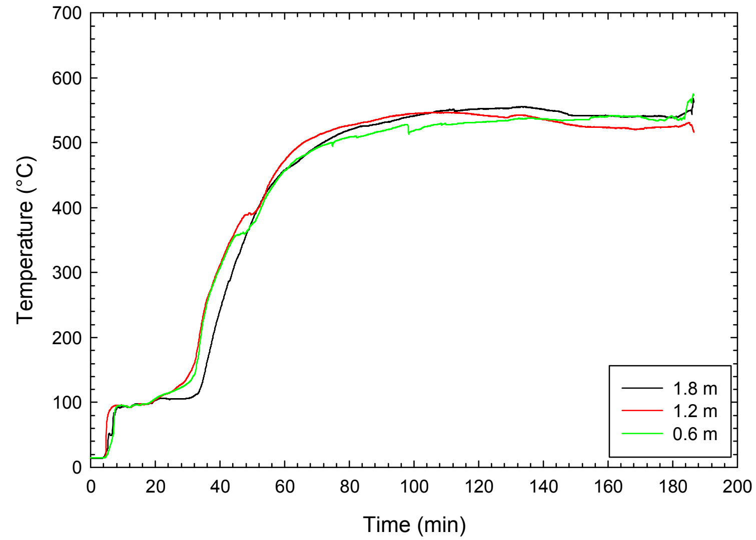


Figure 23. Temperatures interface CLT and gypsum board interior loadbearing wall (bedroom north).

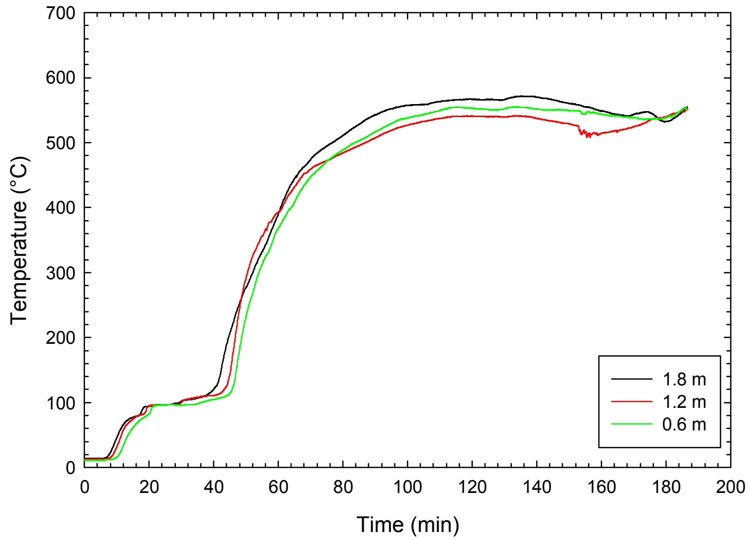


Figure 24. Temperatures interface CLT and gypsum board interior loadbearing wall (living room south).

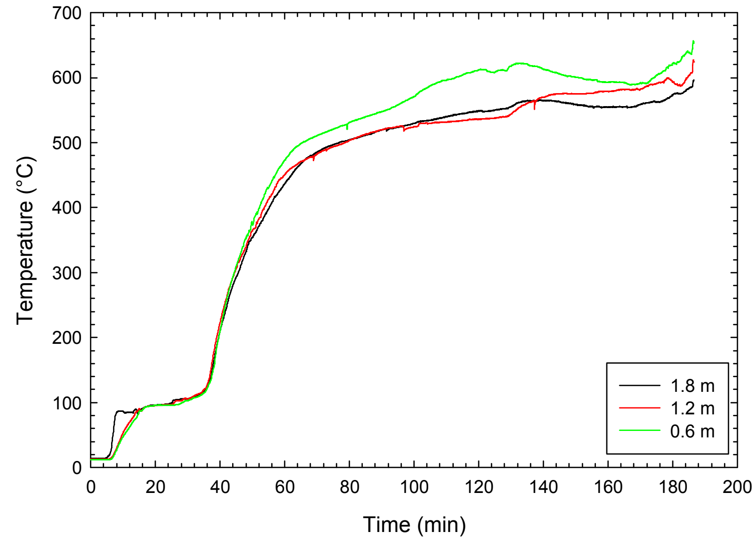


Figure 25. Temperatures interface CLT and gypsum board interior loadbearing wall (living room north).

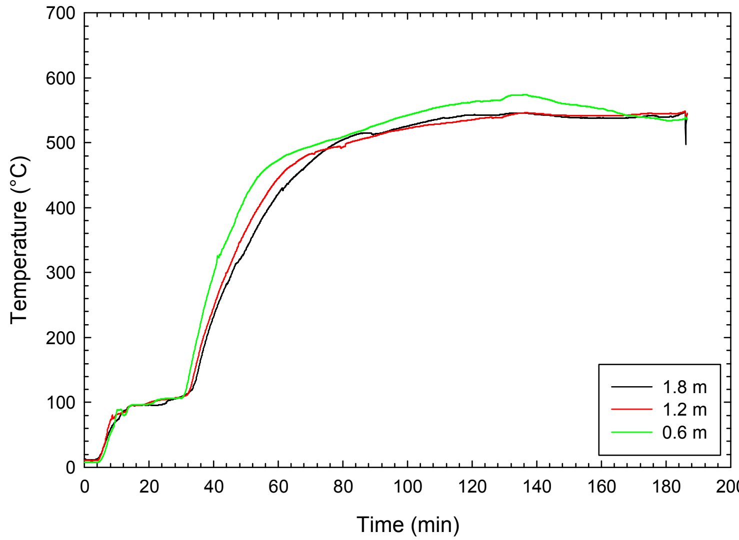


Figure 26. Temperatures interface CLT and gypsum board north exterior bedroom wall (east).

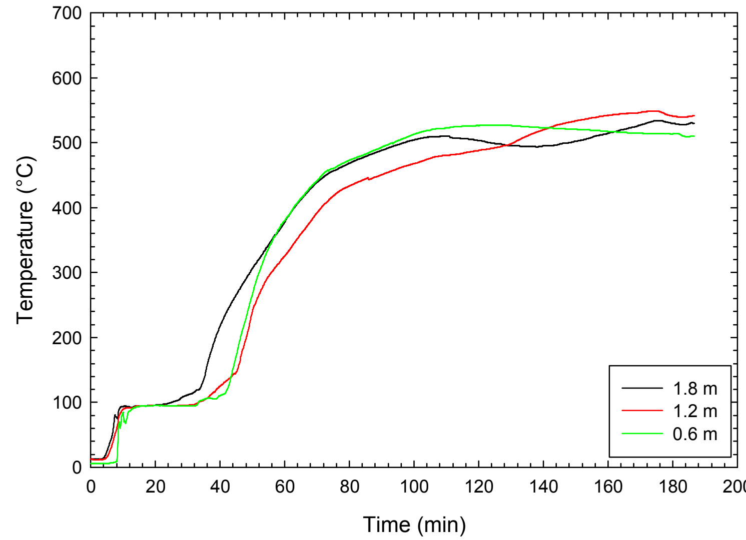


Figure 27 Temperatures interface CLT and gypsum board north exterior bedroom wall (west).

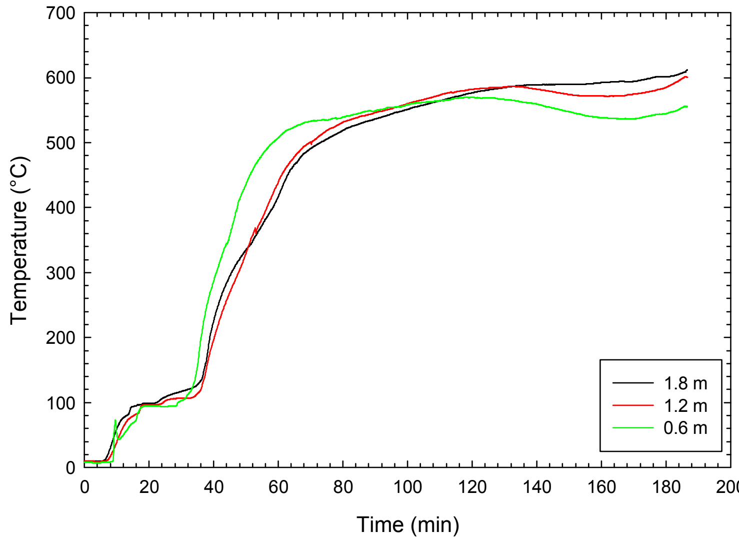


Figure 28. Temperatures interface CLT and gypsum board north exterior living room wall (east).

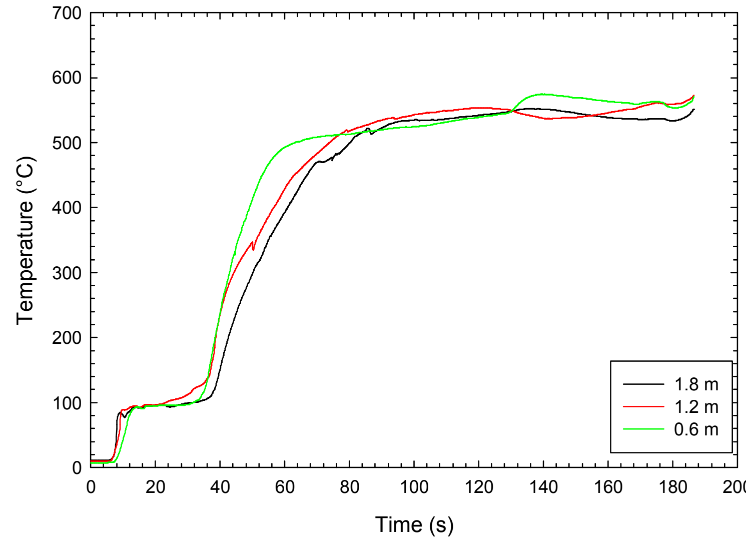


Figure 29. Temperatures interface CLT and gypsum board north exterior living room wall (west).

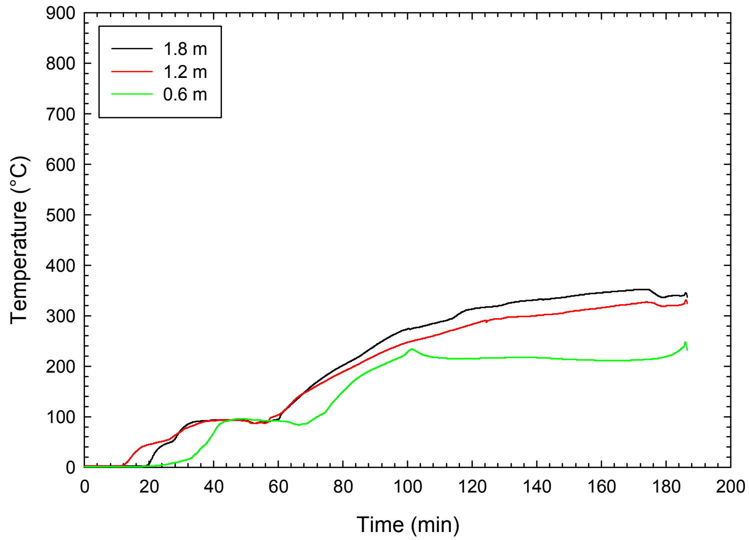


Figure 30. Temperatures east living room/kitchen wall cavity (south).

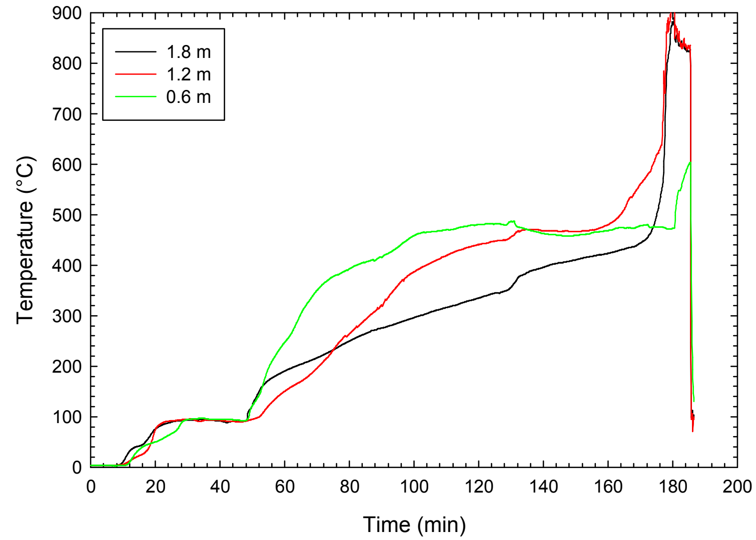


Figure 31. Temperatures east living room/kitchen wall cavity (center).

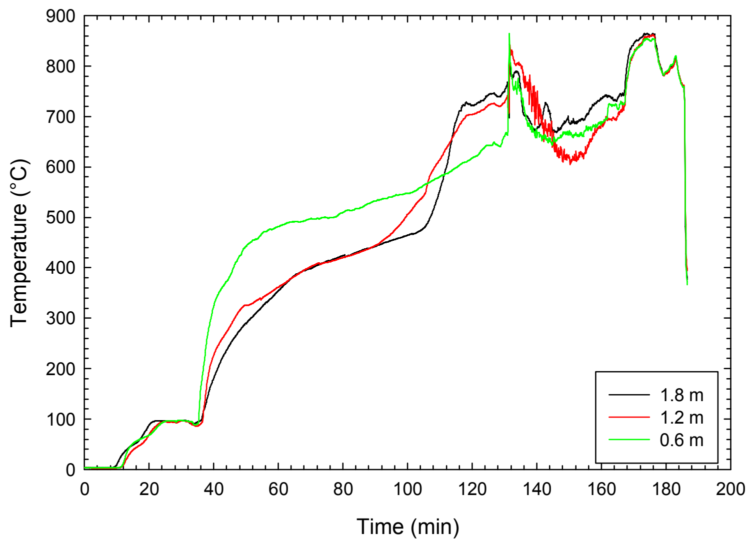


Figure 32. Temperatures east living room/kitchen wall cavity (north).

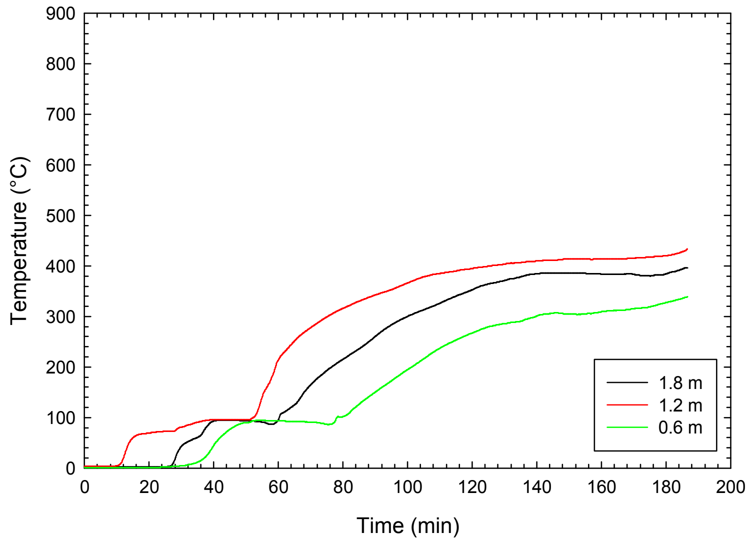


Figure 33. Temperatures south corridor wall cavity (east).

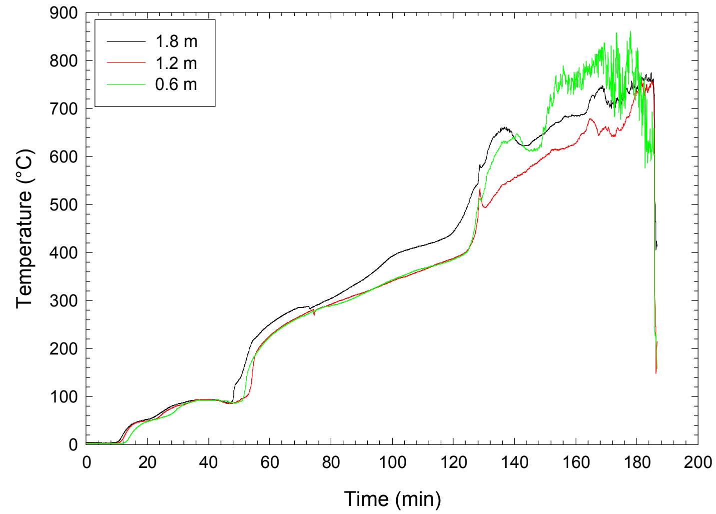


Figure 34. Temperatures south corridor wall cavity (center).

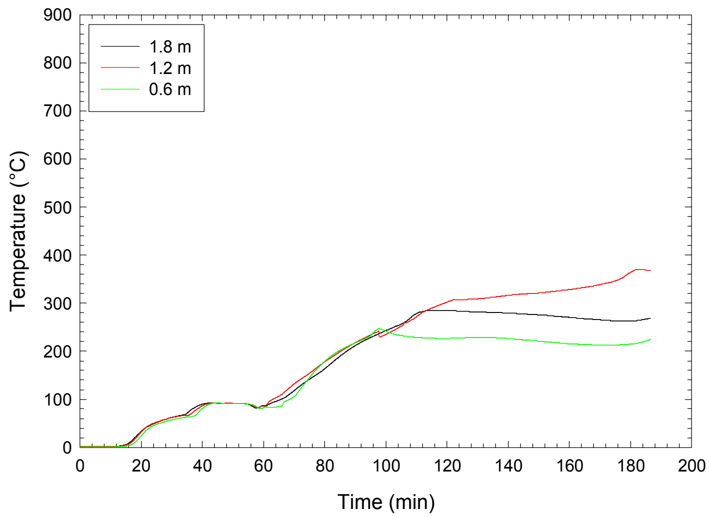


Figure 35. Temperatures south corridor wall cavity (west).

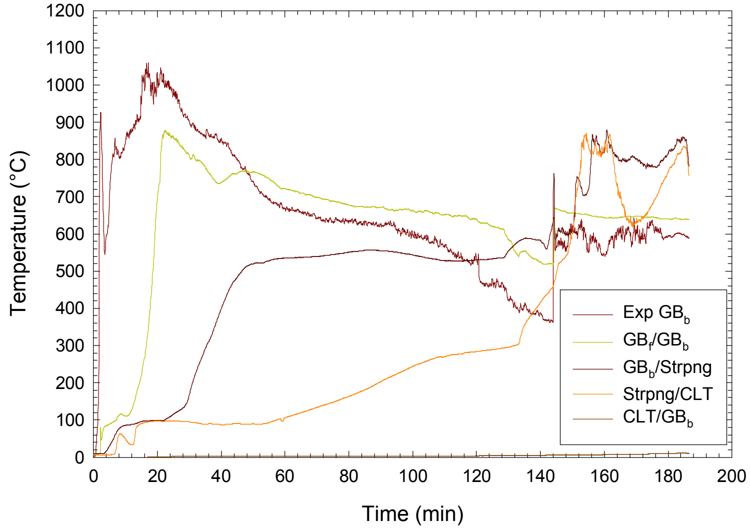


Figure 36. Temperature profiles at 1.2 m height in West bedroom wall.

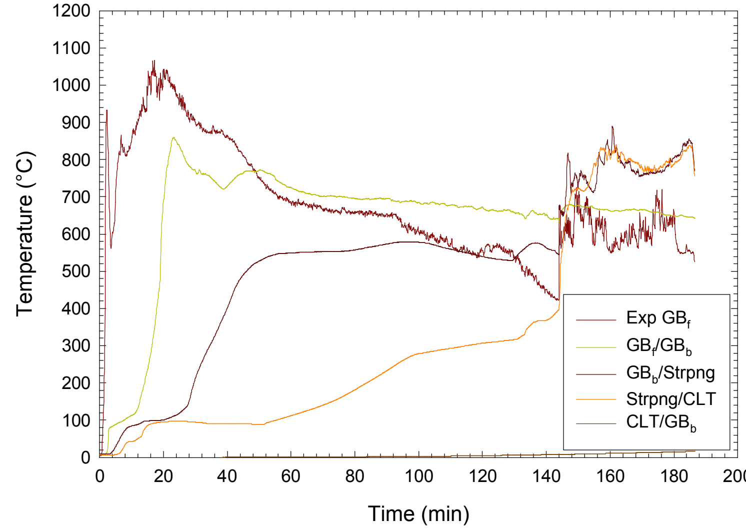


Figure 37. Temperature profiles at 1.8 m height in West bedroom wall.

Exp GB$_f$	Exposed surface of face layer of gypsum board.
GB$_f$/GB$_b$	Interface between gypsum board layers on exposed (fire) side of the wall assembly.
GB$_b$/Strpng	Interface between base layer of gypsum board and 41 mm x 41 mm wood strapping.
Strpng/CLT	Interface between 41 mm x 41 mm wood strapping and CLT panel.
CLT/GB$_b$	Interface between CLT and gypsum board on unexposed (outer) side of the wall assembly.

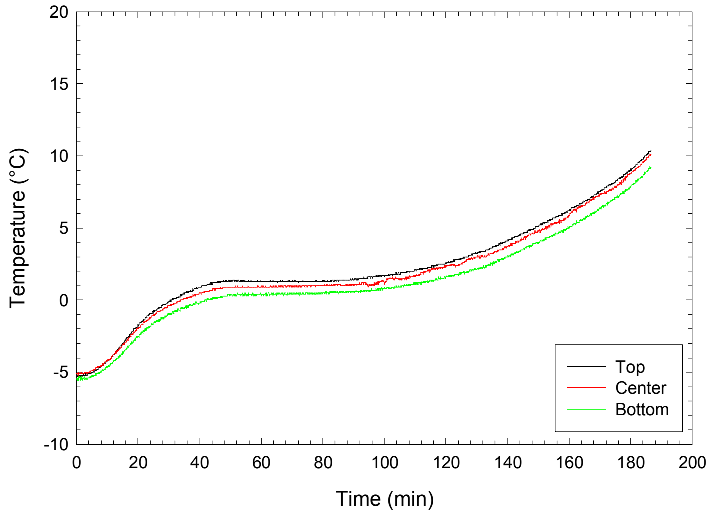


Figure 38. Temperatures unexposed side of West bedroom wall (South).

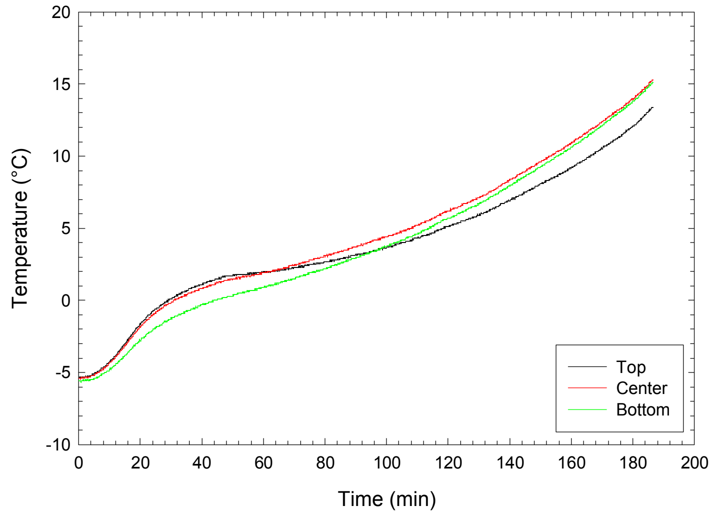


Figure 39. Temperatures unexposed side of West bedroom wall (Center).

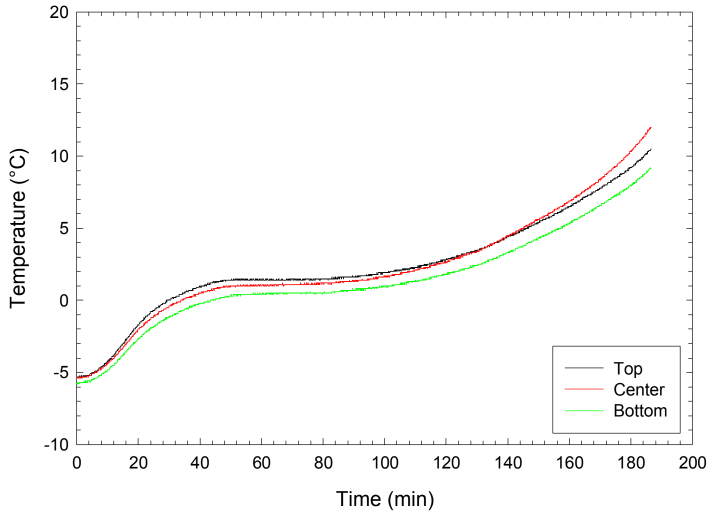


Figure 40. Temperatures unexposed side of West bedroom wall (North).

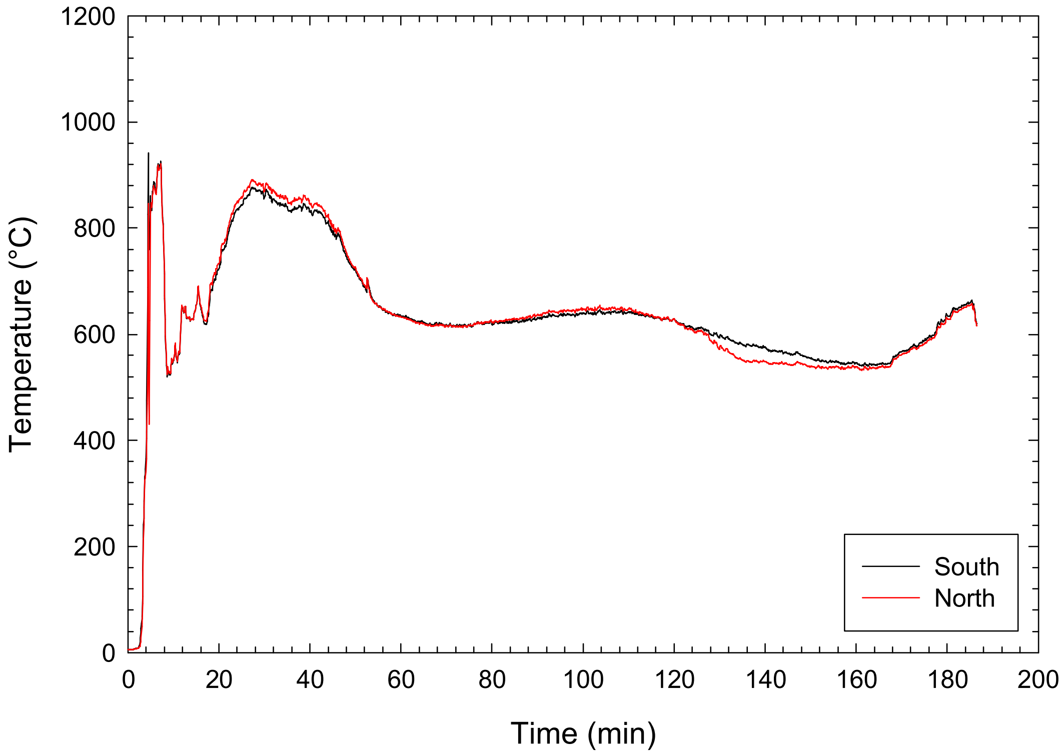


Figure 41. Temperatures on unexposed (living room) side of living room/bedroom door.

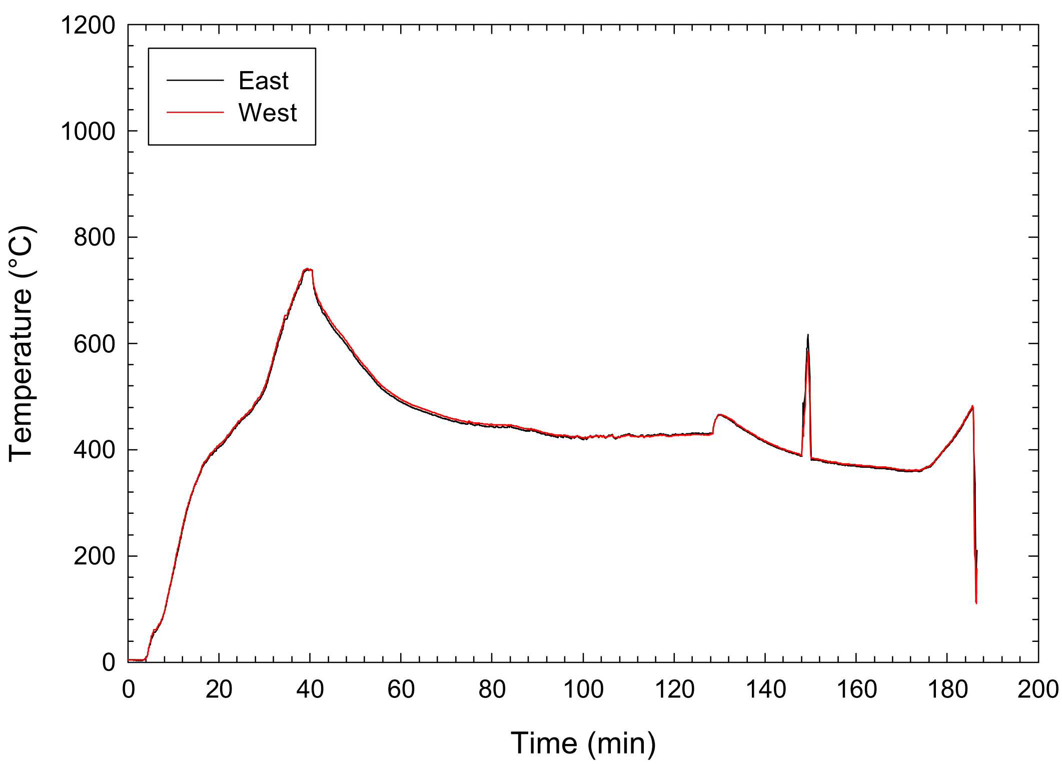


Figure 42. Temperatures on unexposed (corridor) side of corridor entryway door.

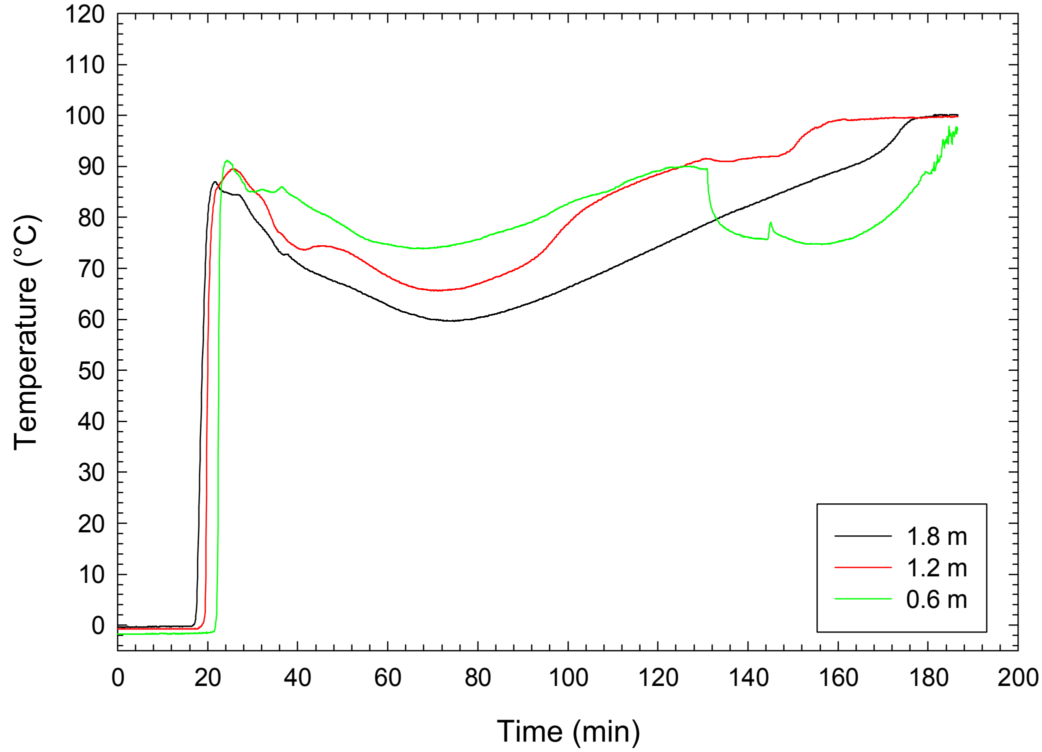


Figure 43. Temperatures in joint between CLT panels in West bedroom wall.

11.3 Temperatures in Ceiling Assembly

11.3.1 Ceiling Assembly in Bedroom

On the underside of the ceiling/floor assembly between the middle and highest storeys, two layers of gypsum board were directly attached to the CLT. Nine thermocouples were located between the base layer of gypsum board and the CLT ceiling panels in the bedroom. The thermocouples were located at the quarter- and mid-widths and lengths of the bedroom area, excluding the closet. The approximate location of the thermocouples in the ceiling/floor assemblies are shown in the sketch in Figure 9.

The measured temperatures are shown in Figure 44, Figure 45 and Figure 46. The initial temperature profiles were similar to those measured in the loadbearing partition wall between the bedroom and the living room.

1. There was an initial temperature rise to approximately 90°C. The time required to reach this temperature was 12 – 15 min with the fastest temperature increases at the centre and the North end of the bedroom. Slightly longer times were required in the South end of the bedroom with the slowest temperature increase in the Southeast corner.
2. There was a second phase during which the temperatures remained < 100°C during the calcination of the gypsum board. This phase lasted until 32 – 41 min. Once the gypsum board was calcinated, there was a more rapid temperature increase. The times at which the temperatures exceeded 300°C are shown in Table 4. There was considerable variation in the times with the earliest time (46 min) in the southeast section of the room and the longest time (111 min) at the center-west quarter-point of the room.
3. The encapsulation time for the two layers of gypsum board directly attached to the CLT ceiling/floor panel was 45 min based on a single point temperature increase of 270°C. The single point criterion was first exceeded at the southeast quarter point of the room. Based on the average temperature increase for the nine thermocouples, the 250°C average temperature increase criterion was exceeded at 69 min.
4. After calcinations of the gypsum board, there was a short period with high temperature increases. After approximately 60 min, there was a slower temperature increase. Unlike the temperature profiles in the loadbearing partition wall assembly, the temperatures continued to slowly increase until the end of the test. However, the temperatures remained lower than those measured in the wall assembly with the temperatures in the ceiling/floor assembly remaining < 500ºC until the end of the test. The results indicate that there was minimal or no flaming combustion on the ceiling/floor panels in the bedroom and that the base layer of gypsum board may have remained in place throughout the test. These results suggest that the heat losses to the thicker CLT panels used for the ceiling/floor assembly played a significant role in the performance of the gypsum board encapsulation.

11.3.2 Ceiling Assembly in Living Room/Kitchen Area

Nine thermocouples were located between the base layer of gypsum board and the CLT panels in the ceiling above the living room/kitchen. The thermocouples were located at the quarter- and mid-widths and lengths of the living room/kitchen area. The approximate location of the thermocouples in the ceiling/floor assemblies are shown in the sketch in Figure 9.

The measured temperatures are shown in Figure 47, Figure 48 and Figure 49. The initial temperature profiles were similar to those measured in the living room side of the loadbearing partition wall between the bedroom and the living room.

1. There was an initial temperature rise to approximately 90°C. The time required to reach this temperature was 15 – 21 min, with the fastest temperature increases at the North-West quarter point of the living room. Slightly longer times were required in the South end of the living room/kitchen area.
2. There was a second phase during which the temperatures remained < 100°C during the calcination of the gypsum board. This phase lasted until 36 – 51 min. Once the gypsum board was calcined, there was a more rapid temperature increase at the interface. The times at which the temperatures exceeded 300°C are shown in Table 5. There was less variation in the times than in the ceiling/floor assembly above the bedroom. The earliest time (49 min) was at the thermocouple location at the center of the living room at the north end. The longest time (77 min) was at the southwest quarter-point of the room over the kitchen area.
3. The encapsulation time for the two layers of gypsum board directly attached to the CLT ceiling/floor panel was 48 min, based on a single point temperature increase of 270°C. The single point criterion was first exceeded at the thermocouple location at the center of the North end of the living room. Based on the average temperature increase for the nine thermocouples, the 250°C average temperature increase criterion was exceeded at 55 min.
4. After calcination of the gypsum board, there was a short period with high temperature increases. After approximately 60 min, there was a slower temperature increase measured by the thermocouples on the east and west sides of the room until near the end of the test. For the thermocouples located on the centerline of the room, peak temperatures of approximately 600°C were measured, indicating flaming combustion on the CLT ceiling/floor panels. This includes near the end of the test when visible flames were observed on some CLT panels along the centerline of the room. It was also noted that at some locations the base layer of gypsum board remained in place until the end of the test. These results suggest that the heat losses to the thicker CLT panels used for the ceiling/floor assembly played a significant role in the performance of the gypsum board encapsulation.

11.3.3 Interface Temperature Profiles in Bedroom Ceiling Assembly

Five thermocouples were located at the center of the bedroom to measure the temperatures at each interface between the various materials used in the construction of the CLT ceiling/floor assembly separating the second and third storeys. The temperatures measured using these five thermocouples provide data on the temperature profiles within the ceiling/floor assembly and the time required for heat transfer through the assembly. The locations of the five thermocouples, starting in the fire area (bedroom), are as follows.

1. Exposed surface of the face layer of gypsum board.
2. Interface between the face and base gypsum board layers on the exposed (fire) side of the CLT ceiling/floor assembly.
3. Interface between the base layer of gypsum board and the CLT panel.
4. Interface between the CLT panel and base layer of cement board on the unexposed (upper) side of the ceiling/floor assembly.

5. Interface between the base and face layers of cement board on the unexposed (upper) side of the CLT ceiling/floor assembly.

The temperatures measured at each interface in the ceiling assembly are shown in Figure 50.

General comments regarding the temperatures measured at each interface between the various materials in the CLT ceiling/floor assembly are as follows:

1. There was a rapid increase in the temperature measured at the exposed surface of the face layer of gypsum board. A peak temperature of approximately 1200ºC was measured at 12 min. There was a secondary peak at 19 min indicating that the thermocouple may have fallen off and was likely measuring the air temperature in the room. The temperature subsequently decreased until approximately 22 min at which time the data indicates the thermocouple may have failed. The data for the remainder of the test is included in the plot. However, the location of the thermocouple is not known.
2. There was a rapid increase in temperature at the interface between the two layers of gypsum board on the exposed side of the assembly. The temperature exceeded 90°C at 5 min, 100°C at 8 min and 300°C at 16 min. The temperature increase at this location exceeded 270°C at 15 min, indicating a single layer of 12.7 mm Type X gypsum board would provide a limited encapsulation time with the fire exposure in the bedroom. Subsequently, there was a rapid increase to a temperature comparable to the temperature measured in the bedroom at 18 min and peak temperatures of approximately 1300°C at 23 min, indicating falloff of the face layer of gypsum board. Subsequently, the temperature slowly decreased until approximately 128 min when a sharp decrease in temperature occurred indicating fall off of the base layer of gypsum board at the thermocouple location.
3. The temperature exceeded 90°C at 5 min, 100°C at 22 min and 300°C at 28 min. The temperature increase at this location exceeded 270°C at 28 min. This encapsulation time is considerably shorter than at other locations in the ceiling floor assembly (45 min). Unlike the other temperature profiles at the interface between the gypsum board and the CLT, the temperatures at the center of the assembly increased to a peak of approximately 560°C at approximately 48 min and subsequently decreased slowly. After 128 min, the temperature was comparable to the temperatures measured in the bedroom indicating the base layer of gypsum board had fallen off at the thermocouple location. Near the end of the test, the temperatures increased to > 600°C indicating flaming combustion of the CLT.
4. The temperature at the interface between the CLT and the base layer of cement board had an initial peak at approximately 22 min. The temperature decreased until approximately 50 min and subsequently slowly increased for the remainder of the test. The temperature increase after more than 2 hours was < 9°C.
5. The temperature at the interface between the base and face layer of cement board on the unexposed side of the CLT ceiling/floor assembly slowly increased throughout the test. The temperature increase was < 7.5°C.

11.3.4 Temperatures in Joint between CLT Panels in Bedroom Ceiling Assembly

Thermocouples were located in the joint between CLT panels 11_02 and 11_03 in the bedroom ceiling/floor assembly (see Figure A-7) just above the bedroom. The two panels were at the center and North end of the assembly, respectively. The joint was approximately 1.8 m from the North end of the structure.

Thermocouples were located in the section of the joint that was parallel with the ceiling/floor at mid-depth of the 175 mm thick CLT panel. The thermocouples were at the quarter and mid-widths of the bedroom. The temperatures measured in the CLT joint are shown in Figure 51.

The temperature in the joint remained at ambient until approximately 16 min. There was a small temperature peak of several degrees at approximately 22 min at the mid-width of the bedroom. Otherwise, the temperature increased slowly throughout the tests with comparable temperatures measured at the 3 locations. The temperature increase over the entire test period was < 9°C.

11.3.5 Temperatures Measured on Unexposed Side of Ceiling Assembly above Bedroom

Nine thermocouples covered with pads used in standard fire resistance tests [9] were located on the exposed surface (top) of the face layer of cement board in the bedroom area on the highest storey. The thermocouples were located at the quarter- and mid-widths and lengths of the bedroom area, excluding the closet. In plan view, these thermocouples were at the same location as the thermocouples located at the interface between the base layer of gypsum board and the CLT panels above the bedroom area on the fire floor, as shown in Figure 9.

The temperatures measured at the different locations are shown in Figure 52, Figure 53 and Figure 54. There was very little increase in the temperatures measured on the unexposed side of the ceiling/floor assembly throughout the test. There was limited variation in the temperature with location. The average and single point temperature increase at the end of the test was 6.0°C and 7.3°C (center of the room), respectively. These temperature increases are well below the requirements in CAN/ULC S101 [9] (140°C average and 180°C single point temperature increase).

11.3.6 Summary of Temperatures in Ceiling Assembly

The encapsulation times for the ceiling assembly are summarized in Table 6. Some general observations based on the results are:

1. A single layer of gypsum board (12.7 mm thick Type X) provides limited encapsulation time (15 min). This time is based on a single measurement at the center of the bedroom ceiling. However, the time is comparable to the encapsulation times determined for a single layer of gypsum board on the wall assemblies.
2. The encapsulation time for the two layers of 12.7 mm gypsum board directly applied to the CLT panels varied, depending on the measurement used. The shortest time observed in this test was for the thermocouple located at the center of the bedroom ceiling (28 min). This time is shorter than the encapsulation time determined for the two layers of gypsum board directly attached to the CLT on the loadbearing partition wall (35 – 45 min). However, the encapsulation times determined using the 9 thermocouple arrays located in the ceiling in the bedroom and living room were comparable to those determined in the wall assembly (45 and 48 min).

For the walls with gypsum board directly attached to the CLT panels, the temperatures measured between the gypsum board and the CLT eventually reached a plateau with the temperature remaining < 600°C. Other than at the center of the bedroom ceiling, the temperatures at the interface between the based layer of gypsum board and the CLT panels in the ceiling/floor assembly did not reach a plateau. The temperature tended to increase throughout the test and at many locations was < 500°C until the end of the test.

There were indications of limited flaming combustion on the CLT panels in the ceiling/floor assembly during the test. The areas noted were along the north-south centerline in the living room/kitchen area and at the center of the bedroom ceiling. Indications are that, at other locations, the base layer of gypsum board may have remained in place on the ceiling until the end of the test.

The results of measurements on the unexposed (upper) side of the CLT panels in the ceiling/floor assembly indicate minimal heat transfer through the panels. The temperature increases were < 10°C.

Overall, the results suggest that heat losses to the CLT in the ceiling/floor assembly improved the performance of the gypsum board. Further investigations are required to quantify the effect of the thickness of the CLT on the encapsulation time, the temperatures at the interface between the encapsulation material and the CLT and the fall-off of the encapsulation material.

Table 4. Time to reach 300ºC at gypsum board/CLT interface bedroom ceiling.

Thermocouple Location	Time (min)
Southeast	46
South-center	102
Southwest	54
Center-east	52
Center	NA
Center-west	111
Northeast	86
North-center	106
Northwest	99

NA – Not available – thermocouple failed.

Table 5. Time to reach 300ºC at gypsum board/CLT interface living room/kitchen ceiling.

Thermocouple Location	Time (min)
Southeast	57
South-center	57
Southwest	77
Center-east	60
Center	51
Center-west	63
Northeast	55
North-center	49
Northwest	74

Table 6. Encapsulation times based on measurements in ceiling assembly of the middle storey (fire floor).

Ceiling Assembly	Encapsulation	Number and location thermocouples	Encapsulation Time (min)	
			Average ΔT 250°C	Single Point ΔT 270°C
Bedroom	1 layer 12.7 mm thick Type X GB	1 thermocouple GB_f/GB_b interface	NA	15
	2 layers 12.7 mm thick Type X GB	9 thermocouples GB_b/CLT	69	45
	2 layers 12.7 mm thick Type X GB	1 thermocouple GB_b/CLT interface	NA	28
Living room/Kitchen	2 layers 12.7 mm thick Type X GB	9 thermocouples joist cavity	55	48

GB – Gypsum Board NA – Not applicable.
GB_f – Gypsum board face layer. GB_b – Gypsum board base layer RMC – Resilient metal channel.

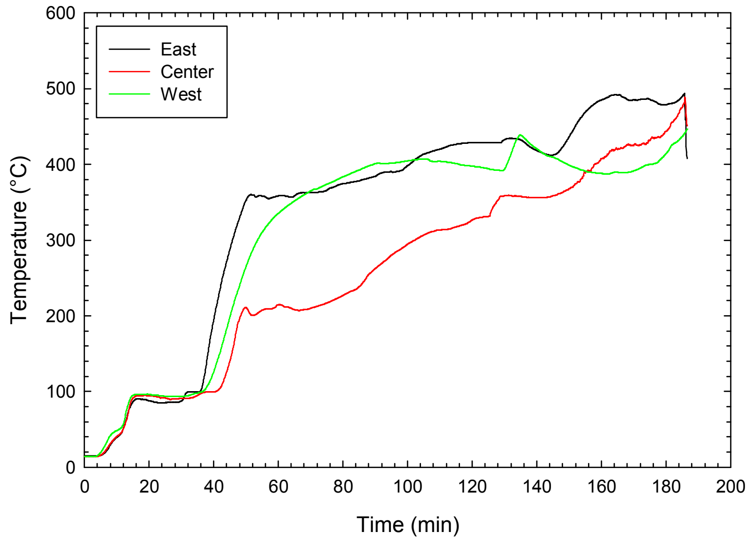


Figure 44. Temperatures gypsum board/CLT interface bedroom ceiling (south).

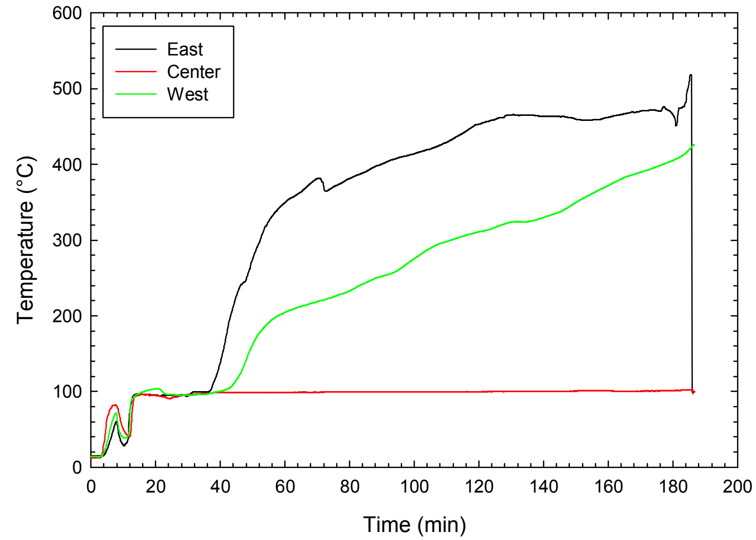


Figure 45. Temperatures gypsum board/CLT interface bedroom ceiling (center).

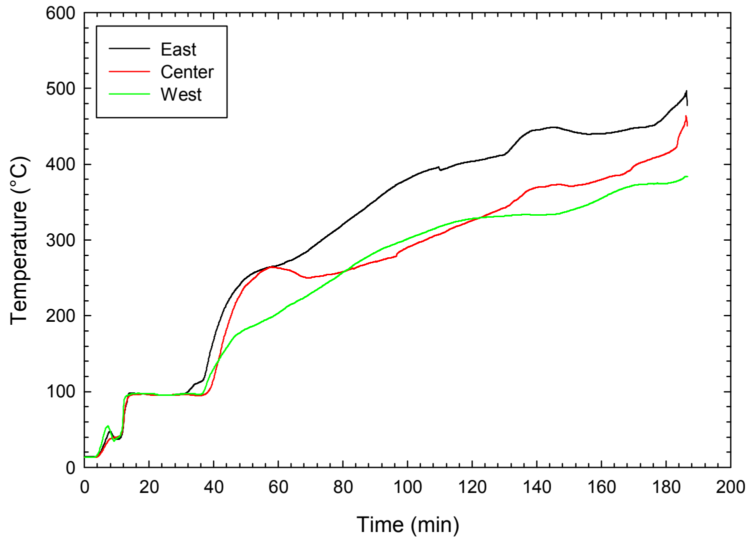


Figure 46. Temperatures gypsum board/CLT interface bedroom ceiling (north).

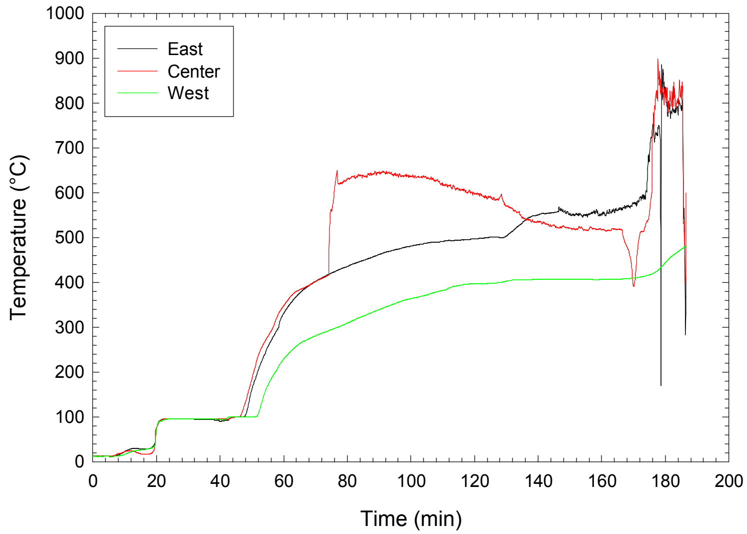


Figure 47. Temperatures gypsum board/CLT interface living room/kitchen ceiling (south).

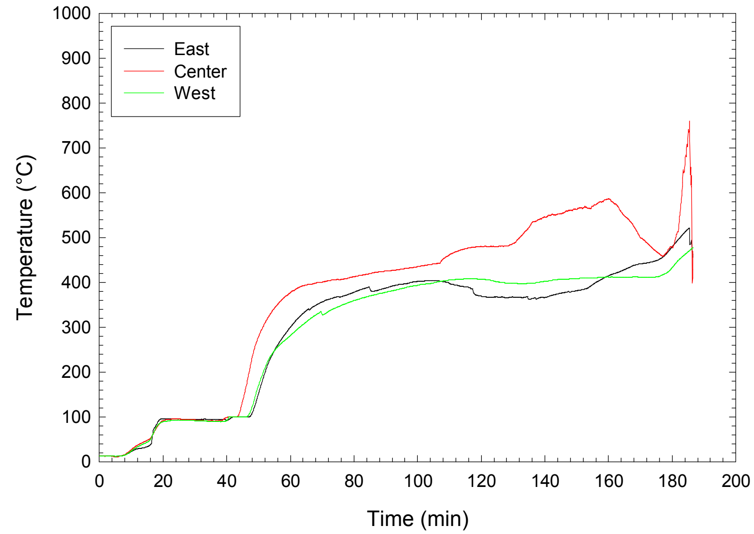


Figure 48. Temperatures gypsum board/CLT interface living room/kitchen ceiling (center).

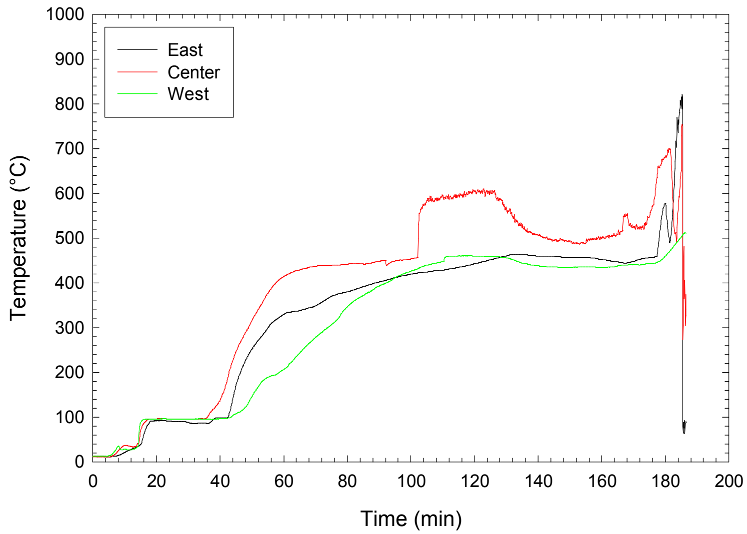


Figure 49. Temperatures gypsum board/CLT interface living room/kitchen ceiling (north).

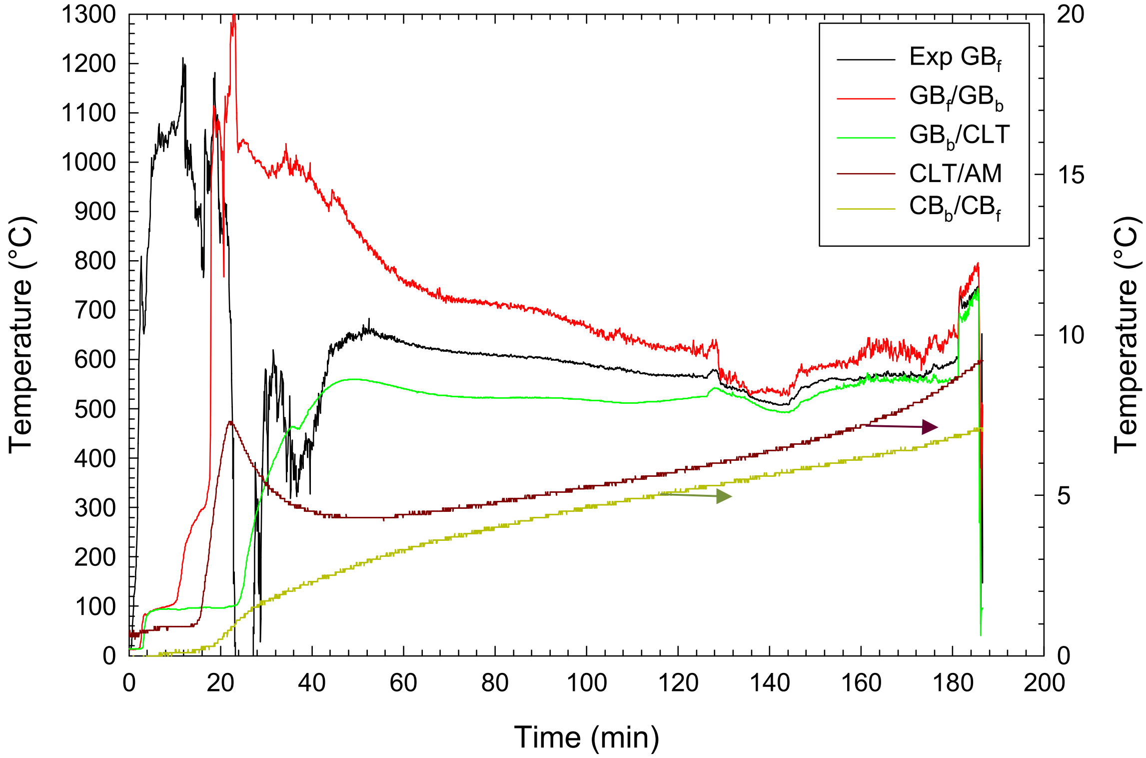


Figure 50. Temperature profiles in ceiling/floor assembly at center of the bedroom (CLT/CB_b and CB_b/CB_f plotted versus right axis).

Exp GB_f	Exposed surface of face layer of gypsum board.
GB_f/GB_b	Interface between face and base layers of gypsum board.
GB_b/CLT	Base layer interface with CLT.
CLT/AM	Interface between CLT and acoustic membrane.
CB_b/CB_f	Interface between base and face layer of cement board.

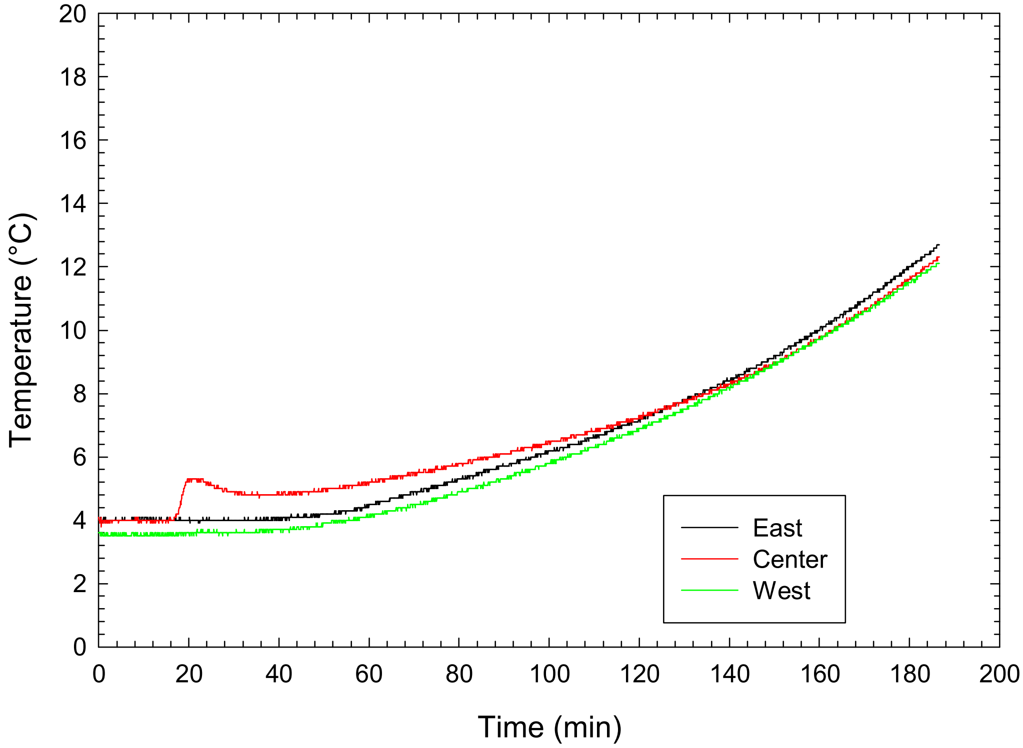


Figure 51. Temperature profiles in joint between CLT panels in ceiling/floor above bedroom.

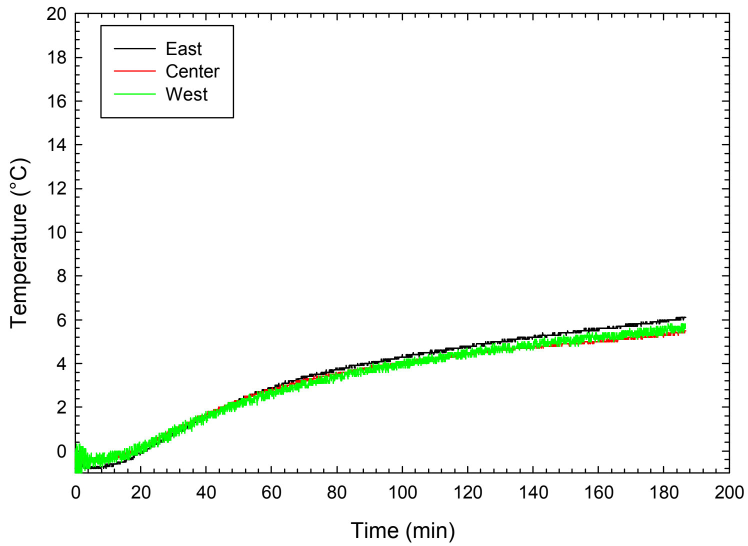


Figure 52. Temperature unexposed side of ceiling floor assembly (south) above bedroom.

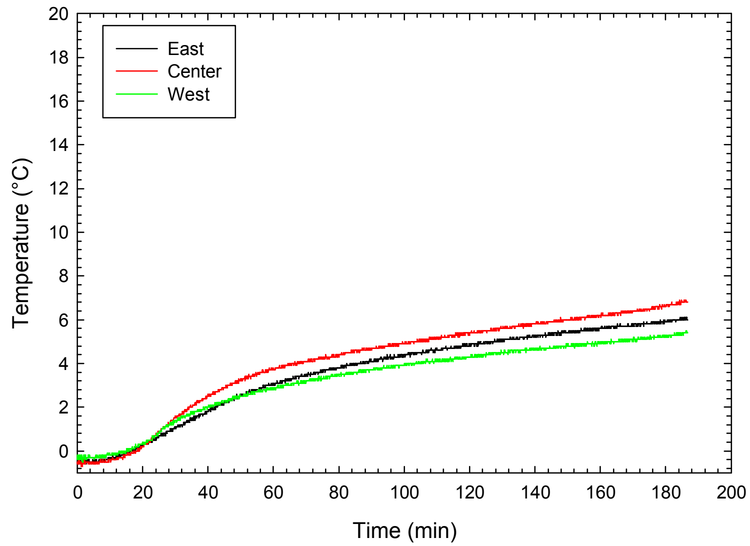


Figure 53. Temperature unexposed side of ceiling floor assembly (center) above bedroom.

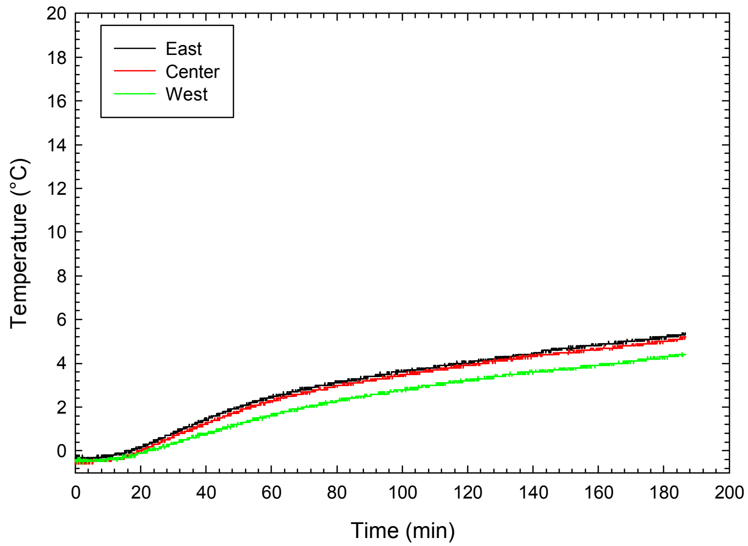


Figure 54. Temperature unexposed side of ceiling floor assembly (north) above bedroom.

11.4 Temperatures in the Floor Assembly of the Fire Floor

11.4.1 Floor Assembly in Bedroom

Nine thermocouples were located between the CLT panels and the layer of acoustic membrane located below the two layers of cement board and hardwood flooring in the floor assembly below the bedroom area. The thermocouples were located at the quarter- and mid-widths and lengths of the bedroom area, excluding the closet. In plan view, these nine thermocouples are at the same location as the thermocouples in the ceiling/floor assembly shown in Figure 9.

The temperatures measured at the interface between the CLT panels and the acoustic membrane are shown in Figure 55, Figure 56 and Figure 57. Observations based on the temperature profiles are as follows:

1. Initially, there was minimal temperature increase at the interface between the layer of acoustic membrane and the CLT panels. This initial phase was followed by a rapid temperature increase with temperatures exceeding 90°C between 19 and 30 min, depending on the location in the room. The earliest temperature increase was at the North-East corner of the room and the slowest at the southeast quarter point.
2. The initial temperature increase was followed by a steady temperature phase. The duration of this phase varied considerably depending on the location in the bedroom. The temperatures exceeded 100°C between 23 min at the northeast quarter point and 57 min at the southeast quarter point.
3. Once the water was driven off from the two layers of cement board, there was a more rapid temperature increase at the interface between the acoustic membrane and the CLT panels. The times at which the temperature reached 300°C are listed in Table 7. There was considerable variation in the times with the earliest time (37 min) at the east side of the room at mid-length (Center) and the longest time (101 min) at the southeast quarter-point of the room.
4. The encapsulation time for the hardwood flooring combined with the two layers of cement board and acoustic membranes laid over the CLT panels was 36 min, based on a single point temperature increase of 270°C. The single point criterion was first exceeded at the east side of the room at its mid-length (center). Based on the average temperature increase for the nine thermocouples, the 250°C average temperature increase criterion was exceeded at 47 min. (Three criteria for determining the effectiveness of an encapsulation material or system in protecting the combustible structural elements were assessed using intermediate scale furnace tests. [15] The criteria which uses an average temperature increase of 250°C and a single point temperature increase of 270°C is based on the temperature at which wood begins to char (300°C). The encapsulation time is earlier than the time to reach 300°C noted in Table 7 since the temperature in the floor assembly at the start of the test was < 12.5°C.)
5. After the water was driven off from the cement board, there was a short period with high temperature increases. At most locations, the temperature reached a peak between 350 and 550°C and subsequently decreased. The two exceptions were the temperatures measured at the southwest quarter point and the south-center of the bedroom, where the temperature reached and maintained a temperature plateau. The times at which the maximum temperatures occurred varied depending on the location in the bedroom with the earliest times at approximately 60 min.

11.4.2 Living Room/Kitchen Floor Assembly Unexposed Side

Nine thermocouples were located on the unexposed side of the floor between the single layer of gypsum board (ceiling) in the lowest (first) storey and the CLT panels in the floor assembly below the living room/kitchen area. The thermocouples were located at the quarter- and mid-widths and lengths of the living room/kitchen area. (Note: These thermocouples were installed from the top of the CLT panels through holes drilled in the CLT.)

The temperatures measured by the nine thermocouples are shown in Figure 58, Figure 59 and Figure 60. Initially, the temperatures were similar to those measured at the same location on the unexposed side of the bedroom floor/ceiling assembly (see next Section). For the initial 80 min, there was minimal increase in temperature (< 5°C) with a peak temperature between 50 and 60 min.

After the initial peak, the temperature decreased until approximately 80 min, at which time there was a rapid increase to peak temperatures of up to 350°C. After the peak temperature, the temperature decreased to 110°C or less. The temperature subsequently increased near the end of the test.

The measured temperature exceeded 300°C for a short time at two locations during the initial peak (southeast quarter point in the kitchen area and the northwest quarter point in the living room area). The temperatures were also > 300°C at several locations at the end of the test.

A possible explanation for the unexpected high temperatures on the unexposed side of the CLT panels is that hot gases flowed through the holes drilled for mounting the thermocouples on the unexposed face of the CLT panels.

11.4.3 Unexposed Side of the Bedroom Floor/Ceiling CLT Panels

Nine thermocouples were located on the unexposed side of the floor between the single layer of gypsum board (ceiling) in the lowest storey and the CLT panels in the floor assembly below the bedroom. The thermocouples were located at the quarter- and mid-widths and lengths of the bedroom area excluding the closet. (Note: These thermocouples were installed from the top of the CLT panels through holes drilled in the CLT.)

The temperatures measured by the nine thermocouples are shown in Figure 61, Figure 62 and Figure 63. Initially, the temperatures increased slowly to an initial peak temperature of approximately 8°C at approximately 38 min. At most locations, the temperature slowly decreased to approximately 120 min and subsequently increased until the end of the test.

Temperature peaks occurred at some locations after 60 min. However, the temperature remained < 100°C. A possible explanation for the unexpected localized peak temperatures on the unexposed side of the CLT panels is that hot gases flowed through the holes drilled for mounting the thermocouples on the unexposed face of the CLT.

11.4.4 Interface Temperature Profiles in Bedroom Floor Assembly

Seven thermocouples were located at the center of the bedroom to measure of the temperature at each of the interfaces between the various materials used in the construction of the floor/ceiling assembly separating the middle and lowest storeys.

The locations of the seven thermocouples, starting in the fire area (bedroom), were as follows.

1. On the exposed side (top) of the hardwood flooring.
2. Interface between the acoustic membrane and the hardwood flooring.
3. Interface between the face layer of cement board and acoustic membrane.
4. Interface between the base and face layers of cement board.
5. Interface between the acoustic membrane and the base layer of cement board.
6. Interface between the single layer of gypsum board (ceiling) in the lowest (first) storey and CLT panels.
7. Unexposed face of single layer of gypsum board (ceiling) on the unexposed side of the CLT floor assembly.

The temperatures measured using these thermocouples are shown in Figure 64.

General comments regarding the temperatures measured at each interface between the various materials in the CLT floor/ceiling assembly are as follows:

1. **Exposed surface of the hardwood flooring.** There was an initial rapid increase in temperature to an initial peak of 800ºC at 3 min. After a short temperature dip, the temperature increased to >700ºC at 4 min and remained above this temperature until approximately 50 min. The peak temperature was 950ºC at approximately 21 min. This peak temperature coincided with the peak temperature at the interface between the acoustic membrane and the cement board indicating the acoustic membrane was burning. After 30 min, the temperatures measured at the interface between the hardwood flooring and the acoustic membrane and the acoustic membrane and cement board followed the same general trend indicating that the hardwood flooring and the acoustic membrane had been consumed. After 50 min, the temperature remained steady between 650 and 700ºC until approximately 120 min after which there was a rapid decrease in temperature.
2. **Interface between the acoustic membrane and the hardwood flooring**. There was minimal temperature increase until approximately 6 min. Subsequently, the temperature increased rapidly reaching 600ºC at 12 min and a peak temperature of 886ºC at 18 min indicating that the acoustic membrane was likely burning. After 30 min, the temperature followed the same general trend as the temperature measured by the thermocouples on the exposed surface of the hardwood flooring.
3. **Interface between the face layer of cement board and acoustic membrane.** The initial temperature profile was similar to that at the interface between the hardwood flooring and the acoustic insulation with an initial time lag prior to temperature beginning to increase. Subsequently, the temperature increased rapidly reaching a peak temperature of 836ºC at 20 min and remained steady until approximately 30 min. After 30 min, the temperatures were comparable to those measured by the thermocouples at the exposed surface of the hardwood flooring and between the hardwood flooring and the acoustic membrane until 120 min indicating that the acoustic membrane and hardwood flooring had been consumed by 30 min. The temperatures measured by this and the two other thermocouples located above the cement board were consistent with

the temperatures measured in the bedroom. After 120 min, the temperature measured by this thermocouple did not decrease unlike the temperature measured by the other two thermocouples.

4. **Interface between the base and face layers of cement board.** The temperature at the interface between the two layers of cement board began to steadily increase after 10 min. The temperature increase exceeded 270ºC at 20 min and the temperature was > 300ºC at 21 min. The maximum temperature was approximately 613ºC at 47 min. Subsequently, the temperature decreased until the end of the test. (The reason for the dip in temperature between 84 and 104 min is not known but may be due to fall-off of the gypsum board on the ceiling.) The results indicate that the combination of the face layer of cement board and the hardwood flooring provided a 20 min encapsulation time.
5. **Interface between the acoustic membrane and the base layer of cement board.** The temperature at the interface between the base layer of cement board and the acoustic membrane began to steadily increase after 13 min. The temperature increase exceeded 270ºC at 33 min and the temperature was > 300ºC at 34 min. The maximum temperature was approximately 493ºC at 68 min. The temperatures were not measured at the interface between the CLT and the acoustic membrane. However, based on the temperatures measured at the interface between the cement board and the acoustic insulation, there may have been some charring of the CLT panels but there would be no flaming combustion. After 68 min, the temperature decreased until the end of the test. The results indicate that the combination of the two layers of cement board and the hardwood flooring provided a 33 min encapsulation time.
6. **Interface between the single layer of gypsum board (ceiling) in the lowest (first) storey and CLT panels.** There was an initial peak temperature of 6.3ºC at 38 min. Subsequently, the temperature decreased until approximately 115 min after which there was a gradual increase in temperature until the end of the test. The maximum temperature increase was 8.4ºC.
7. **Unexposed face of single layer of gypsum board (ceiling) on the unexposed side of the CLT floor assembly**. The temperature increase over the test duration was 1.5ºC.

11.4.5 Summary of Temperatures in Floor Assembly

The encapsulation times for the floor assembly are summarized in Table 8. Some general observations based on the results are:

1. The hardwood flooring combined with the acoustic membrane and a single layer of cement board provides limited encapsulation time (20 min). This time is based on a single measurement at the center of bedroom floor.
2. The encapsulation time for the hardwood flooring combined with the two layers of acoustic membrane and the two layers of 12.7 mm cement board varied depending on the measurement used. The shortest time was based on the thermocouple located at the center of the bedroom floor between the base layer of cement board and the acoustic membrane (33 min). However, this time was comparable to the single point results (Section 11.4.1) from the nine thermocouples located at the interface between the acoustic insulation and the CLT panels (36 min).

The results of measurements on the unexposed side of the CLT panels indicate minimal heat transfer through the panels. The temperature increases were typically < 10°C at the interface between the CLT and the gypsum board on the unexposed side of the assembly. However, higher peak temperatures (< 100°C) were measured at some locations after 60 min in the bedroom floor/ceiling assembly. At approximately 80 min, peak temperatures of up to 350°C were measured at the 9 locations in the living room/kitchen floor/ceiling assembly. A possible explanation for the unexpected high temperatures on the unexposed side of the CLT panels is that hot gases flowed through the holes drilled for mounting the thermocouples on the unexposed face of the CLT.

Table 7. Time temperature reached 300ºC at interface between acoustic membrane and CLT panel.

Bedroom Thermocouple Location	Time (min)
Southeast	101
South-center	54
Southwest	59
Center-east	37
Center	50
Center-west	43
Northeast	44
North-center	43
Northwest	50

Table 8. Encapsulation times for floor assembly of the middle storey (fire floor).

Floor Assembly	Encapsulation	Number and location thermocouples	Encapsulation Time (min)	
			Average ΔT 250°C	Single Point ΔT 270°C
Bedroom	Hardwood floor + acoustic membrane + 1 layer of cement board	1 thermocouple CB_f/CB_b interface	NA	20
	Hardwood floor + acoustic membrane + 2 layers of cement board	1 thermocouple CB_b/AM interface	NA	33
	Hardwood floor + acoustic membrane + 2 layers of cement board + acoustic membrane	9 thermocouple AM/CLT interface	47	36

CB_f/CB_b - Interface between face and base layer of cement board at center of bedroom floor.
CB_b/AM - Interface between the base layer of cement board and the acoustic membrane in the bedroom floor.
AM/CLT- Interface between the acoustic membrane and CLT using data from 9 thermocouples in bedroom floor.
NA Not applicable.
DNR Did not reach

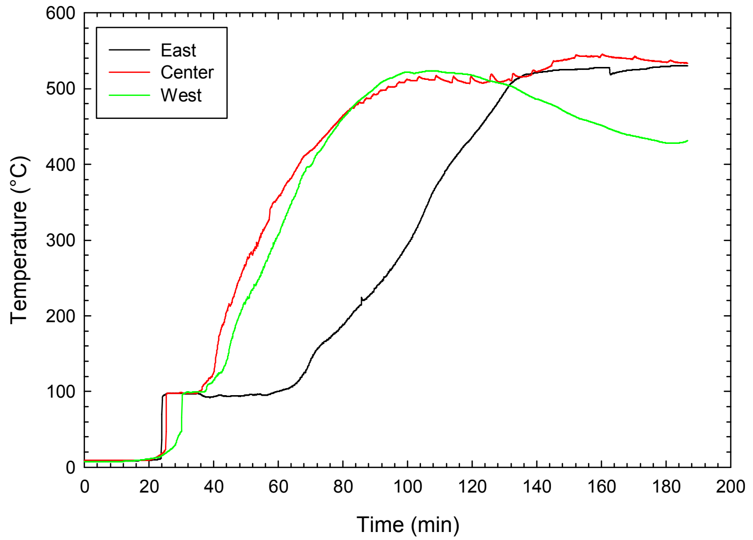


Figure 55. Temperatures interface acoustic membrane and CLT bedroom floor (south).

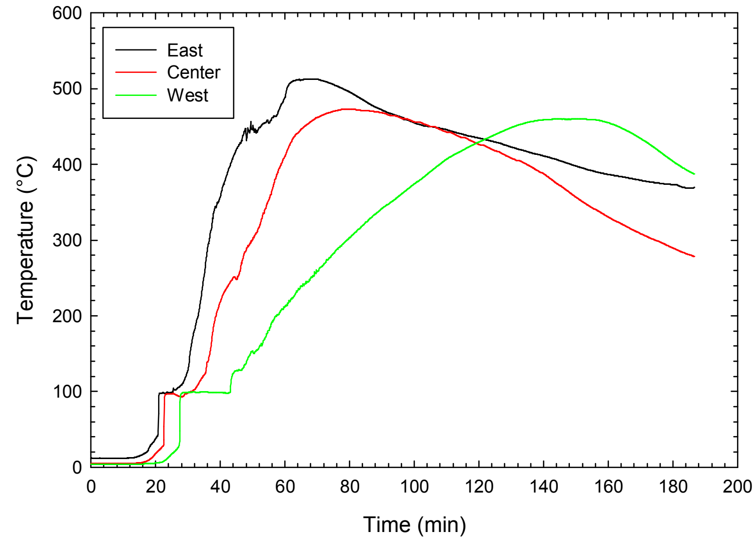


Figure 56. Temperatures interface acoustic membrane and CLT bedroom floor (center).

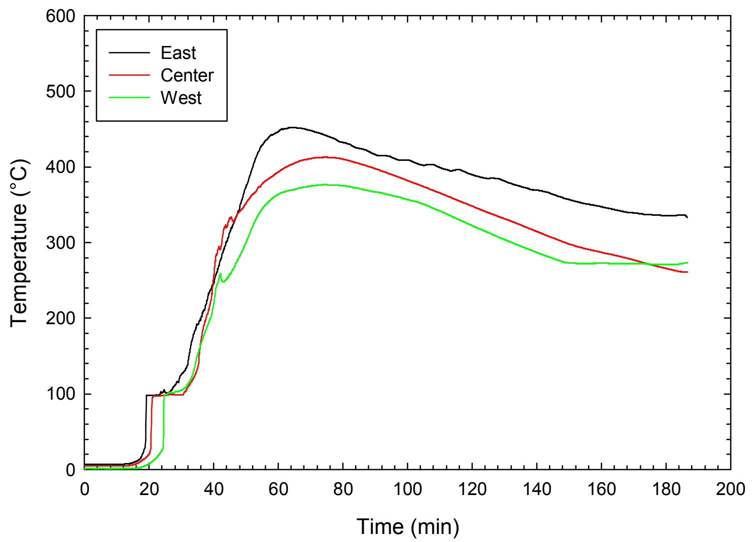


Figure 57. Temperatures interface acoustic membrane and CLT bedroom floor (north).

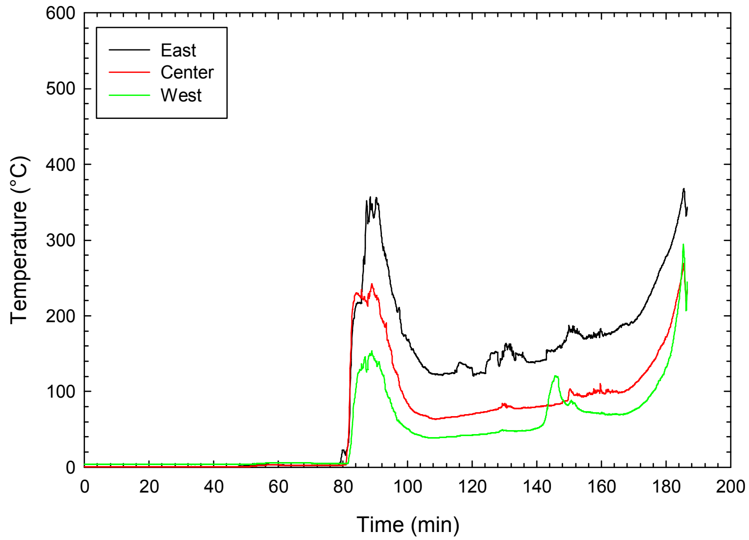


Figure 58. Temperatures CLT/GB on the unexposed side of living room/kitchen floor (south).

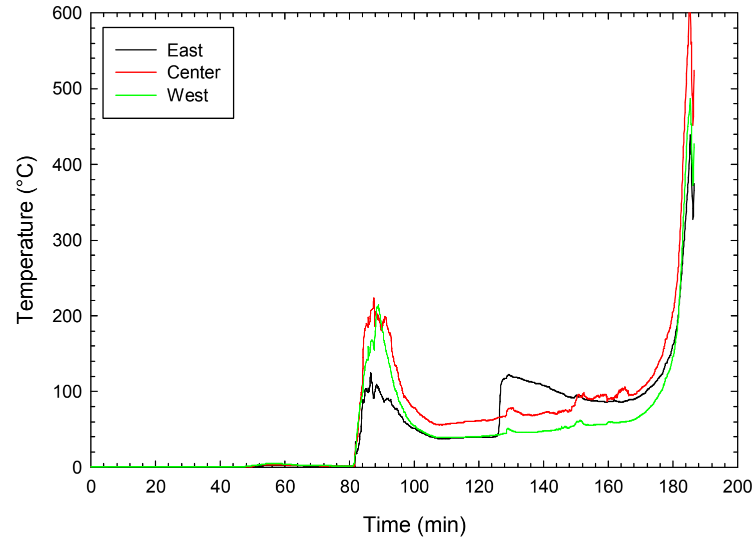


Figure 59. Temperatures CLT/GB on the unexposed side of living room/kitchen floor (center).

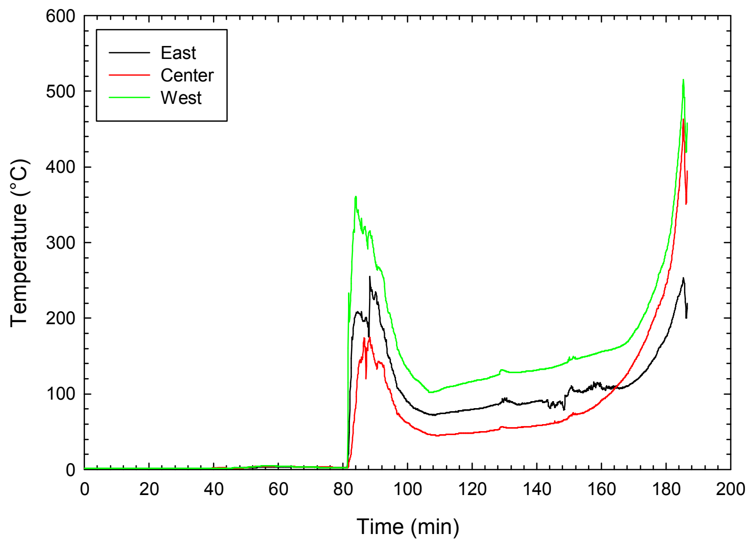


Figure 60. Temperatures CLT/GB on the unexposed side of living room/kitchen floor (north).

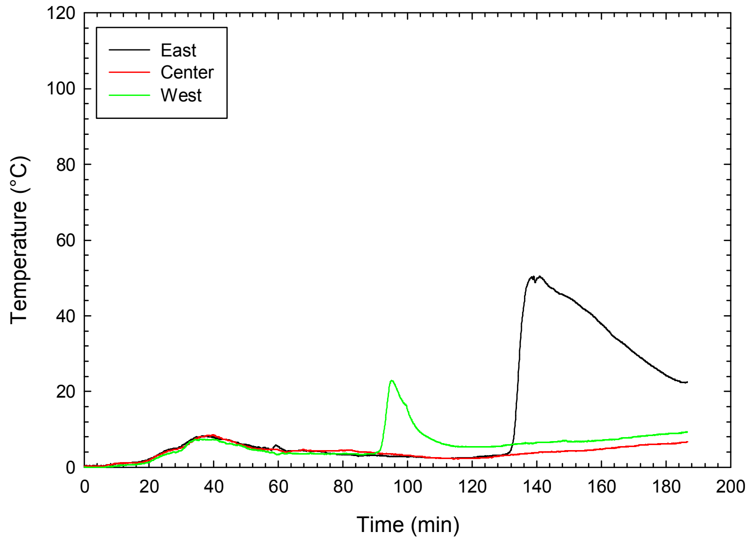


Figure 61. Temperatures CLT/gypsum board on the unexposed side of bedroom floor (south).

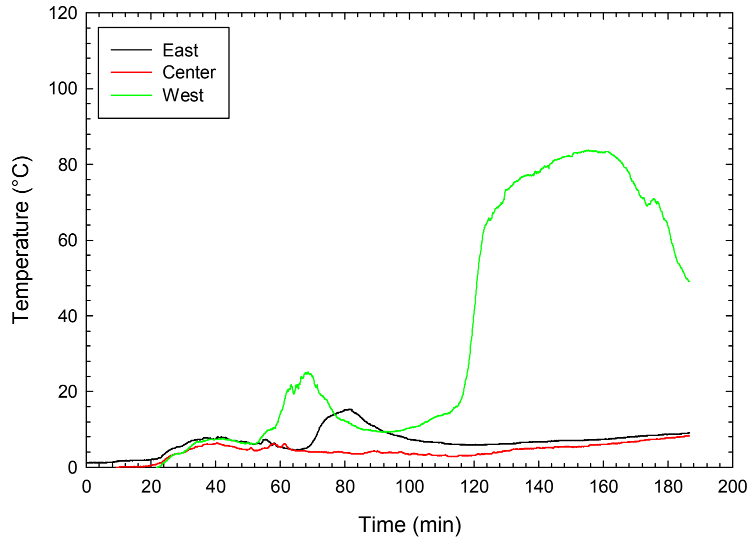


Figure 62. Temperatures CLT/gypsum board on the unexposed side of bedroom floor (center).

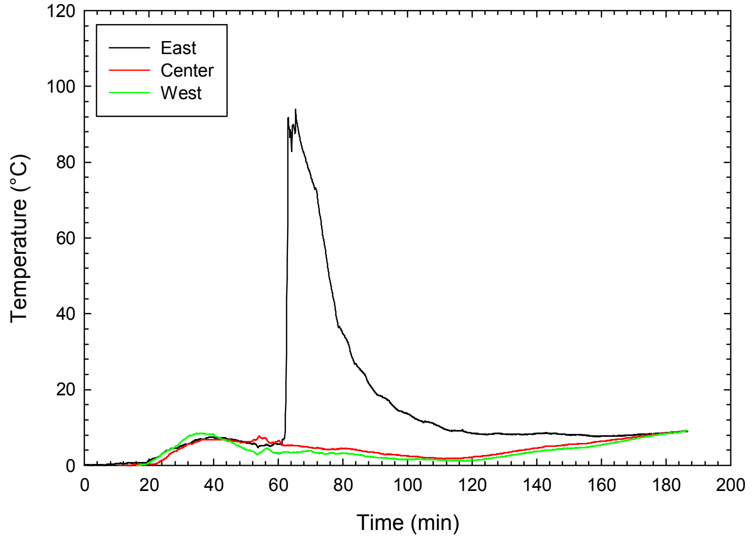


Figure 63. Temperatures CLT/gypsum board on the unexposed side of bedroom floor (north).

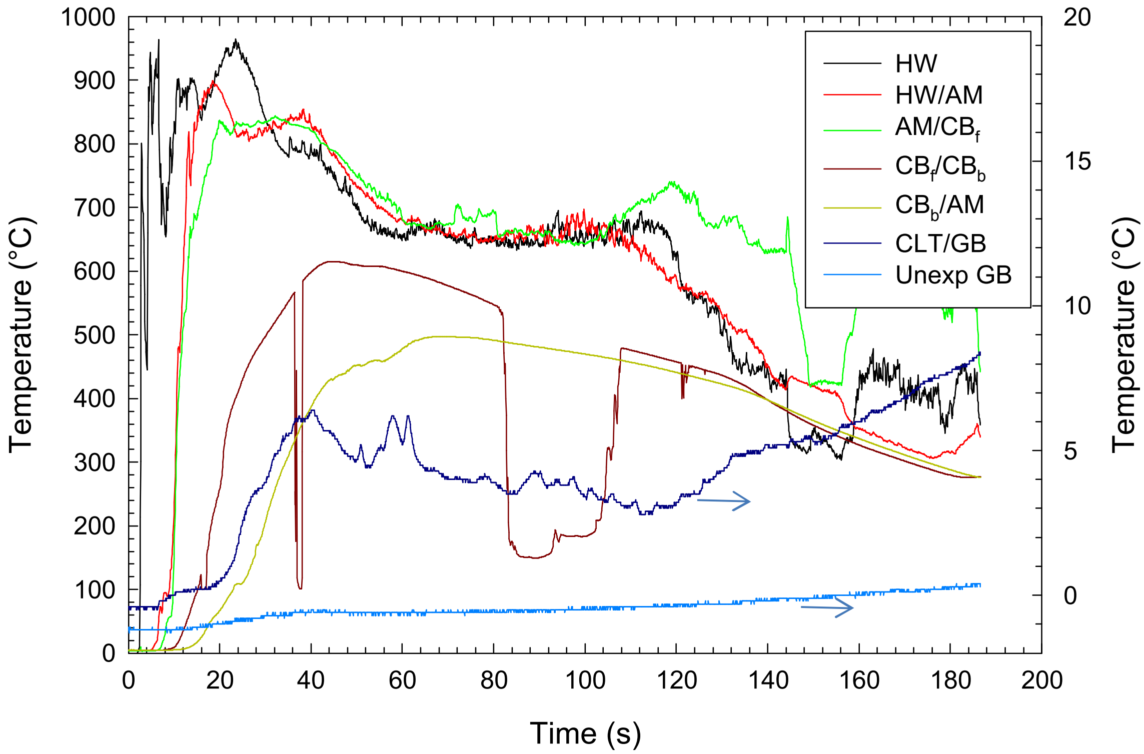


Figure 64. Temperature profiles in floor assembly at center of the bedroom (Plots CLT/GB$_b$ and Unexp GB$_b$ versus right axis).

HW	Exposed face of hardwood floor
HW/AM	Interface between hardwood flooring and acoustic membrane.
AM/CB$_f$	Interface between acoustic membrane for hardwood floor and cement board.
CB$_f$/CB$_b$	Interface between face and base layer of cement board.
CB$_b$/AM	Interface between cement board and acoustic membrane.
CLT/GB$_b$	Interface between CLT and gypsum board on unexposed side.
Unexp GB$_b$	Unexposed surface of gypsum board on unexposed side.

11.5 Temperatures Measured in the Highest Storey

Thermocouple trees were located in the bedroom and living room and kitchen area on the third storey. Each tree was located at the center of the respective area. The thermocouples were located at the 0.4, 1.4 m heights and 1.8 m (25 mm below the ceiling). The temperatures measured in the highest storey bedroom and living room/kitchen areas are shown in Figure 65 and Figure 66, respectively.

Initially, there was a gradual increase in the temperatures at the two thermocouples located near the ceiling to a peak temperature at approximately 50 min. The maximum temperature increase was approximately 15°C. After the initial peak, the temperature slowly decreased until near the end of the test.

The temperatures at the two lower heights gradually increased until 50 – 60 min. Subsequently, there was a slower increase in the temperatures until the end of the test. The temperature increase at the 0.4 and 1.4 m heights in the living room/kitchen area was 9°C and 11°C, respectively. The temperature increases at these heights in the bedroom were 8 and 10°C.

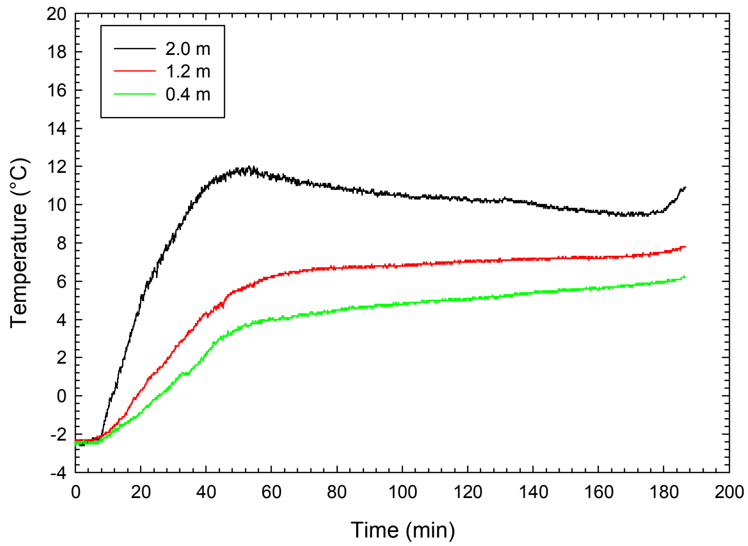


Figure 65. Temperature in bedroom area highest storey.

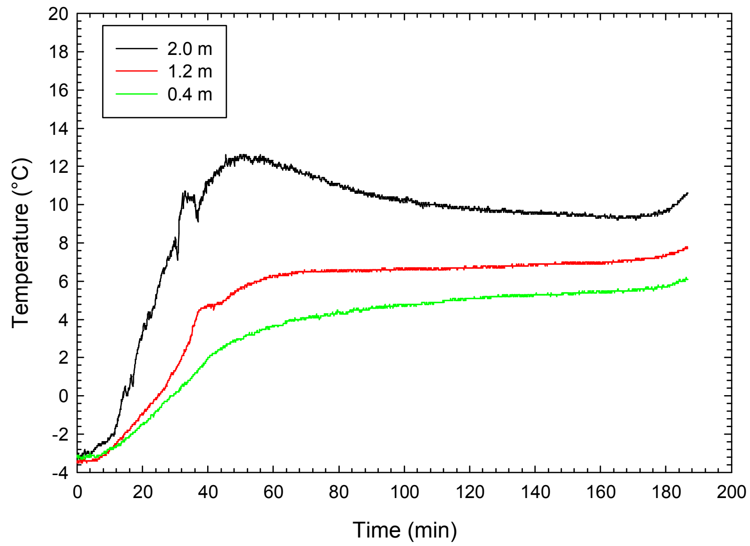


Figure 66. Temperatures in living room/kitchen area highest storey.

11.6 Heat Fluxes to the Exterior Wall Façade

Heat fluxes to the exterior wall façade were measured using heat flux meters located 3.5 m above the top of the openings in the bedroom and living room. The meters were centered on the openings. This location is consistent with the location used for measuring heat fluxes in exterior wall fire testing in accordance with CAN/ULC S134 [6]. The heat fluxes measured at these two locations are shown in Figure 67. A one-minute running average similar to that used in CAN/ULC S134 [6] was used to smooth the results.

There was an initial 18 kW/m^2 peak in the heat flux from the flame from the bedroom opening just after 3 min. This corresponded to the occurrence of flashover in the bedroom. Subsequently, the heat flux decreased to 5.7 kW/m^2 around 6 min. The heat flux was between 5 and 10 kW/m^2 until 43 min. After 43 min, it decreased until the end of the test.

The heat flux above the opening in the living room exterior wall started increasing just after 4 min. It reached a peak value around 16 min (25.7 kW/m^2). High heat fluxes (15 – 25 kW/m^2) were sustained until approximately 30 min. After 30 min, the heat flux rapidly decreased and after 43 min the heat flux above the living room opening was slightly higher than but comparable to the heat flux above the bedroom opening. Near the end of the test there was an increase in the heat flux with the ignition of some of the CLT ceiling panels.

The reason for the difference in the heat fluxes to the façade above the two openings is not known. In the test with the LWF apartment, the peak heat fluxes above the two openings were comparable [3]. The video records for this CLT fire test indicate that the flame heights were similar above the two openings. One possibility was that the heat flux meter located above the bedroom opening was defective. The other possibility is that the flame above the bedroom opening was shifted off-center in this test.

The heat fluxes at both locations were below the 35 kW/m^2 limit specified in the 2010 NBC [1] for combustible cladding systems tested using CAN/ULC S134 [6]. In addition, limited vertical flame spread was observed on the exterior wall façade.

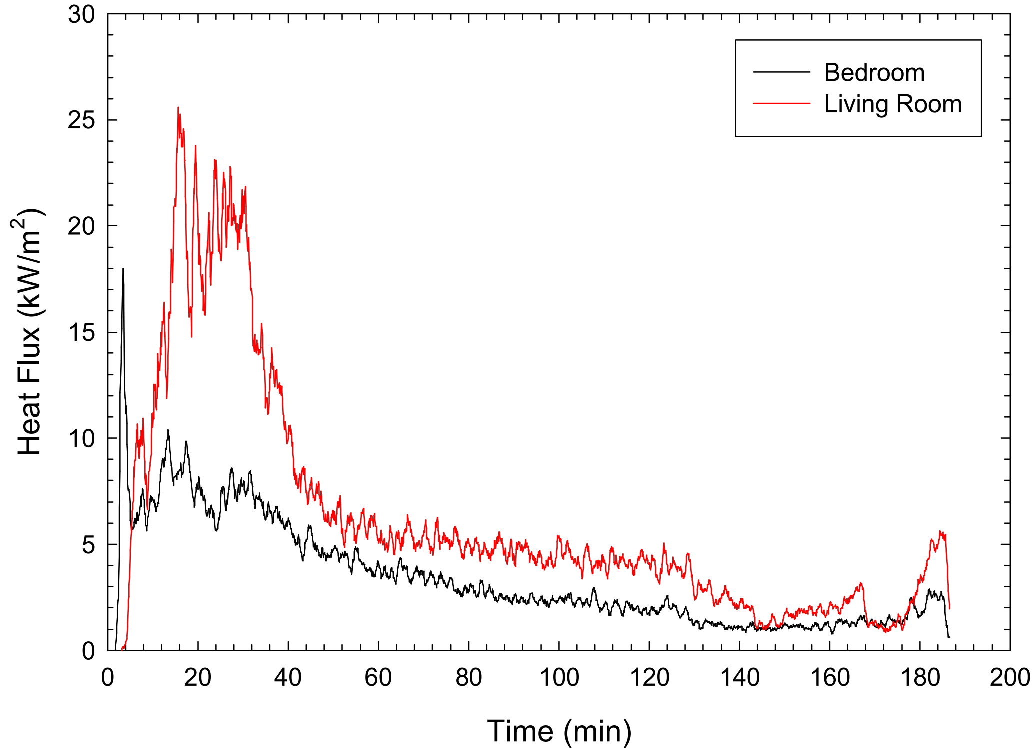


Figure 67. Heat flux to façade.

11.7 Heat Fluxes from the Openings

Heat fluxes were measured at various locations exterior to the fire area. This included:

1. Two heat flux meters facing the bedroom opening with both meters centered on the opening. The heat flux meters were located 2.4 and 4.8 m from the opening.
2. Two heat flux meters facing the living room opening with both meters centered on opening. The heat flux meters were located 2.4 and 4.8 m from the opening.

The measured heat fluxes for the bedroom and living room openings are shown in Figure 68 and Figure 69, respectively.

There was a rapid increase in the heat fluxes measured for the bedroom opening coinciding with flashover in the bedroom, with a peak heat flux at 3 min (26 kW/m^2). Subsequently, the heat flux at the 2.4 m distance was > 15 kW/m^2 until approximately 40 min, with a second peak between 13 and 14 min (25 kW/m^2). After 40 min, the heat flux decreased until near the end of the test, when there was a small increase in the heat flux as flames began to develop on some of the exposed CLT panels within the apartment.

The heat flux measured at the 4.8 m location followed the same general trend as that measured at 2.4 m. However, the heat fluxes were lower with the increased distance. The heat flux at the 4.8 m distance was > 5 kW/m^2 until approximately 40 min. The initial peak heat flux was 9.5 kW/m^2 at 3 min. The second peak heat flux between 13 and 14 min was 8.5 kW/m^2. After 40 min, the heat flux decreased until near the end of the test.

There was an initial heat flux measured by the heat flux meters located in front of the living room opening with the flames extending through the opening in the bedroom exterior wall. After 6 min, there was a rapid increase in the heat flux from the living room opening with the flashover of the living room/kitchen area.

The heat flux measured at the 2.4 m location was > 12.5 kW/m^2 between 8 and 47 min. A peak heat flux of 24 kW/m^2 was measured at approximately 29 min. After 47 min, the heat flux decreased until near the end of the test.

For the meter located 4.8 m from the opening, the heat flux was > 5 kW/m^2 between 8 and 46 min. A peak heat flux of 8 kW/m^2 was measured at approximately 15 min. After 46 min, the heat flux decreased until the end of the test.

Overall, the heat fluxes measured by the heat flux meters viewing the two openings were comparable. With the fire originating in the bedroom, there was a delay in the heat fluxes measured through the living room opening. However, the peak levels were comparable (approximately 25 kW/m^2) for the heat flux meter located 2.4 m from the opening. High heat fluxes were sustained until 40 – 45 min. Subsequently, the heat fluxes decreased until near the end of the test, when there was a small increase with the flames that began to develop on some of the CLT ceiling panels.

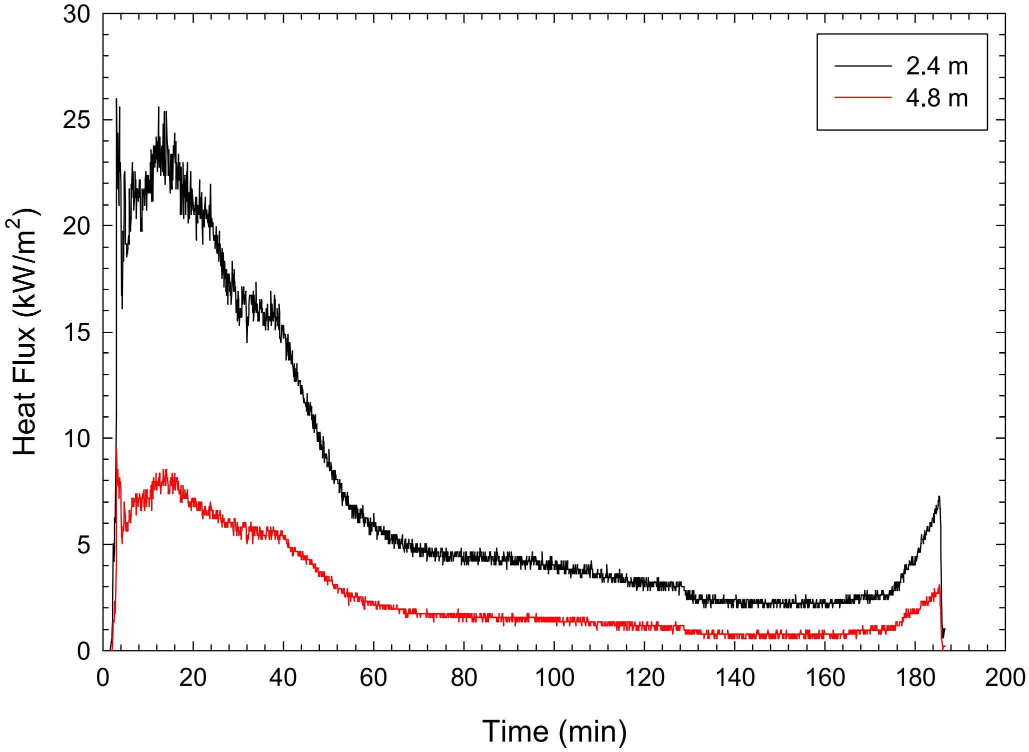


Figure 68. Heat flux from bedroom opening.

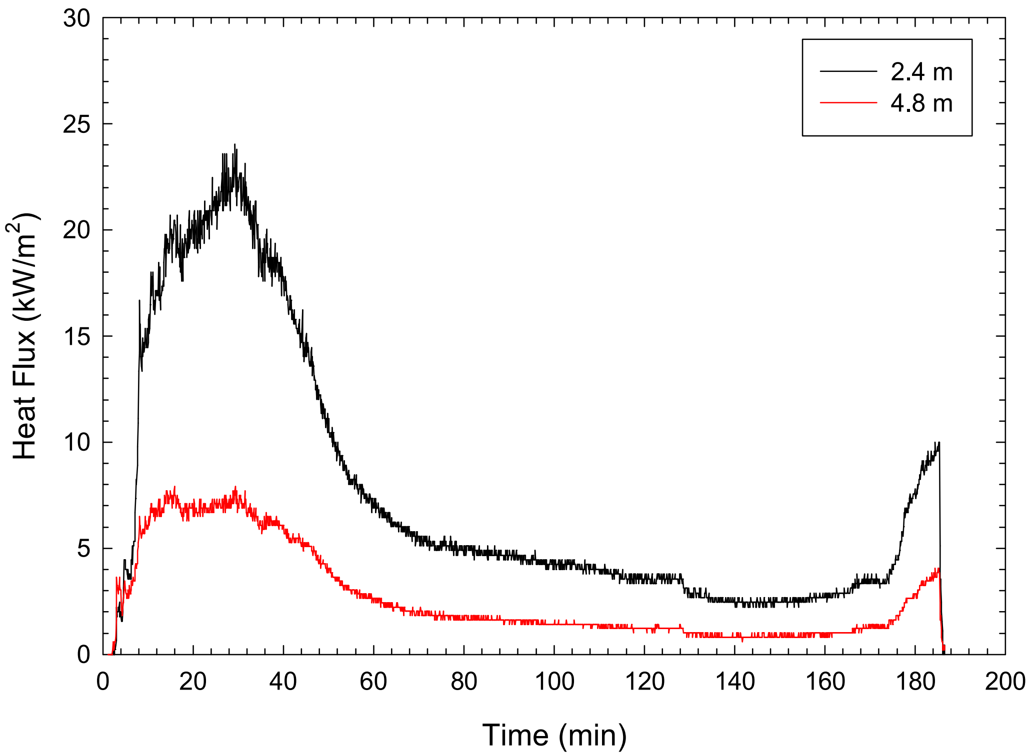


Figure 69. Heat flux from living room opening.

11.8 Duct Measurements

The smoke and hot gases produced by the fire was collected using a 10.67 by 10.67 m hood system mounted above the test setup (Figure 2). The hood system was connected through a duct system to an exhaust fan system.

A measuring station was setup in the duct system at which a thermocouple was used to measure the smoke temperature and a bi-directional probe (pitot tube) was used to measure the pressure difference produced by the flow in the duct. These measurements were used to estimate the equivalent volumetric flow rate at standard conditions as well as the mass flow rate in duct. The results are shown in Figure 70.

The initial mass flow rate in the exhaust duct was 22 – 23 kg/s. As the temperature of the smoke increased (Figure 71), the mass flow rate was reduced with a minimum of approximately 18 kg/s at approximately 15 min.

In addition, smoke samples were taken from the center of the duct and were analyzed to determine the concentrations of O_2, CO and CO_2. The CO and CO_2 concentrations are shown in Figure 72 and the O_2 concentration is shown in Figure 73.

There was an initial peak/minimum in the CO_2 and O_2 concentrations between 3 and 4 min. This corresponds to the occurrence of flashover in the bedroom. After the initial peak, there was a decrease in the CO_2 concentration and increase in the O_2 concentrations until 5 min. Subsequently, the CO_2 concentration increased and the O_2 concentration decreased to a maximum CO_2 and minimum O_2 concentrations were 1.06% and 18.6%, respectively, at approximately 15 min. After 15 min, there was a slow decrease in the CO_2 concentration and a slow increase in the O_2 concentration until 38 min, after which, there was a more rapid change in the concentrations as the fire decayed.

There was a decrease in the CO_2 concentration and increase in the O_2 concentration at approximately 128 min. This corresponds to the time at which the door to the corridor fell into the apartment. The results suggest that subsequently some smoke may not have been collected by the hood. The changes in concentrations at the end of the test are consistent with the partial burning of the exposed CLT in the ceiling assembly.

The CO concentration had an initial peak concentration (0.37%) at 3 min. There was a second peak (0.33%) just after 6 min. The concentrations were > 0.18% until approximately 20 min after which there was a slow decrease until 50 min. Subsequently, there was a gradual increase in concentrations until 140 min (0.1%).

The heat release rate was calculated using the oxygen depletion method [13]. The calculated results and a 1-minute running average are shown in Figure 74. Also shown is the ventilation-limited heat release rate within the apartment (8.26 MW) based on the two openings in the bedroom and the living room [17].

There was an initial peak heat release rate of 8.4 MW between 3 and 4 min. This corresponds to the occurrence of flashover in the bedroom and is well above the ventilation limited heat release rate for the ventilation opening in the bedroom (4.13 MW). This suggests that much of the heat output was produced in the external flame. This is consistent with the results of the heat flux measured above the opening, which showed a peak heat flux between 3 and 4 min (Figure 67).

After the initial peak, the heat release rate decreased to 6 MW at 5 min and subsequently increased to a second peak (approximately 8 MW) between 13 and 18.0 min. After the second peak, the heat release rate gradually decreased. However, total heat output from the fire in the apartment remained above 7 MW until approximately 38 min.

The second peak heat release rate was comparable to the ventilation limited heat output within the apartment (8.2 MW). However, Figure 67 indicates that, at this time, there were extensive flames outside the apartment. As a result, the measured heat release rate should be higher than the ventilation limited heat release rate within the apartment. During this time period, there was a buildup of smoke within the main test facility indicating some smoke was not collected by the exhaust system. As such, the measured peak heat release rate from the apartment fire is lower than the actual heat output until approximately 38 min.

Fire tests with real furnishing conducted as part of a project to develop information on design fires [10] indicated that, after the initial peak heat release rate, the heat release rate was comparable to the ventilation limited heat release rate within the fire area. Based on this, the total heat output from the fire would be approximately 15% higher than the measured result during this stage.

For the purpose of this project, the primary concern is the potential contribution of the wood structural elements to the fire severity. With the encapsulation of the structural elements, there would be minimal contribution to the fire until at least 30 min and in most locations until after 40 min or later. As such, the measured heat release rate provides representative results during the period of interest.

After 38 min, there was a continuous decay in the heat output to approximately 3.3 MW at 128 min. With the failure of the corridor entryway door at 128 min, there was a drop in the measured heat output indicating some smoke exiting the apartment through the opening may not have been collected by the exhaust system. There was a gradual increase in the heat release rate at the end of the test with the partial burning of some of the exposed CLT ceiling.

The smoke obscuration was also measured in the exhaust duct. The results are shown in Figure 75.

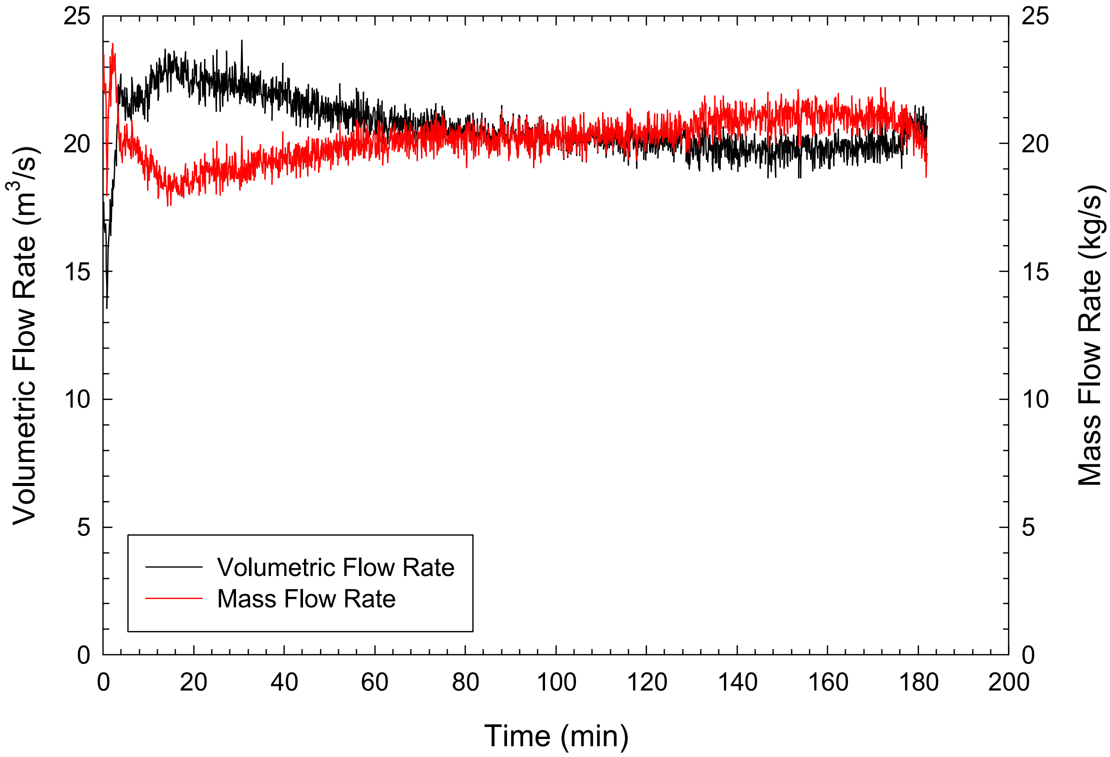


Figure 70. Volumetric and mass flow rate in exhaust duct.

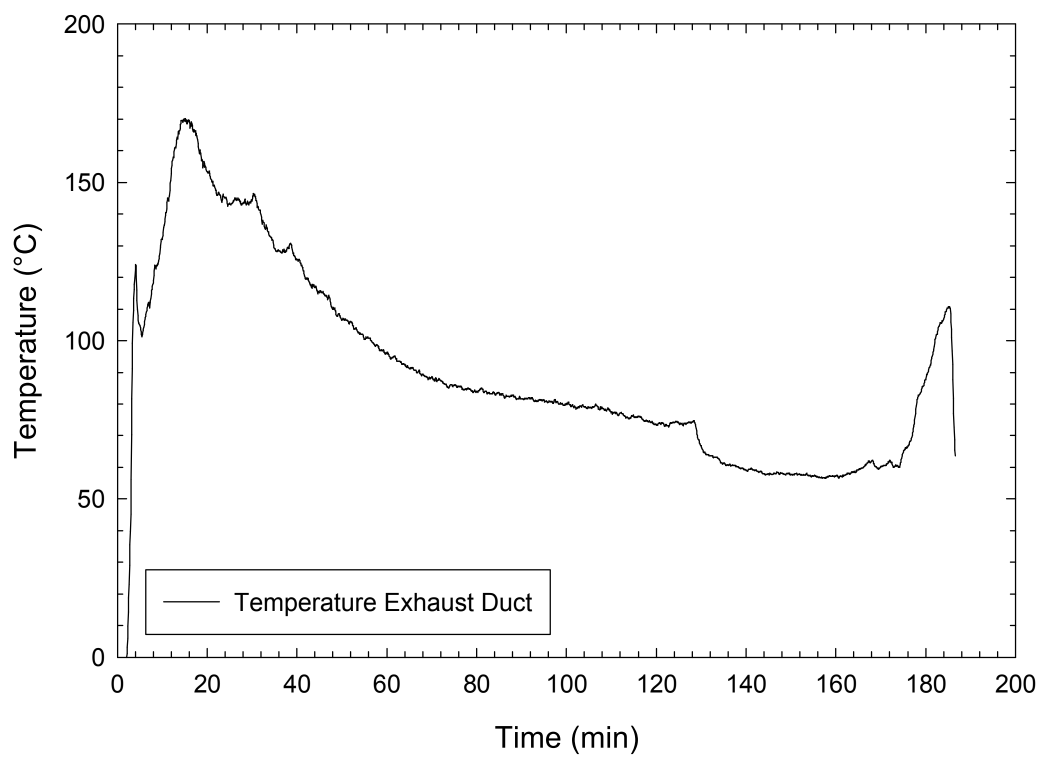


Figure 71. Temperature in exhaust duct.

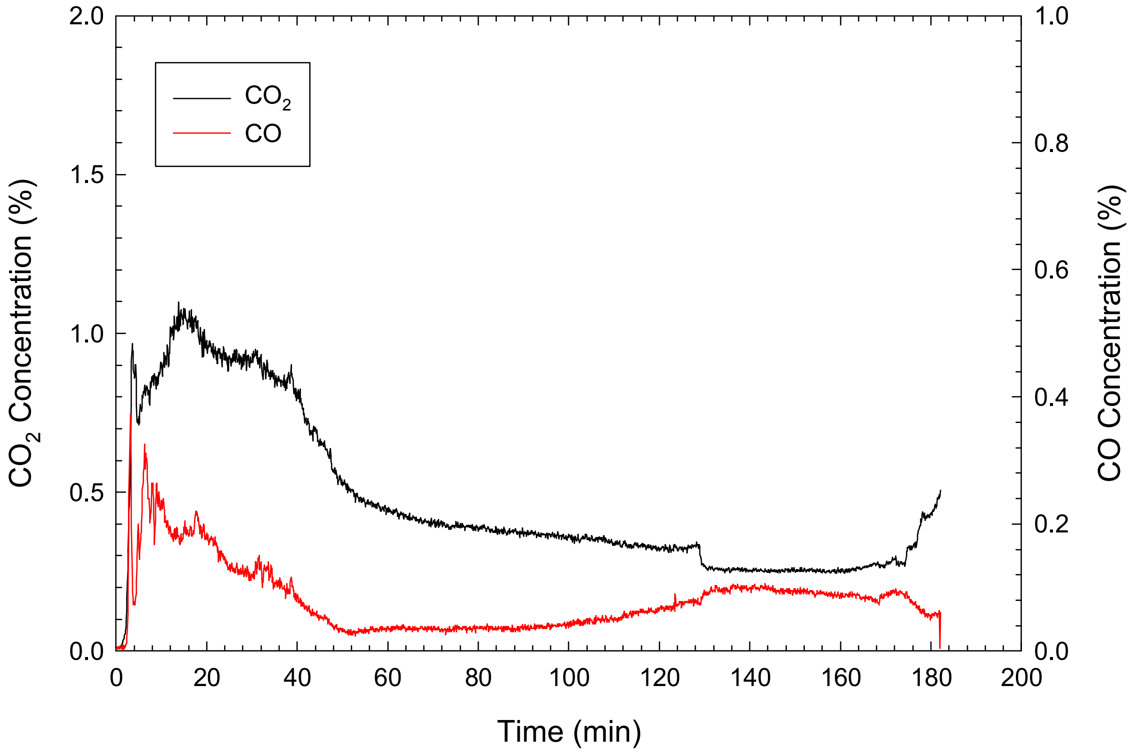


Figure 72. CO and CO_2 concentrations in the exhaust duct.

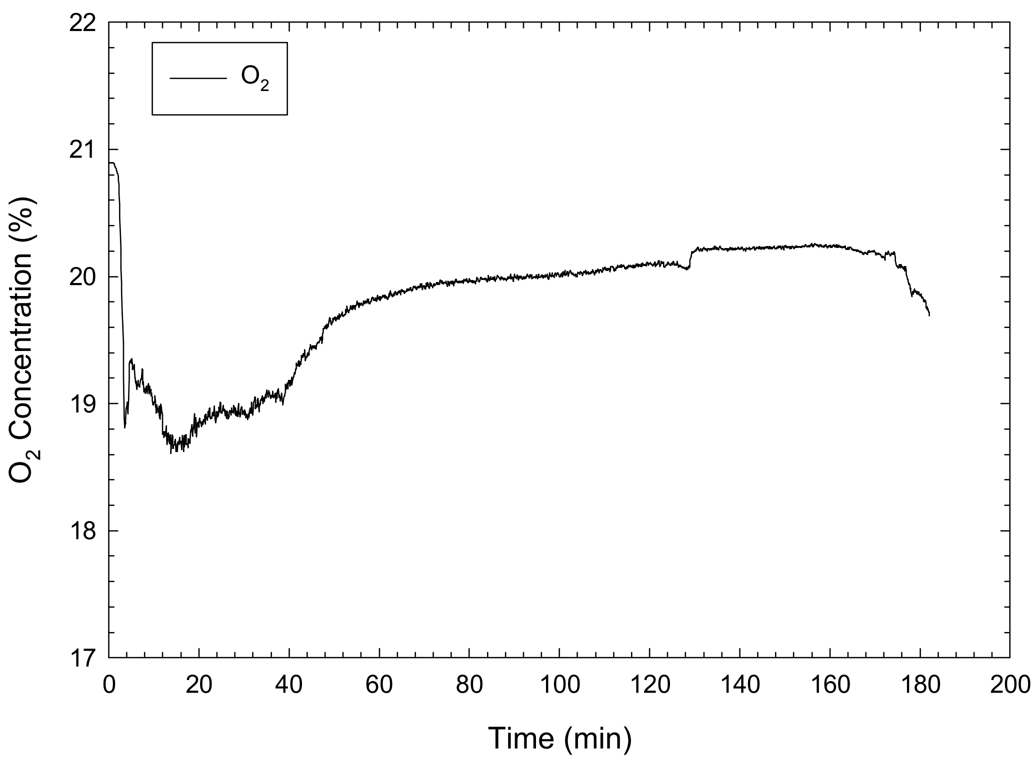


Figure 73. Oxygen concentration in the exhaust duct.

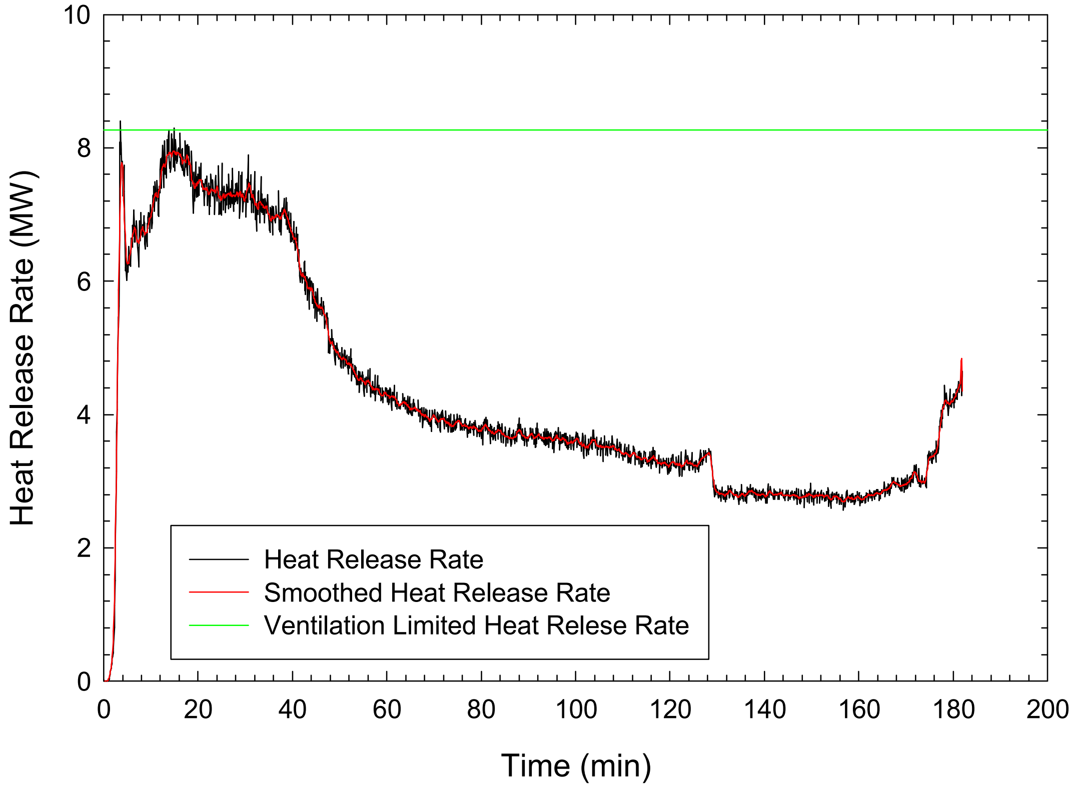


Figure 74. Heat release rate.

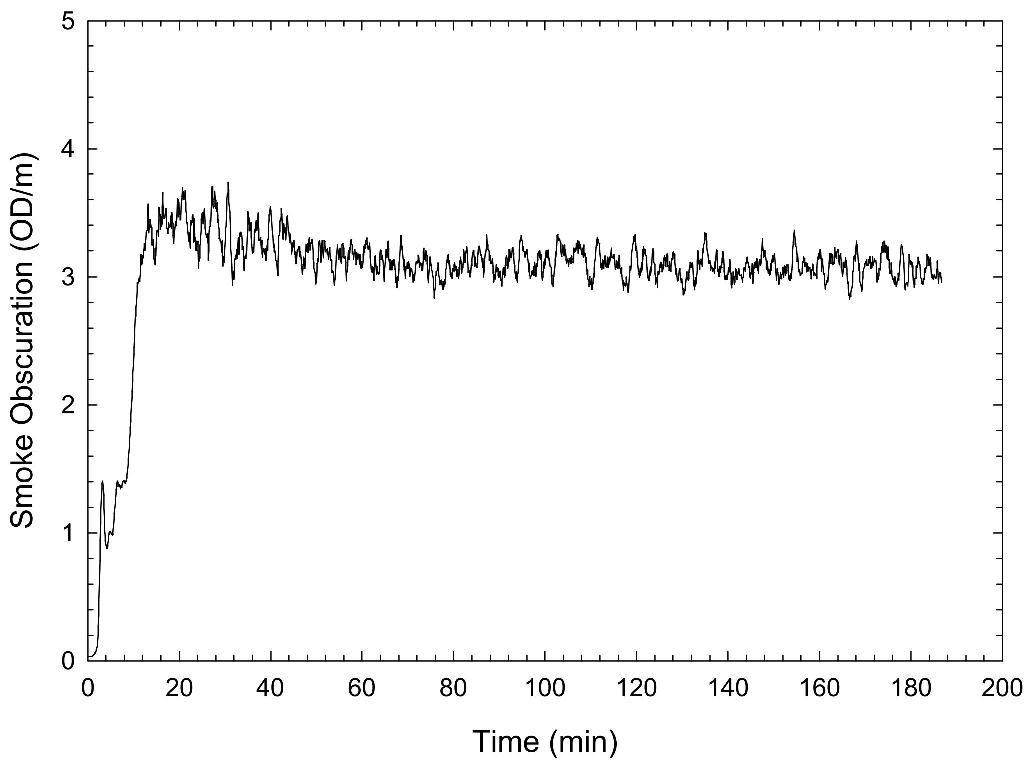


Figure 75. Smoke obscuration measured in exhaust duct.

12 DISCUSSION AND TIMELINE

Figure 76 shows the average and maximum temperatures measured at the four thermocouple tree locations in the bedroom. This includes: a) the average temperature measured near the ceiling (2.4 m height), b) the average temperature measured at the 1.4 and 2.4 m heights and c) the maximum temperature measured by the thermocouples on the thermocouple trees (0.4, 1.4 and 2.4 m heights). Also shown is the average temperature measured at the 2.4 m height in a bedroom test (PMF-03) conducted for a project to develop information to be used as a basis for establishing 'design fires' for multi-family residential buildings [10] and the standard time-temperature curve used in standard fire resistance tests [9]. Observations based on the plots shown in Figure 76 are:

1. The plots showing the average temperature near the ceiling and the average temperature in the upper layer (1.4 and 2.4 m heights) are comparable during the initial 50 min indicating that the temperatures were uniform with height in the upper portion of the bedroom. After 50 min, the two temperature plots are comparable; however, the average temperatures at the 2.4 m height are slightly higher indicating a hotter area below the ceiling.
2. The temperatures shown in the maximum temperature plots were consistently higher than the average temperatures during the initial 50 min indicating there were hot regions in the bedroom.
3. Between 65 and 130 min, the maximum temperature (yellow line in Figure 76) is higher than the average temperatures in the upper layer. This difference is due to the temperature measured by the thermocouple at the 0.4 m height in the North-West quarter of the bedroom. These high temperatures may indicate a malfunction of the thermocouple or an item burning near the thermocouple exposing it to direct flames. Without this thermocouple's data considered, the maximum and average temperatures are comparable between 65 and 130 min (green line in Figure 76. The average temperatures are lower than the maximum temperature after the entryway door fell in at 128 min.
4. The fuel load used in Test PMF-03 was similar to that used in the CLT apartment. However, there were some variations in the average temperature profiles :
    a. Higher temperatures were measured in the CLT apartment fire test between 5 and 15 min. During this time, the door between the bedroom and the living room was destroyed by the fire and the fire in the living room developed. Prior to the full development of the fire in the living room, additional ventilation may have been provided to the fire in the bedroom. Also, the temperatures in a fire compartment are dependent on the heat losses to the room boundaries [17]. The temperature differences may indicate that there was less heat loss to the wall and floor assemblies in the CLT apartment than in the PMF-03 test with noncombustible wall and ceiling assemblies.
    b. At approximately 23 min, the temperatures in the apartment bedroom began to decrease, whereas the decrease in temperatures in PMF-03 began at approximately 30 min. The fire loads were similar in the two test setups except that a combustible subfloor in PMF-03 (15.5 mm thick (nominal 5/8") OSB) was not protected by cement board, providing additional fuel load for the fire. The exact time at which the partition wall between the bedroom and the bathroom/entryway failed is not known. However, indications are that the fire entered the stud cavity between 14 and 17 min. There was a decrease in the temperatures in the stud cavity between 22 and 23 min, which may indicate the

gypsum board on the bathroom/entryway side of the wall was falling off and allowing the high temperature air in the bedroom to escape.

   c. After 30 min, the temperatures measured in PMF-03 decreased until the end of the test. In the CLT apartment test, after reaching a peak and then beginning to decrease at 23 minutes, the temperatures in the bedroom stayed steady between 27 and 40 min. After 40 min, the temperatures decreased steadily until 128 min. Between 40 and 60 min, the rate of temperature decrease in the CLT apartment was similar to but slightly slower than in Test PMF-03. This suggests that, after 40 min, the temperatures decreased as the fire decayed due to consumption of the combustibles in the apartment area.

5. The standard time-temperature curve used in fire resistance tests is also shown in Figure 76. During the initial 48 min, the temperatures measured in the apartment were higher than the standard time-temperature curve. As a result, the fire involving the room contents produced a more severe exposure to the room boundaries than is used for standard fire-resistance testing. After 48 min, the temperatures in the room continuously decreased until near the end of the test, when there were flames observed on some of the CLT ceiling. The fire severity in the CLT apartment test was less than the standard time-temperature curve during the later stages of the test (> 48 min).

Table 9 shows the times at which the main fire events occurred in the bedroom. The main fire events were as follows:

1. The fire developed rapidly with flashover at approximately 3.0 min
2. Highest temperatures were experienced between 6 and 23 min
3. Peak radiant heat flux through the opening remained high and highest heat fluxes were measured above the exterior wall opening between 15 and 23 min
4. After 23 min, there was a general decrease in temperature until approximately 28 min
5. At 28 min, there was a temperature plateau, with temperatures > 1000°C that lasted until 40 min.
6. After 40 min, the temperatures decreased until near the end of the test.

Figure 77 shows the maximum and average temperatures measured in the living room/kitchen area. Also shown is the standard time-temperature curve used in standard fire resistance tests [9]. Observations based on the plots shown in Figure 77 are:

1. The plots showing the average temperature near the ceiling and the average temperature in the upper layer (1.4 and 2.4 m heights) are comparable indicating that the temperatures were uniform with height in the upper portion of living room/kitchen.
2. The temperatures shown in the maximum temperature plots were significantly higher than the average temperatures until 40 min indicating there were hot regions in the living room and kitchen area. The fire in the living room and kitchen did not develop uniformly throughout the entire area. This is illustrated by the plots of the average upper layer temperature (1.4 and 2.4 m heights) at each thermocouple tree location shown in Figure 78. There was a faster development of the fire in the North end of the living room. The area with the peak temperature subsequently progressed to the center of the living room, the kitchen and finally the entryway.
3. The temperatures, based on averages over the living room and kitchen areas, are higher than the standard time-temperature curve until 52 min (Figure 77). However, the temperatures averaged over the entire area may not give the best indication of the fire severity and its impact on the room boundaries. As shown in Figure 78, the average temperature at the North end of the living room was higher than the standard time-

temperature between 6 and 50 min. However, the temperatures in the entryway only exceeded the standard time-temperature curve for a short period between 30 and 52 min.

Table 10 shows the times at which the main fire events occurred in the living room and kitchen. The main fire events were as follows:

1. Initial temperature increases were observed in the living room area between 2 and 3 min.
2. Between 4 and 5 min, the temperatures in the living room were > 600°C indicating flashover in this area.
3. Temperatures varied depending on location in the kitchen/living room area, with maximum temperature occurring at the North end of the living room at 29 - 30 min and in entryway at 39 min.
4. Radiant flux through the opening remained high between 10 and 50 min.
5. Peak heat flux to the façade above the living room opening was at 16 min and high heat fluxes were sustained until 30 min.
6. After 45 min, the temperatures decreased until near the end of the test.

A primary objective of the simulated apartment fire test was to investigate the protection (encapsulation time) provided for the structural elements by the gypsum board and cement board. The measured encapsulation times for the encapsulation systems are summarized in Table 11. Some general comments based on the results are:

1. A single layer of 12.7 mm thick gypsum board (regular or Type X) provided limited protection (<16 min).
2. The encapsulation time for the two layers of gypsum board varied depending on location in the apartment (27.8 - 47.6 min).
3. Extended encapsulation times were determined using the temperature measurements in the wall stud spaces formed by the 2 x2 strapping (> 57 min). This suggests that the initial effects of the fire will be at the interface between the base layer of gypsum board and the strapping. Longer times are required before the temperatures in the cavities will affect the structural elements. These results suggest that encapsulation systems with the encapsulation layer separated from the structural element should be investigated as a method of improving encapsulation times.
4. The combination of the hardwood flooring and the two layers of cement board provided 33 min encapsulation time for the bedroom floor ceiling assembly. Note: this is shorter than the encapsulation time determined for the same system in the LWF apartment test [3]. The reason for the difference is not known but needs to be investigated.

Table 9. Summary of fire events regarding the bedroom.

Time (min)	Description
0	Bed ignited using propane burner
0.3	Smoke alarm responded at 19 s
4	Flashover in bedroom
4	Short duration high heat flux to façade above exterior wall opening
6 - 23	Sustained high temperatures
15 - 23	Peak in heat flux to façade above exterior wall opening and in radiant flux from opening.
18	Fall-off of face layer of gypsum board on ceiling at center of room.
23 - 28	Decreasing temperatures – failure of partition into the bathroom.
28 - 40	Temperature plateau – temperature > 1000°C.
> 40	Decreasing temperatures
128	Decrease in temperatures – corridor entryway door failed.
170	Increasing temperature – flames observed on some of the CLT ceiling.
180	Test stopped.

Table 10. Summary of fire events regarding living room and kitchen area.

Time (min)	Description
2 - 3	Initial temperature increase at ceiling
4 - 5	Temperature living room areas > 600°C indicating flashover
10 - 50	High heat flux through exterior wall opening
16	Peak heat flux to façade above exterior wall opening
29 - 30	Maximum temperature in living room.
34	Maximum temperature in kitchen.
39	Maximum temperature in entryway
> 45	Decrease in temperature at all heights and locations.
128	Decrease in temperatures – corridor entryway door failed.
170	Increasing temperature – flames observed on some of the CLT ceiling.
180	Test stopped.

Table 11. Summary of encapsulation times.

Time (min)	Encapsulation/Location
13	Single layer 12.7 mm thick regular gypsum board based on temperatures measured in the stud cavity of the partition between the bedroom and bathroom.
15	Single layer 12.7 mm thick Type X gypsum board, center bedroom ceiling.
16	Single layer 12.7 mm thick Type X gypsum board, west bedroom wall.
20	Hardwood flooring and a single layer of cement board, center bedroom floor .
28	Two layers of 12.7 mm thick Type X gypsum board, center bedroom ceiling.
33.0	Hardwood flooring and two layers of 12.7 mm thick cement board, center bedroom floor..
33	Two layers of 12.7 mm thick Type X gypsum board, west bedroom wall, based on temperature measured between gypsum board and 41 mm x 41 mm (2 in. x 2 in.) wood strapping.
36	Two layers of 12.7 mm thick Type X gypsum board, interior loadbearing wall, bedroom side of wall.
38	Two layers of 12.7 mm thick Type X gypsum board, exterior wall, bedroom side of wall.
45.0	Two layers of 12.7 mm thick Type X gypsum board, bedroom ceiling, based on temperatures measured by nine thermocouples between base layer of gypsum board and CLT panels.
48	Two layers of 12.7 mm thick Type X gypsum board, living room/kitchen ceiling, based on temperatures measured by nine thermocouples between base layer of gypsum board and CLT panels.
>57	Two layers of 12.7 mm thick Type X gypsum board, west bedroom wall, based on temperatures measured by the nine thermocouples in wall cavities formed by 41 mm x 41 mm (2 in. x 2 in.) wood strapping.

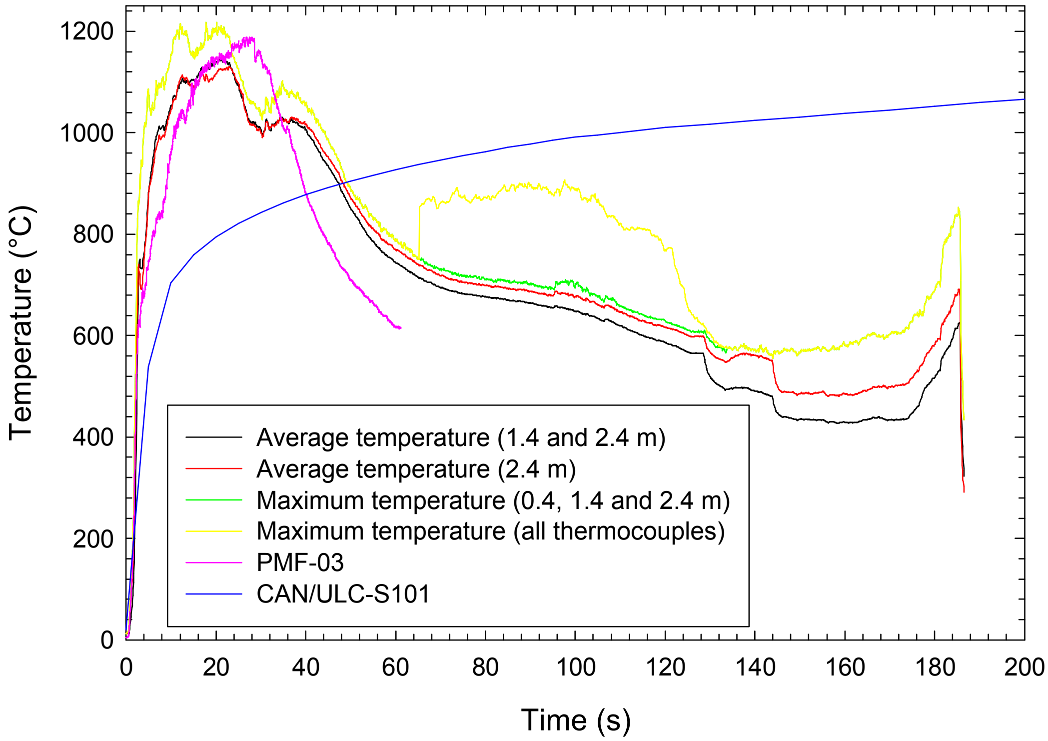


Figure 76. Maximum and average temperatures in bedroom.

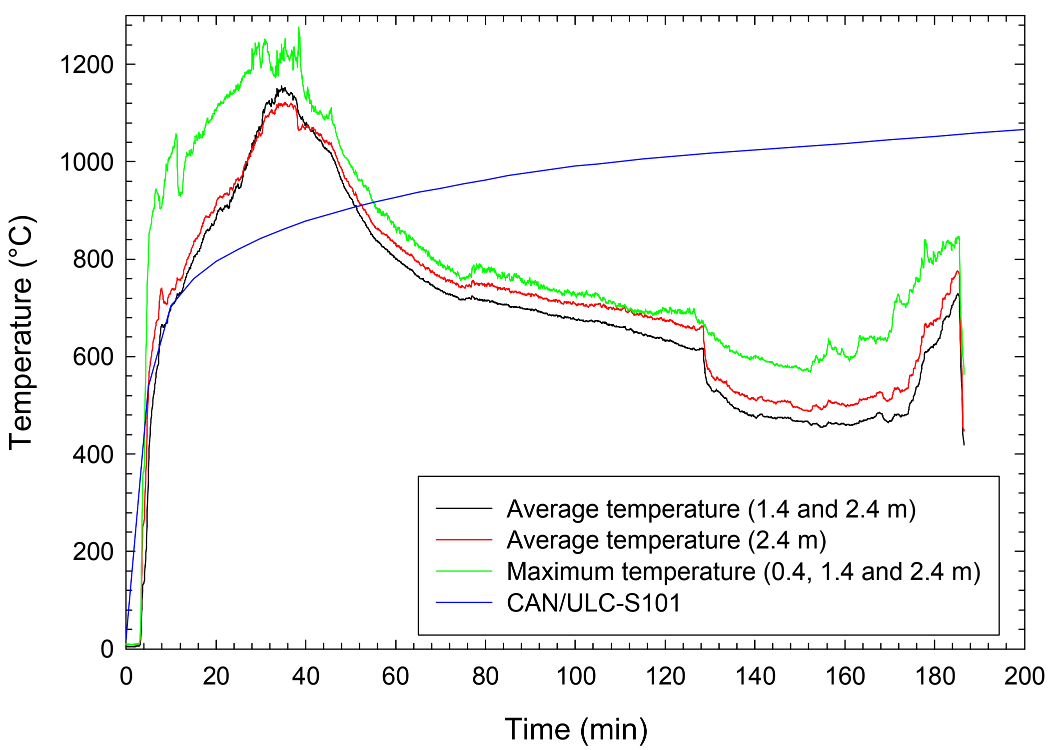


Figure 77. Maximum and average temperatures in living room/kitchen.

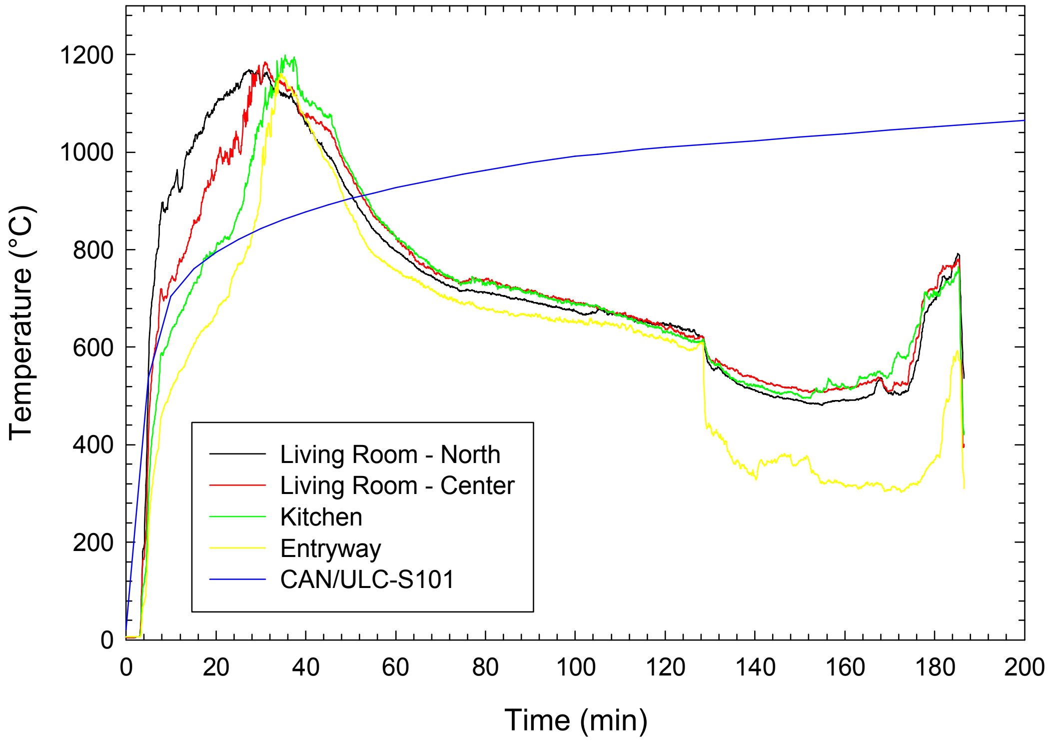


Figure 78. Average temperatures at thermocouple trees in living room/kitchen (1.4 and 2.4 m heights).

13 SUMMARY

A project, Wood and Wood-Hybrid Midrise Buildings, was undertaken to develop information to be used as the basis for alternative and acceptable solutions for mid-rise and taller building construction using wood structural elements. As part of this project, large-scale fire experiments were conducted to evaluate the fire performance of two encapsulated combustible wood systems; a lightweight wood-frame (LWF) system and a cross-laminated timber (CLT) system. A third full-scale fire test was conducted using a lightweight steel-frame structural system. Each experiment involved construction of a test set-up consisting of an apartment unit, representing a portion of a mid-rise (e.g. six-storey) building. This report provides the results of the fire test with an encapsulated CLT test apartment.

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16 APPENDIX A – DRAWINGS FOR CLT STRUCTURAL ASSEMBLY

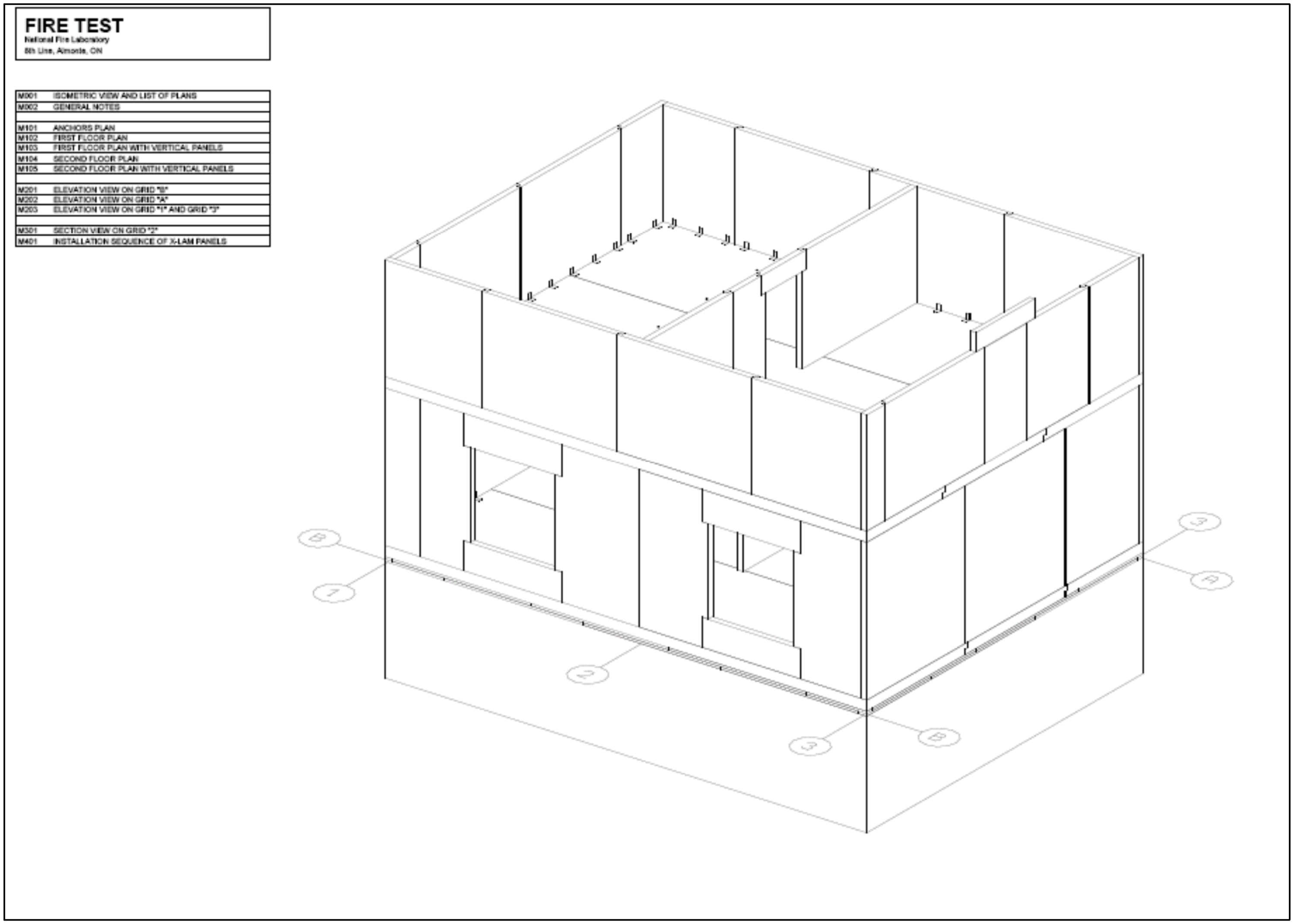

Figure A-1. Isometric view of CLT structural assembly.

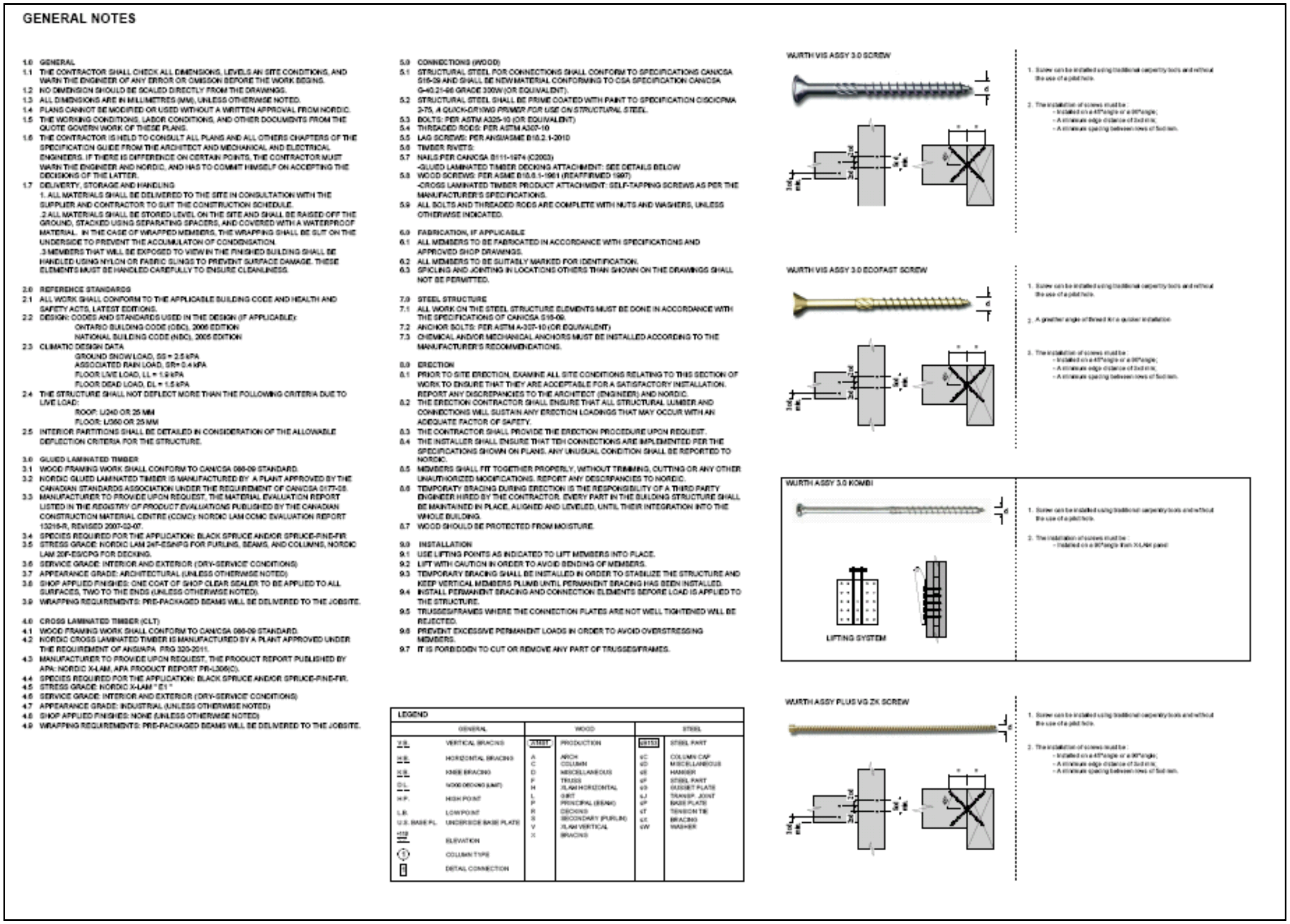

Figure A-2. General notes for CLT structural assembly.

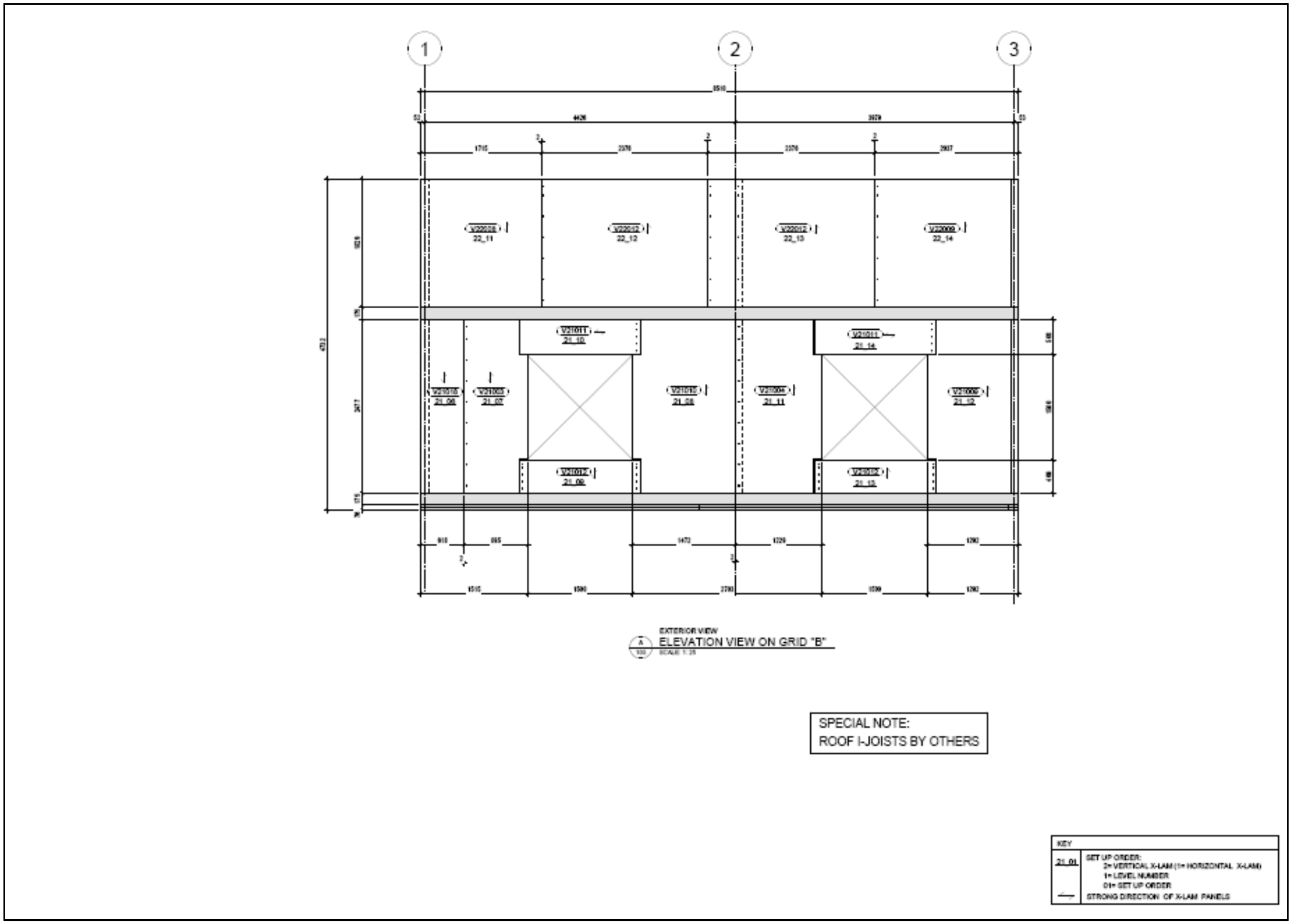

Figure A-3. Elevation view on Grid “B” for CLT structural assembly.

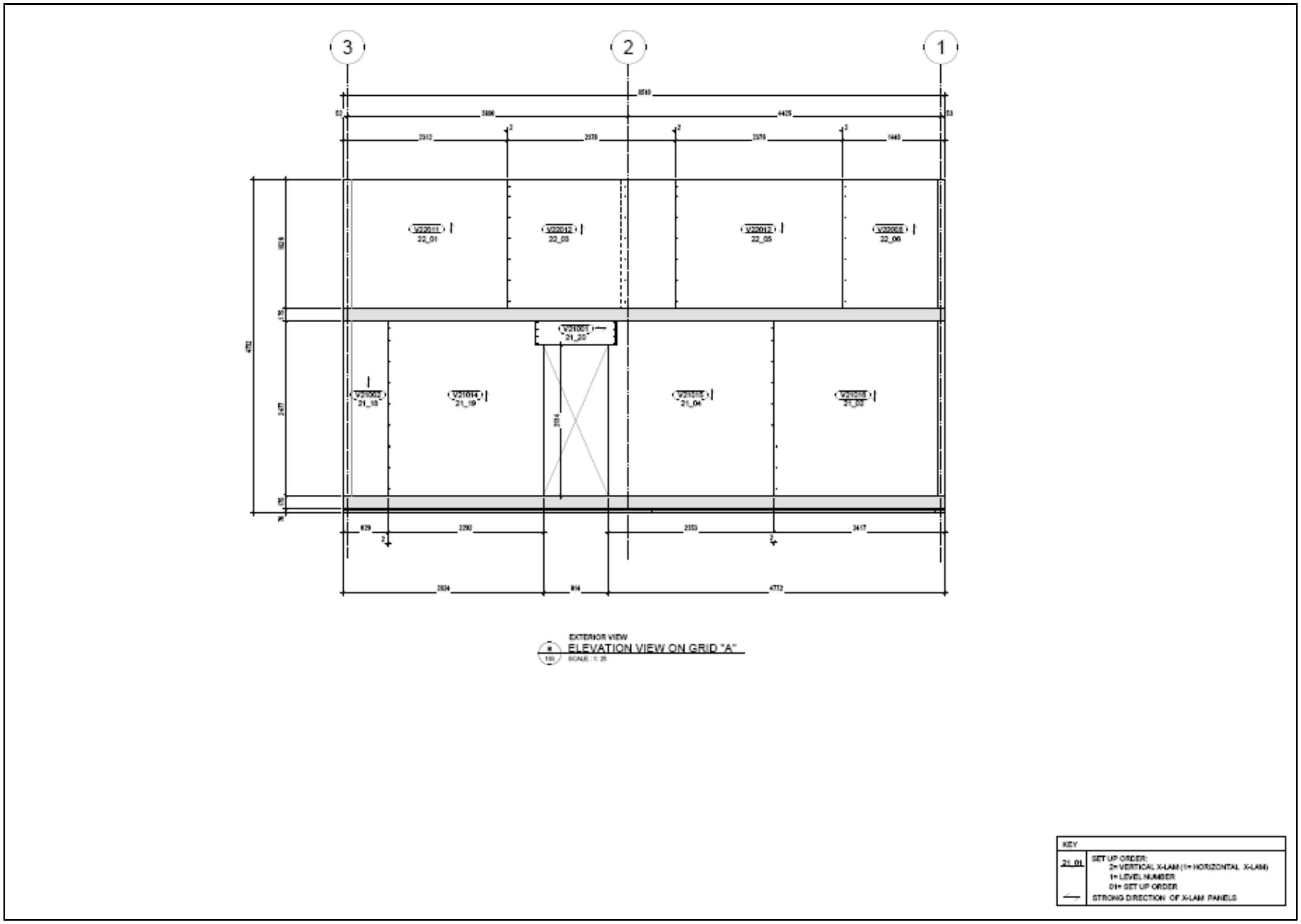

Figure A-4. Elevation view on Grid “A” for CLT structural assembly.

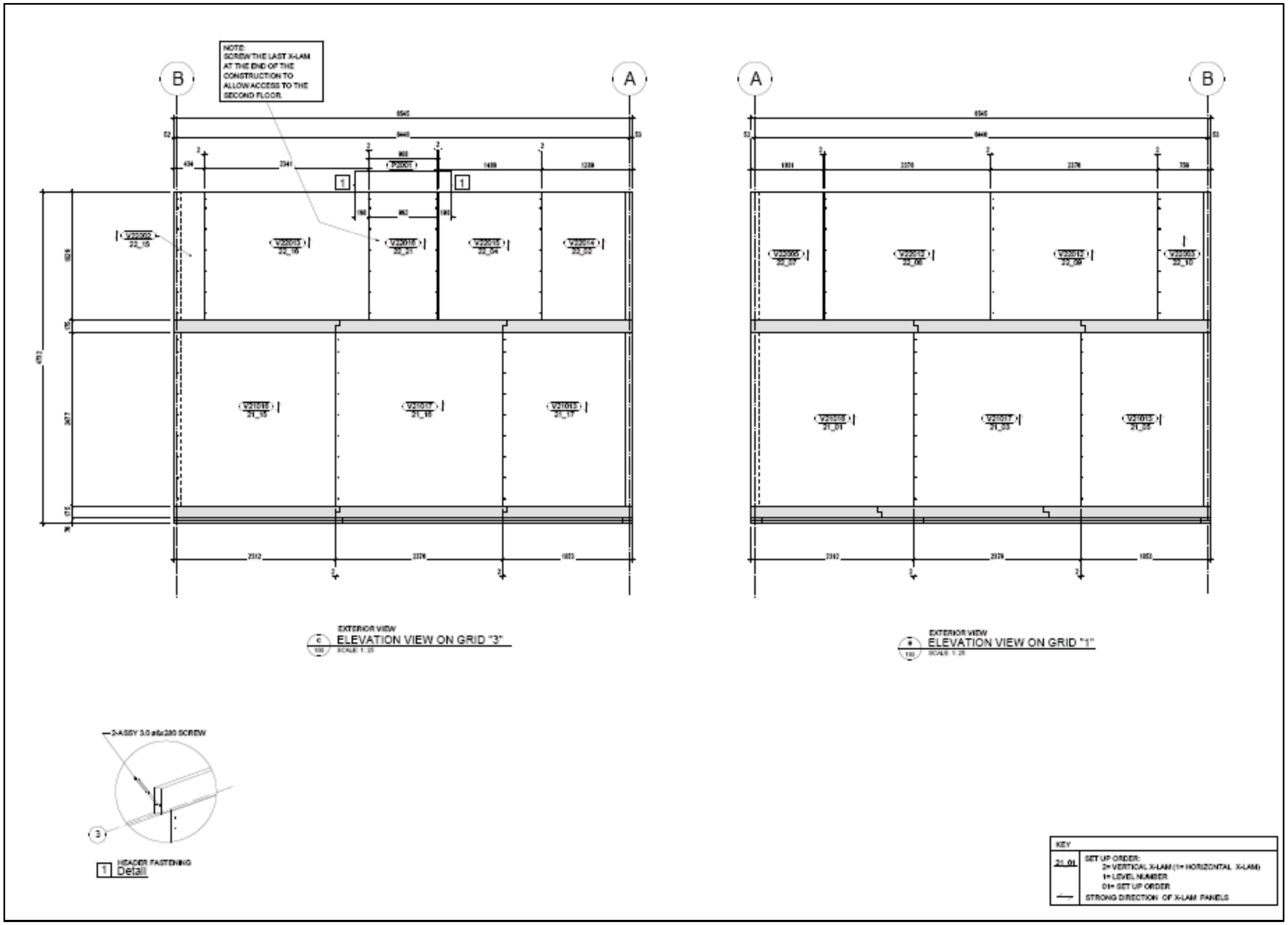

Figure A-5. Elevation views on Grid “1” and “3” for CLT structural assembly.

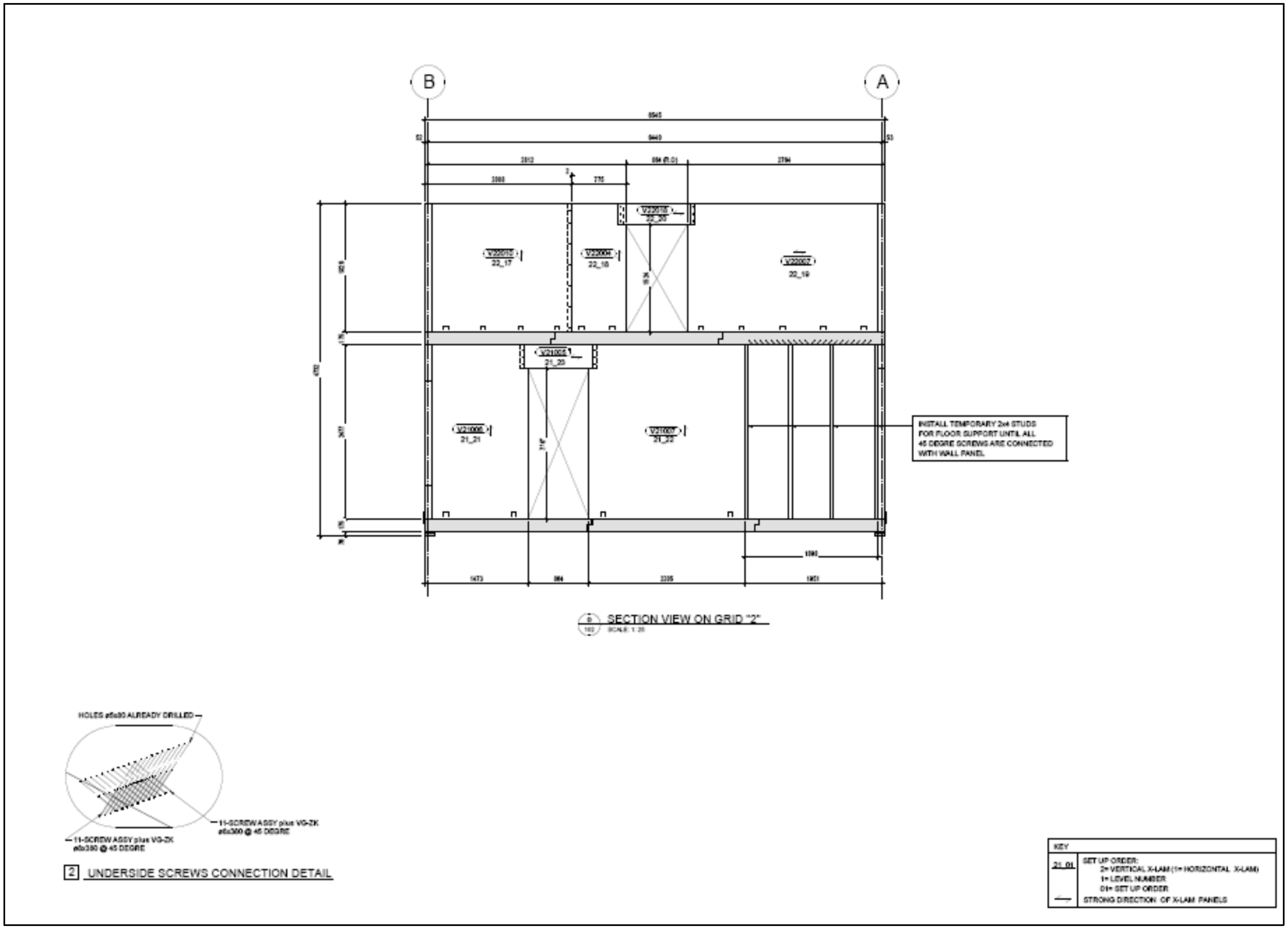

Figure A-6. Section view on Grid “2” for CLT structural assembly.

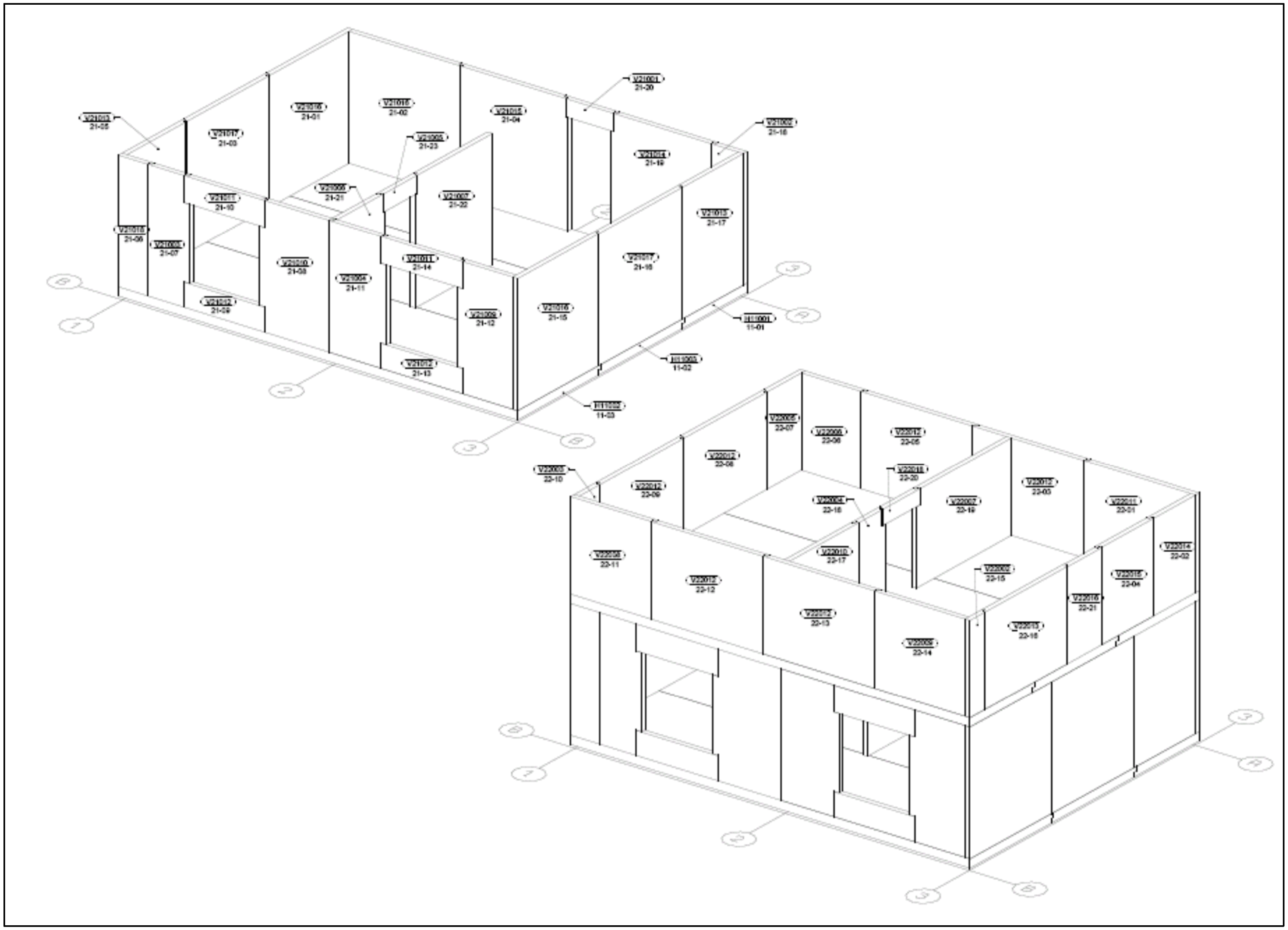

Figure A-7. Installation sequence for wall panels for CLT structural assembly.