Solutions for mid-rise wood construction: second apartment fire test with encapsulated lightweight wood frame construction: report to Research Consortium for Wood and Wood-Hybrid Mid-Rise Buildings

Lougheed, G.D.; Su, J.Z.

Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/21274557
Client Report (National Research Council of Canada. Construction), 2014-12

NATIONAL RESEARCH COUNCIL CANADA

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

Solutions for Mid-Rise Wood Construction: Second Apartment Fire Test with Encapsulated Lightweight Wood Frame Construction

CLIENT REPORT: A1-004620.1

December 31, 2014

National Research Council Canada   Conseil national de recherches Canada

Canada

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

Solutions for Mid-Rise Wood Construction: Second Apartment Fire Test with Encapsulated Lightweight Wood Frame Construction

G.D. Lougheed and J.Z. Su

Report No. A1-004620.1
Report date: December 31, 2014
Contract No. A1-004620
Prepared for Canadian Wood Council

85 pages

NRC·CNRC

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ALTERNATIVE SOLUTION FOR MID-RISE WOOD CONSTRUCTION: SECOND APARTMENT FIRE TEST WITH ENCAPSULATED LIGHTWEIGHT WOOD FRAME CONSTRUCTION

G.D. Lougheed and J.Z. Su

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]) and a cross-laminated timber (CLT) system (1 experiment [4]). 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.

The intent was to provide the opportunity for comparison of the fire performance of the encapsulated LWF and CLT systems to that of the LSF system. However, after the initial 15 min, there were differences in the fire conditions within the apartment in the test of the LSF system that made this comparison difficult. The main factors that contributed to the differences were:

1. The calcination of the single layer of 12.7 mm thick Type X gypsum board used on the apartment ceiling at approximately 15 min and its fall-off at approximately 20 min. This resulted in heat losses to the steel joists, steel pan and concrete slab and a reduction in temperatures within the apartment. However, sustained temperatures > 600°C and in some areas > 800°C were measured in the joist cavity space and on the steel joists for up to 15 min depending on location.
2. At approximately 20 min, the gypsum sheathing on the exterior wall started to fall-off. This allowed more ventilation air to enter the apartment resulting in a more extensive fire throughout the apartment. While this increased the heat fluxes measured at various

locations exterior to the fire area, it also resulted in a more rapid burn out of the fuel especially in the living room and kitchen area and an earlier onset of fire decay, at approximately 26 min.

The overall effect of these two changes to the fire dynamics within the apartment was to reduce both the temperature and duration of the interior fire exposure to the wall and floor assemblies.

As a result of these differences, it was decided to conduct a second test of a full-scale, unsprinklered apartment using LWF assemblies. The second test arrangement was similar to the first LWF apartment test; the one significant difference was to alter the construction of the exterior wall for the apartment so that it was more similar to the exterior wall assembly used in the LSF apartment test. Once again, the intent was to try to provide an opportunity for comparison of the fire performance of an LWF system to that of the LSF system.

In all three of the original test apartment designs (first LWF, LSF and CLT), the exterior wall assembly with the openings did not support an assembly that was required to have a fire-resistance rating. As a result, it was not required to be designed to have a 1-h fire-resistance rating. However, in the first LWF test, the interior side of the wood studs in the exterior wall was protected using two layers of 12.7 mm thick Type X gypsum board, to encapsulate the wood members, even though they were not supporting the floor-ceiling assembly of the storey above. For the second LWF test, the interior side of the studs was sheathed with a single layer of 12.7 mm thick regular gypsum board, as was done in the code-conforming noncombustible LSF test arrangement.

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

2 GENERAL TEST ARRANGEMENT

The previous 3 tests were conducted using a three-storey test setup [3, 4, 5}. However, in those tests, the fire had limited effect on the highest (third) storey. For this reason, and because of the very tight time schedule, it was decided to eliminate the highest (third) storey from the test setup of the second LWF apartment test. However, the weight of third (highest) storey wall and ceiling assemblies was simulated using concrete blocks, in addition to the simulated weight of third-storey furnishings.

As a result, a test setup was constructed to represent a two-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 2 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 second storey 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 the upper storey.

The design for the test structure was developed by the project partners. The general design was similar to 5- or 6-storey mid-rise residential buildings that are currently being built in the province of British Columbia. In the design, an emphasis was placed on maximizing the fuel load provided by the lightweight wood frame structural elements. For example, a close spacing of the wood studs was used (versus the typical 406 mm O.C. spacing) to simulate walls located in the lower (first or second) storeys of a 5- or 6-storey mid-rise residential buildings with large structural loads All the materials used in the construction of the test structure were purchased from local suppliers.

The second storey of the test structure simulated a one-bedroom apartment unit with encapsulated lightweight wood frame structural elements used to construct the walls and floor/ceiling assemblies. One wall (north) simulated a typical 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. The bedroom is separated from the living room by a wood stud loadbearing 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 public 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.

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.

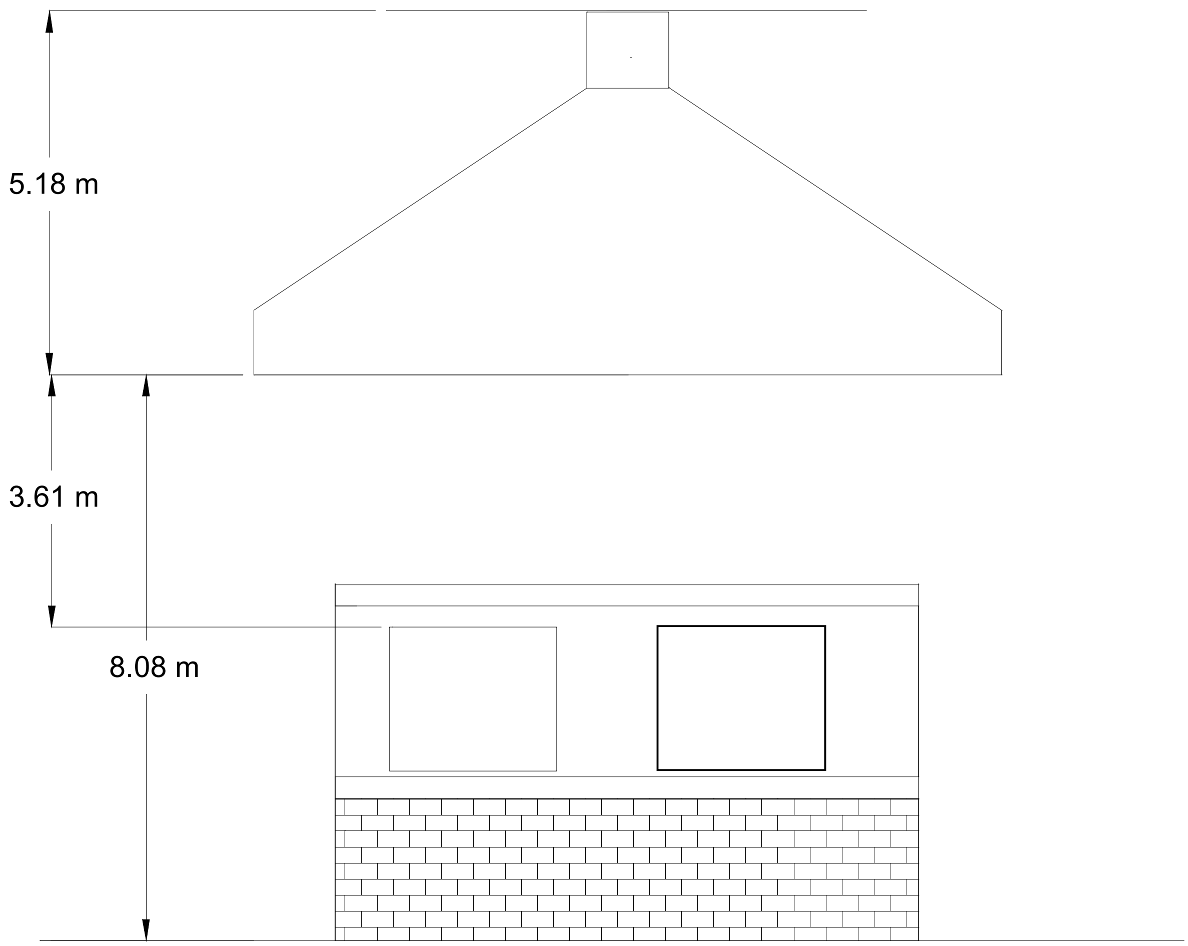


Figure 2. Test setup two-storey elevation.

3 STRUCTURAL ASSEMBLIES (HIGHEST STOREY)

3.1 Wall Assemblies

All the lightweight wood frame (LWF) wall assemblies were loadbearing and were provided with a wood shear panel (oriented strandboard - OSB) installed on one side of the framing, except for the non-loadbearing partitions enclosing the closets and bathroom and the exterior wall. All the walls and partitions were constructed using wood stud framing using dimensional lumber that is sized either 38 mm x 89 mm or 38 mm x 141 mm. However, the spacing and/or arrangement of the wood stud framing differed, depending on the type of wall.

Three types of walls assemblies were used in the LWF 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 shear 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 1-h 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 1-h fire-resistance rating (Figure 4). This wall type was also used as the loadbearing wall with a 1-h fire rating that separated the bedroom and living room.

The Type A walls were constructed using 38 mm x 89 mm wood studs spaced at 152 mm O.C. The stud cavities were filled with glass fibre batt insulation.

The close spacing of the wood studs was used (versus the typical 406 mm O.C. spacing) to simulate walls located in the lower (first or second) storeys of a 5- or 6-storey mid-rise residential buildings with large structural loads, which is similar to some buildings that are now currently being built in the province of British Columbia. This increased use of stud framing maximized the potential fire load provided by the structural elements. Closely spaced single studs were used for the walls rather than a system with built up studs to maximize the stud area exposed to the fire if it penetrated the encapsulation material.

A 1.2 m by 2.4 m x 15.5 mm thick (nominal 5/8") OSB shear panel was mounted on one side of the wall. The shear panels were mounted vertically and covered the wood stud framing, from the bottom plate to the top plate, with a 2 mm gap provided between the adjoining panels.

The OSB shear panels were mounted on the exterior (outer) side of the Type A walls forming the perimeter of the test structure and were also mounted on the living room side of the loadbearing wall that separated the bedroom and living room/kitchen area. The location of the shear panel (on the non-fire side) was selected to minimize the potential time for the fire to penetrate to the primary structural elements (studs) and thereby maximized the potential contribution of the combustible structural elements to the fire.

Fasteners used to attach the OSB shear panels to the studs were 10D common nails with a 3.76 mm diameter and 76 mm long smooth shank. The nails were spaced at 150 mm at the panel edges and at 300 mm along intermediate framing members, with nails on every second stud (305 mm spacing).

Two layers of 12.7 mm thick Type X gypsum board, oriented vertically, were attached on both sides of the wood stud wall.

On the side without the shear panel (the fire side), the base layer of gypsum board was directly fastened to the wood studs along its edges and in the field along the intermediate framing members, using 41 mm long Type S screws spaced at 600 mm O.C. 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 studs along its edges and in the field along the intermediate framing members, using 50 mm long Type S screws spaced at 300 mm O.C. Fasteners in both the face layer and the base layer were used on every second stud (305 mm spacing).

On the side with the shear panel, the base layer of gypsum board was attached over the OSB shear panel with the joints between the panels staggered from those in the OSB. The base layer of gypsum board was fastened to the wood studs along its edges and in the field along the intermediate framing members using 50 mm long Type S screws spaced at 600 mm. The face layer of gypsum board was attached over the base layer of gypsum board and OSB shear panel with the joints between the face layer gypsum board panels staggered from those in the base layer gypsum board. The face layer was fastened to the wood studs along its edges and in the field along the intermediate framing members using 62 mm long Type S screws spaced at

300 mm. Fasteners in both the face layer and the base layer was used on every second stud (305 mm spacing).

3.1.2 Wall Type B

Wall Type B simulated an exterior wall and was located on the north side of the test apartment (Figure 4). The wall was constructed using 2 x 6 staggered studs on 2 x 8 plates. The studs were spaced at 152 mm O.C. on opposite sides (305 mm O.C. on the same side). The stud cavities were filled with glass fibre batt insulation. The glass fibre batts were cut to fit the space between the studs.

Like the Type A walls, the close spacing of the wood studs in this Type B wall was used (versus the typical 406 mm O.C. spacing) to simulate exterior walls located in the lower (first or second) storeys of a 5- or 6-storey mid-rise residential building with large structural loads, which is similar to some buildings that are now currently being built in the province of British Columbia. This was done even though the exterior wall system in the present design of the test structure was non-loadbearing. This increased use of stud framing maximized the potential fire load provided by the framing elements. Closely spaced staggered rows of single studs were used for the walls, rather than a system with more widely-spaced single row of built up studs to maximize the stud area exposed to the fire should it penetrate the encapsulation materials.

In the first LWF test [3], two layers of 12.7 mm thick Type X gypsum board were directly attached to the studs on the interior side of the wall. As discussed above, however, the construction of the exterior wall assembly in the second LWF test was altered so that it was more similar to the exterior wall assembly used in the noncombustible LSF apartment test [5]. Therefore, a single layer of 12.7 mm regular gypsum board was directly attached to the wood studs on the interior side – the same as was used for the interior side of the exterior wall in the noncombustible test assembly.

A layer of vapour barrier was used underneath the regular gypsum board on the interior side. The gypsum board was directly fastened to the studs using 41 mm long Type S screws spaced at 300 mm O.C.

A single layer of 12.7 mm thick regular gypsum sheathing, oriented vertically, was directly fastened to the exterior side of the wood stud wall. The gypsum sheathing was attached to the wood studs along its edges and in the field along each framing member using 32 mm long coarse thread drywall screws spaced at 200 mm O.C. 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 LWF exterior walls using the standard CAN/ULC-S134 fire test method [6]. Those tests showed that the regular gypsum sheathing was sufficient to limit upward exterior flame spread when used as part of the exterior cladding system on the exterior wall for lightweight wood frame assemblies [7]. A non-combustible cladding was not used over the gypsum sheathing in the S-134 test.

An OSB shear panel was not included in the exterior wall. The reasons for not including OSB shear panels in the exterior wall 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 test, there was the possibility of the external flames extending from the opening penetrating back through the exterior gypsum sheathing and eventually involving the OSB panels and wood stud framing elements, 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. Any OSB sheathing, if it were used, would likely be installed on the exterior side of the exterior wall (to the outside of the structural elements). In that configuration, its inclusion (or not) is not expected to impact the test data with respect to the ability of the internal encapsulation of the wood stud walls to protect the studs from a fire originating inside the apartment.
3. Compared to the fuel load contained within the apartment, the inclusion of OSB under the gypsum sheathing on the exterior side of the exterior wall assembly could be considered a relatively small contribution to the total fuel load if present, and thus is not likely to cause significant effect in its absence.

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.

3.2 Floor/ceiling Assemblies

The two floor-ceiling assemblies within the test structure were constructed using 241 mm deep wood I-joists that were spaced at 406 mm O.C. Figure 5 shows the joist layout for the floor/ceiling assembly on the lowest and highest storeys. The I-joists ran in the east-west direction between the bounding (outer) walls that simulated fire separations between suites and the interior loadbearing wall separating the bedroom and the living room/kitchen. In the ceiling/floor assembly between the highest storey and the top of the test structure, a LVL beam was used to support the I-joists in the section between the south end of the interior loadbearing wall and the corridor wall.

For the ceiling/floor assembly between the lowest and highest storey, the east end of each joist were supported by the concrete block structure. Metal beams running in the north-south direction were located between the concrete block walls 4.5 m from the east end of the test arrangement and also at its west end. These beams were used to support the ends of the I-joists near the center of the assembly and at the west end, respectively.

The I-joist span was approximately 4.5 m in the living room and kitchen. It was approximately 4 m in the bedroom and the bathroom/entryway.

For both of the floor/ceiling assemblies, two layers of 12.7 mm thick Type X gypsum board were attached to the wood I-joists using resilient metal channels (RMCs). The RMCs, which ran perpendicular to the wood I-joists, were attached to the bottom flange of the wood I-joists and spaced at 406 mm O.C. The channels were fastened to each joist using 32 mm long Type S screws.

The two layers of gypsum board were attached to the RMCs with the long side (edge) of the panel perpendicular to the resilient channels. The base layer of gypsum board was fastened to the RMCs along its edges and in the field using 25 mm long Type S screws, with the screws at the panel ends and in the field spaced at 600 mm O.C. along the RMCs. 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 is fastened to the RMCs along its edges and in the field using 50 mm long Type S screws, with the screws at the panel ends and in the field spaced at 300 mm O.C. along the RMCs.

For the ceiling/floor assembly between the lowest and highest storey, the subfloor was 15.5 mm thick (nominal 5/8") OSB. Two layers of 12.7 mm thick cement board were located on the top of the subfloor with limited fastening. The 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 face layer of cement board 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 OSB subfloor and the cement board as well as between the cement board and the hardwood floor. The acoustic membranes used in the test assembly are identified as AI-5 and AI-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 insulations tested.

Glass fibre batt insulation with a thickness of 152 mm was placed in the I-joist cavities, resting on the RMCs. The insulation was included in the floor assembly in conjunction with the Code requirements that the floors meet acoustic requirements (STC 50).

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

4 LOWEST STOREY

The lowest storey of the test assembly consisted of 2.0 m high concrete block walls. These walls were used to raise the test assembly off the floor of the NRC research facility. This allowed access to the ceiling (underside) of the ceiling/floor assembly between the lowest and highest storey 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 left open to allow access to the area beneath the test assembly.

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 joists in the ceiling/floor assembly between the first and second storey. 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 wood structural elements to be fastened to the top course in the concrete block walls.

As noted above the ceiling in the lowest storey was two layers of 12.7 mm thick Type X gypsum board, which was attached to RMCs fastened to bottom flange of the floor joists. The joints were not taped.

5 THIRD STOREY

As noted previously, a third storey was not included in the test setup of the second LWF apartment test.

6 STRUCTURAL LOAD

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 LWF wall assemblies used in the test structure, with the level of encapsulation used, would be expected to demonstrate a fire endurance period in the standard (CAN/ULC-S101) fire test of more than 1 h. The LWF floor assembly, with the level of encapsulation used would be expected to have a fire endurance period of more than 1 h.

For this simulated apartment fire test, the floor assembly of the second storey (fire floor) was subjected to a superimposed live load arising from the presence of actual (typical) furnishings, fixtures and other contents.

The third storey was not included in the test setup for the second LWF apartment test; however, the weight of the structural assemblies that were present in the highest storey of the first LWF apartment test [3] was simulated using concrete blocks on the top of the test structure. Additional concrete blocks were added on the top of the test structure to simulate live loads that were the same weight as the furniture and contents on the highest storey and also simulated larger items, such as the bed, in point loading, so that the live loads on the ceiling assembly of the highest storey were the same as in the first LWF test. As a result, the ceiling and wall assemblies of the fire floor of the apartment structure in this test were subjected to a similar total load level as the ceiling and wall assemblies in the middle storey (fire floor) of the first LWF apartment test.

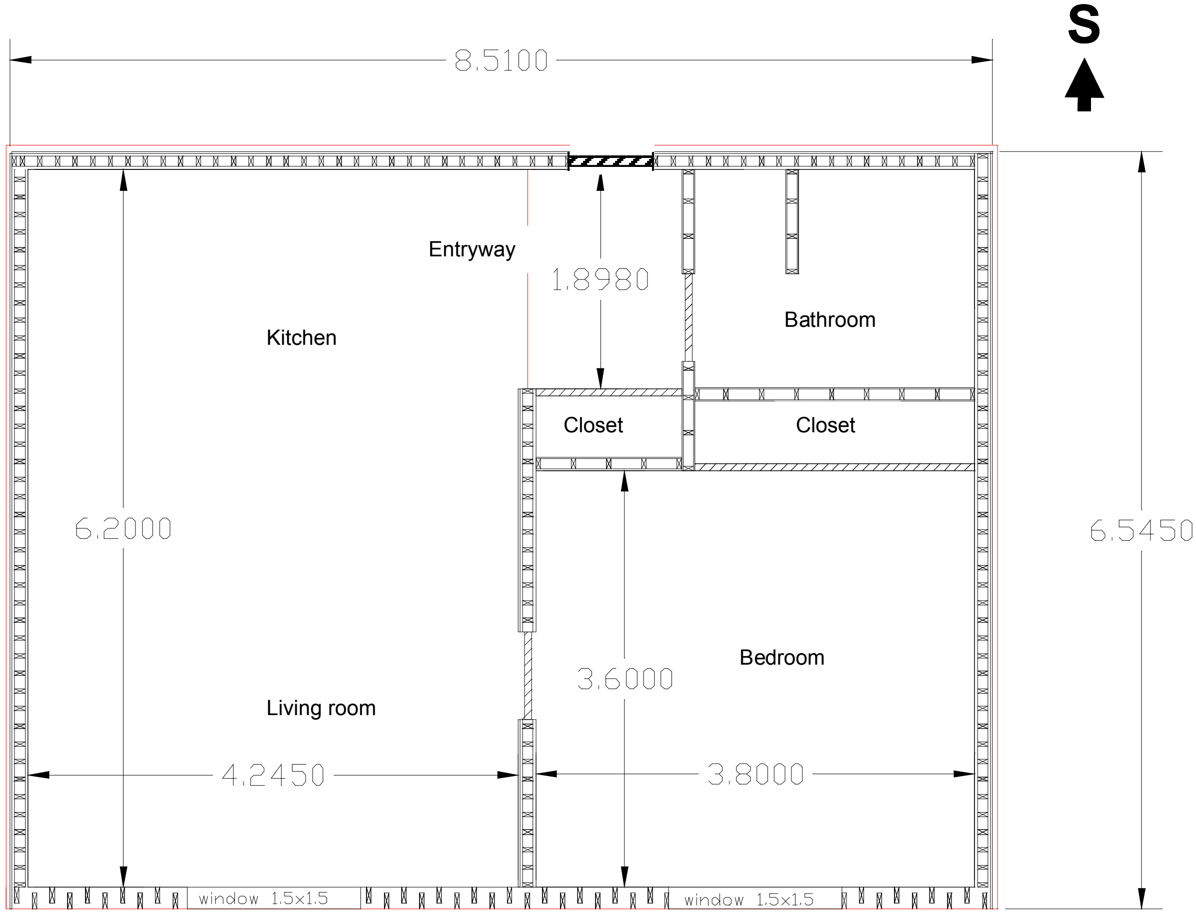


Figure 3. Apartment layout (all measurements in m).

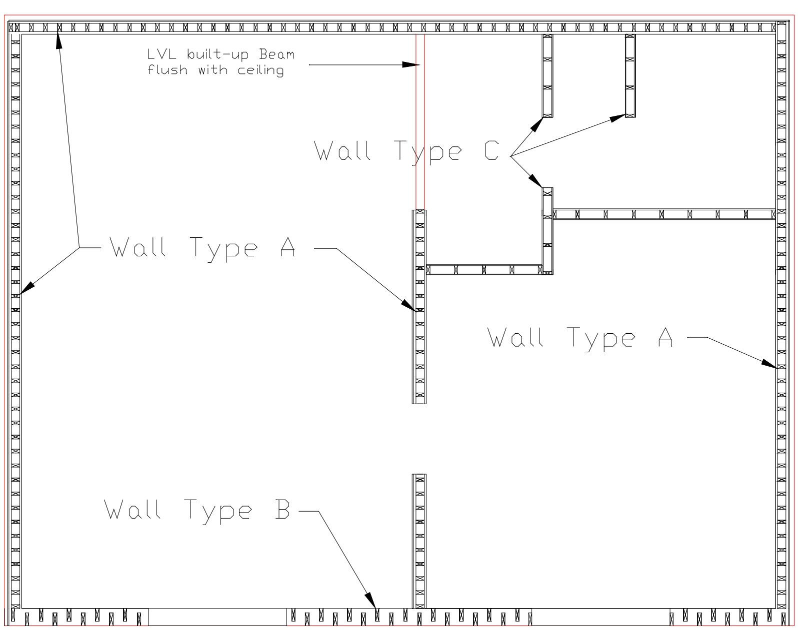
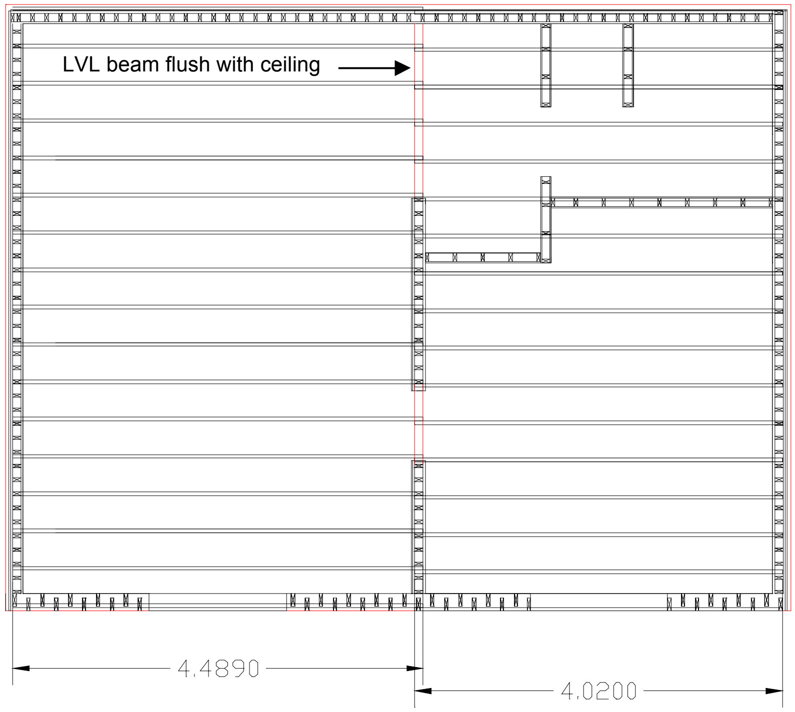


Figure 4. Wall assemblies and stud layout.

Wall Type A. 38 mm x 89 mm wood studs at 152 mm O.C. with stud cavities filled with glass fibre batt insulation. Single layer 15.5 mm thick (nominal 5/8 ") OSB shear panel on one side and two layers of 12.7 mm thick Type X gypsum board on both sides.

Wall Type B. 38 mm x 141 mm staggered wood studs on 38 mm x 184 mm plate. The studs were spaced 152 mm O.C. on opposite sides (305 mm O.C. on the same side), with stud cavities filled with glass fibre batt insulation. Two layers of 12.7 mm thick Type X gypsum board on the interior and one layer of 12.7 mm thick regular gypsum sheathing on the exterior.

Wall Type C. 38 mm x 89 mm wood studs at 406 mm O.C. One layer 12.7 mm thick regular gypsum board each side. Stud cavities filled with glass fibre batt insulation.



Joists. 241 mm deep wood I-joists spaced 406 mm O.C.

Ceilings. Resilient metal channels (not shown) run perpendicular to the joists and spaced 406 mm O.C. Two layers of 12.7 mm thick Type X gypsum board. I-joist floor cavities have 152 mm deep glass fibre batt insulation resting on the RMCs.

Floors. 15.5 mm thick (nominal 5./8") OSB subfloor, with an acoustic membrane on top of the subfloor. Two layers of 12.7 mm thick cement board and another acoustic membrane on top of the cement board. Hardwood flooring in all areas except bathroom on middle floor.. Hardwood flooring and acoustic membranes were not included on the highest storey.

Figure 5. Joist layout in floor assemblies (all measurements in m).

7 FUEL LOAD

The primary fuel load present within the fire floor (second 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.

8 INSTRUMENTATION

Various measurement devices were used in the 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

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 room quarter points (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

Thermocouples were located in the cavities of all the wood stud wall assemblies on the middle storey. The thermocouples were installed in the cavity space prior to the insulation and they measured the temperatures at the interface between the insulation and the OSB shear panel for the Wall Type A assemblies.

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 part of the input data on the temperature profiles in the wall cavities, 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 stud cavities of the wood frame 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. Six thermocouples were located in the loadbearing wall (Wall Type A) between the bedroom and the living room/kitchen area. The thermocouples were at the 0.6, 1.2 and 1.8 m heights and were located at quarter-points along the length of the wall.
3. Three thermocouples were located in the partition (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.
4. 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).
5. 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).
6. Twelve thermocouples were located in the north wall (Wall Type B) with the two openings, which represented an exterior wall without a fire resistance rating. The 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.

8.3 Thermocouples in Ceiling/Floor Assemblies

Thermocouples were located in the I-joist cavities of the floor assemblies both above and below the bedroom and the living room and kitchen areas. The approximate location of thermocouples in the joist cavities in the ceiling/floor assemblies on both storeys (levels) are shown in the sketch in Figure 9. The temperatures measured using these thermocouples provided part of the data on the temperature profiles in the ceiling/floor cavities, which can be used to determine the time required for the fire to penetrate the encapsulation materials within the different rooms. The following lists the number and locations of the TCs in the I-joist cavities of the floor assemblies above and below the fire floor:

1. Nine thermocouples were located in the ceiling joist cavity space 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 in the floor joist cavity space below the bedroom. The thermocouples were located at the quarter- and mid-widths and lengths of the bedroom area excluding the closet.
3. Nine thermocouples were located in the ceiling joist cavity 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 in the floor joist cavity below the living room and kitchen. The thermocouples were located at the quarter- and mid-widths and lengths of the kitchen and living room area.

8.4 Surface and Interface Temperatures

There were twelve 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 lightweight wood frame assembly. The temperatures measured using these thermocouples provided part of the input data on the temperature profiles within the wall assembly and the time required for heat transfer through the wall assembly. These twelve 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 six 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 wood stud wall assembly.
3. Interface between the base layer gypsum board and the wood stud.
4. Interface between the wood stud and the OSB shear panel on the unexposed (outer) side of the wall assembly.
5. Interface between the OSB shear panel and the base layer of gypsum board.
6. Interface between the base and face gypsum board layers.

There were seven 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 wood I-joist ceiling/floor assembly separating the middle and highest storeys. The temperatures measured using these thermocouples provided part of the input data on the temperature profiles within the ceiling/floor assembly and the time required for heat transfer through the assembly. The locations of the seven 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 wood I-joist ceiling/floor assembly.
3. Interface between the base layer of gypsum board and the cavity space.
4. Interface between the resilient channel and the wood I-joist.
5. Interface between the wood I-joist and OSB subfloor.
6. Interface between the OSB and base layer of cement board on the unexposed (upper) side of the ceiling/floor assembly.
7. Interface between the base and face layers of cement board on the unexposed (upper) side of the ceiling/floor assembly.

There were eight 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 wood I-joist ceiling/floor assembly separating the middle and lowest storeys. The temperatures measured using these thermocouples provided part of the input 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. Interface between the face layer of cement board and acoustic membrane used under the hardwood floor.
2. Interface between the face and base layers of cement board.
3. Interface between the OSB subfloor and the acoustic membrane used between the subfloor and the base layer of cement board.
4. Interface between the OSB subfloor and wood I-joist.
5. Interface between the base layer of gypsum board and the cavity space.
6. Interface between the resilient channel and the wood I-joist.
7. Interface between the face and base layer of gypsum board (ceiling) in the lowest storey.
8. Unexposed face of the face layer of gypsum board in the lowest storey.

Note: Unlike the apartment fire test for the CLT test structure, temperatures were not measured on the exposed side (top) of the hardwood flooring or at the interface between the hardwood flooring and the acoustic membrane below.

Nine thermocouples were located under the acoustic membrane on top of the OSB subfloor in floor/ceiling assembly between the middle and lowest storeys. 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 cavity shown in Figure 9.

8.5 Thermocouples in Third Storey

The third storey was not included in the test setup. As such, no thermocouple trees were included above the fire floor. However, nine thermocouples covered with the pads used in standard fire-resistance tests [9] were located on the upper surface (top) of the face layer of cement board above the bedroom area on the second storey (fire floor). 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. These thermocouples were 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, while the thermocouples on the entryway door were located on the unexposed (corridor) side of the door.

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. Since the third storey was not included in the test setup, the heat fluxes to the exterior wall façade were not measured 3.5 m, or at all, above the top of the openings in the bedroom and living room as was done in previous tests, since there was only a short height of exterior wall façade above the top of the openings in the bedroom and living room in this test.

The heat flux meters in Items 1 and 2 were used to provide data on potential exposures from the fire to adjacent buildings.

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 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 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. 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.

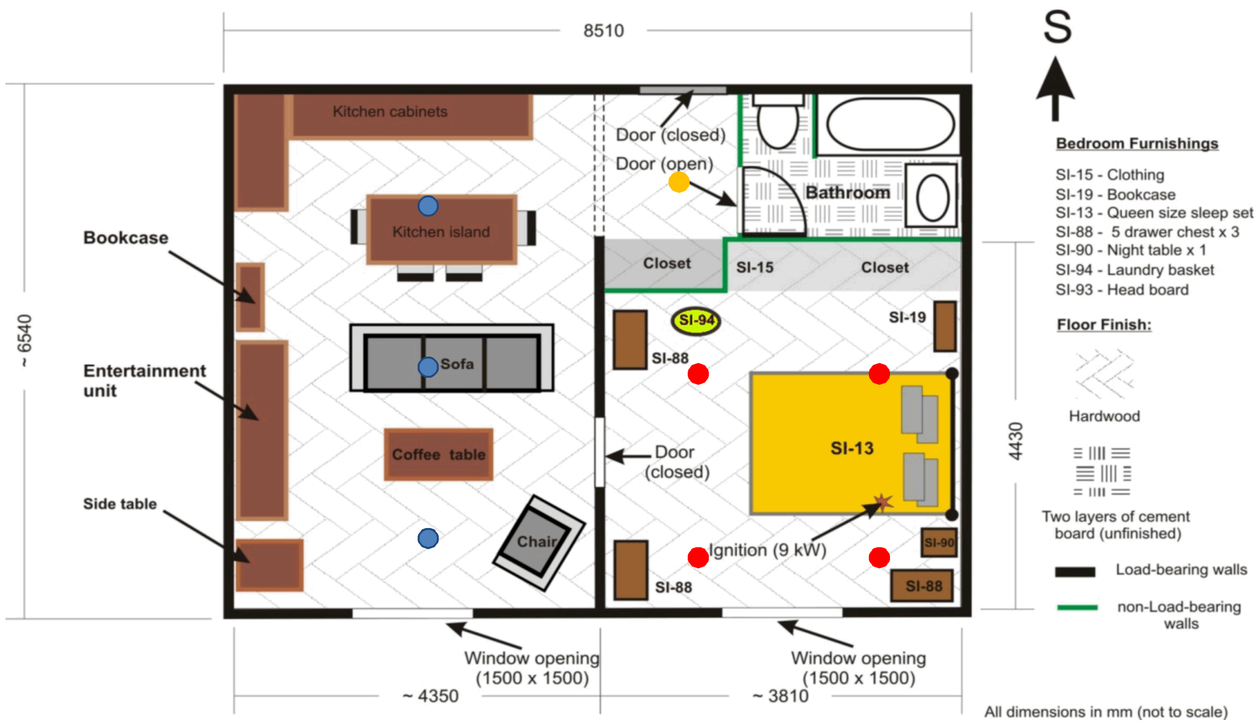


Figure 7. Location of thermocouple trees in the bedroom (●), living room/kitchen (●) and entryway (●).

Figure 8. Sketch showing locations of thermocouples in wall cavities. (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.)

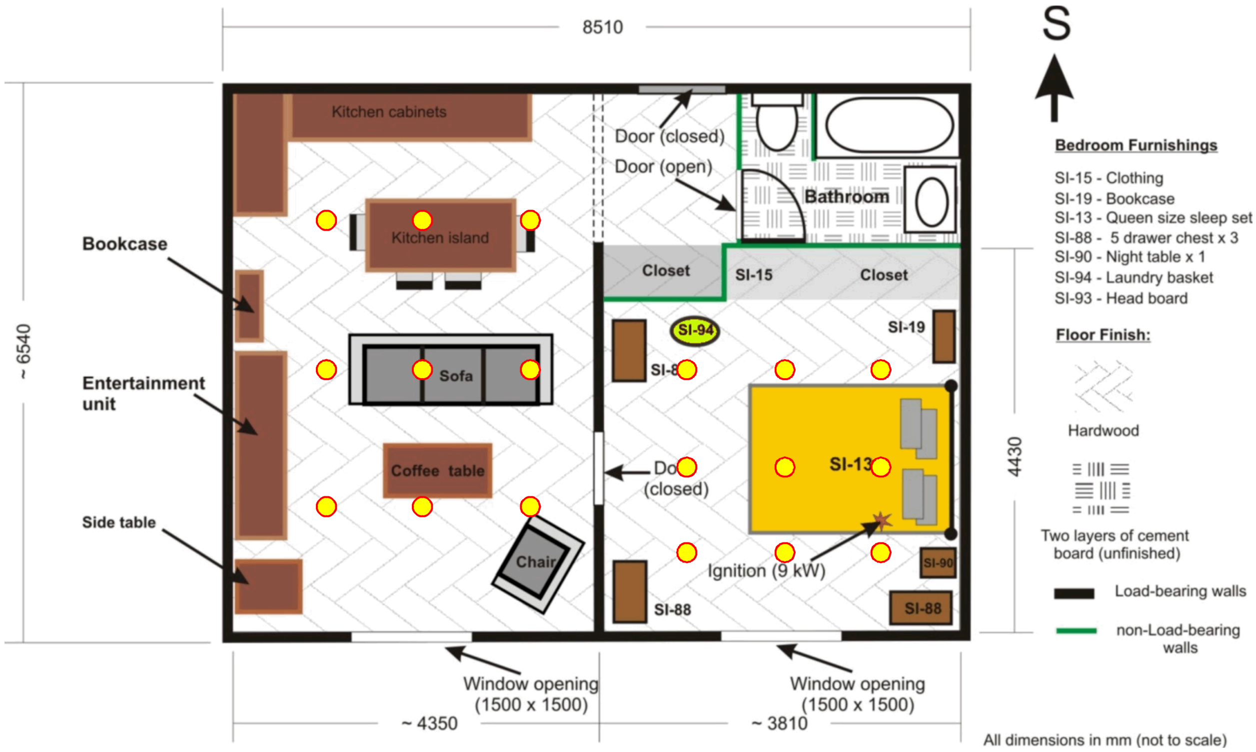


Figure 9. Sketch showing the locations of the thermocouples in the ceiling joist space in the bedroom and living room and kitchen (○).

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.

Standard wood framing was used for windows, including double headers used across the top of the openings. The wood framing at the edges of the opening was 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 within 20 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 between 2 and 3 min. The temperatures at the 0.4 m height at the north end of the bedroom reached 600°C between 3 and 4 min after ignition. The temperature increases at the 0.4 m height at the south end of the bedroom was slower than at the two thermocouple locations near the opening. The temperature reached 600°C between 4 and 5 min at the southeast thermocouple tree location and between 5 and 6 min at the southwest location. The temperature measurements indicate that flashover occurred within 4 min.

The temperatures measured at the 1.4 m height and near the ceiling were comparable throughout the duration of the test. Peak temperatures of 1100 – 1150°C were measured at the southeast thermocouple tree at approximately 11 min. Subsequently, there was a rapid decrease in the temperatures at this thermocouple location. This decrease in temperature corresponded with the rapid temperature increases in the cavity space in the partition wall between the bedroom and the bathroom and entryway.

Peak temperatures of 1100 – 1200°C were measured at the southwest thermocouple tree between 18 and 20 min. The highest temperatures were measure at the 0.4 and 1.4 m heights.

The maximum temperature occurred between 19 and 21 min at the other two thermocouple tree locations at the north end of the bedroom near the opening.

The temperatures measured at the 0.4 m height were typically lower than the temperatures measured at the other two heights. However, during the initial 25 min, the temperatures measured at the 0.4 m height were, at some times, either comparable to or higher than the temperatures at the higher elevations.

After approximately 24 min, there was a gradual decrease in the temperatures measured at all heights, with temperatures < 1000°C after approximately 31 min. After 35 min, the temperatures remained relatively steady (800 - 1000°C) with the burning of the studs in the exterior walls and the joists and the OSB subfloor in the ceiling/floor assembly.

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 kitchen and living room areas 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 temperatures measured in the kitchen and the entryway are shown in Figure 14 and Figure 15, respectively. The temperatures measured at the thermocouple trees located at the center and north end of the living room/kitchen area are shown in Figure 16 and Figure 17, respectively.

The temperatures began to increase in the living room/kitchen area after approximately 3 min. Subsequently, there was considerable variation in the temperatures measured at the four thermocouple tree locations. The most rapid temperature increase occurred at the tree located at the north end of the living room with temperatures measured at all elevations reaching 600°C by approximately 7 min. Subsequently, the temperatures continued to increase at this location with temperatures at the 1.4 and 1.8 m heights > 1000°C between 12 and 35 min. After 30 min, the temperatures decreased to a 800 - 1000°C plateau beginning at approximately 35 min with the higher temperatures at the 1.4 m height.

At the thermocouple tree located the center of the living room/kitchen area (Figure 16), there was an initial rapid temperature increase with a peak temperature of approximately 800°C at the 2.4 m height at approximately 6 min. This initial peak was followed a dip in temperatures to 733°C at 8 min. Subsequently, there was a gradual increase in temperature at all heights to temperatures > 1000°C. At 27 min, there was a rapid decrease in temperature to < 700°C at the 1.4 and 2.4 m heights. This temperature decrease may be due to the fall-off of the base layer of gypsum board and temperature losses to the joist cavity space. The temperatures eventually increased to a 800 - 1000°C plateau beginning at approximately 35 min with the higher temperatures at the 1.4 m height.

At the thermocouple tree located in the kitchen area (Figure 14), the temperatures at the 1.4 and 2.4 m heights reached 600°C within 11 min. Subsequently, there was a gradual increase in temperature at all heights with peak temperatures of approximately 1200°C at the 1.4 m height at 34 min. The temperatures subsequently decreased to approximately 1000°C at 40 min followed by a short steady temperature stage.

The temperatures measured in the entryway had a gradual increase after 7 min reaching peak temperatures of 1000 - 1150°C at approximately 34 min (Figure 15). Subsequently, the temperatures decreased to a temperature plateau starting at approximately 40 min (approximately 1000°C).

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 4 min.
2. A period with sustained high temperatures between 6 and 24 min.
3. An initial decrease in temperature between 24 and 35 min followed by a temperature plateau until the floor collapsed at approximately 48 min.
4. After 48 min, there was a rapid decrease in temperature.

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

1. Initial temperature increases were measured at the ceiling between 3.0 and 4.0 min after the fire was ignited in the bedroom.
2. The fire developed faster in the living room area with temperatures > 600°C at 5.0 min near the ventilation opening and at the center of the living room. The temperatures in the kitchen and the entryway exceeded 600°C at approximately 11min.
3. The maximum temperatures at the north and center living room trees were between 23 and 30 min. After 30 min, the temperatures decreased until 35 min followed by a steady temperature plateau until the floor collapsed at approximately 48 min.
4. The maximum temperatures in the kitchen and entryway were at approximately 34 min. The temperatures subsequently decreased until approximately 40 min followed by a steady temperature plateau until the floor collapsed at approximately 48 min
5. After 48 min, there was a rapid decrease in temperatures at all heights and locations.

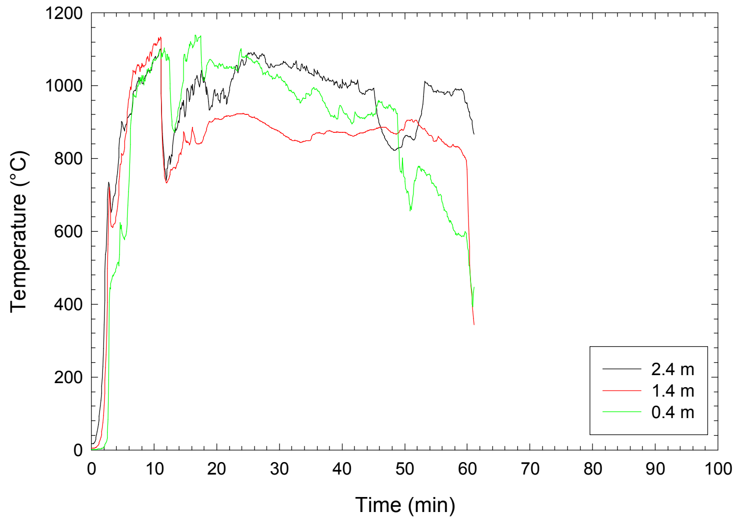


Figure 10. Temperatures southeast bedroom thermocouple tree.

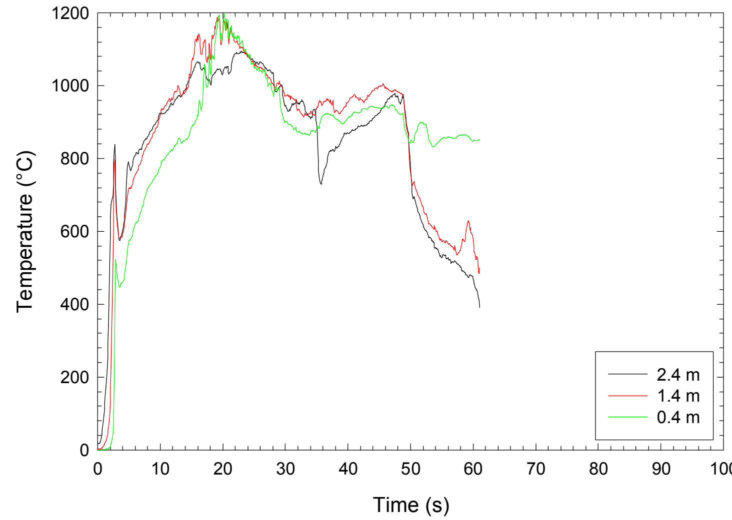


Figure 11. Temperatures southwest bedroom thermocouple tree.

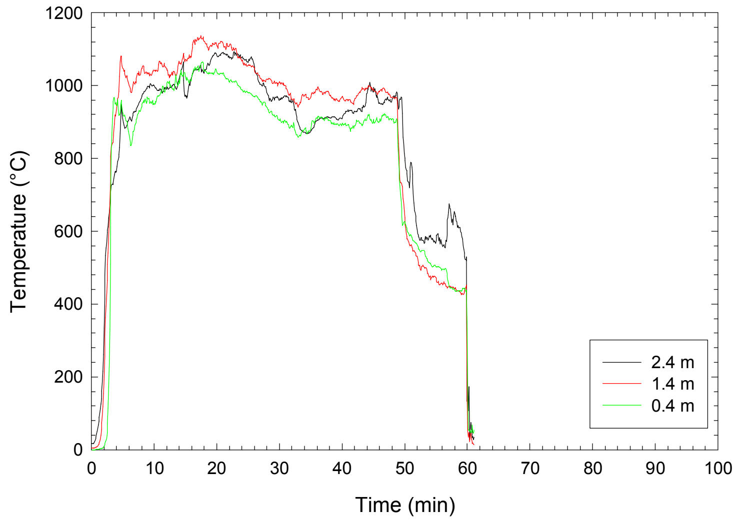


Figure 12. Temperatures northeast bedroom thermocouple tree.

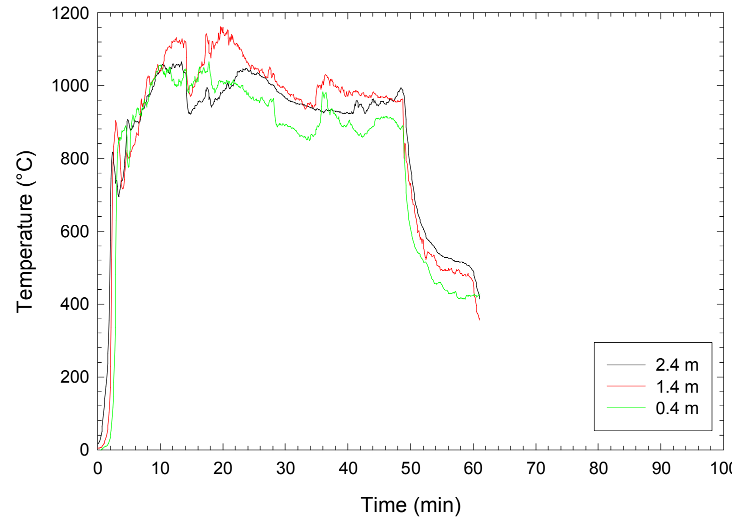


Figure 13. Temperatures northwest bedroom thermocouple tree.

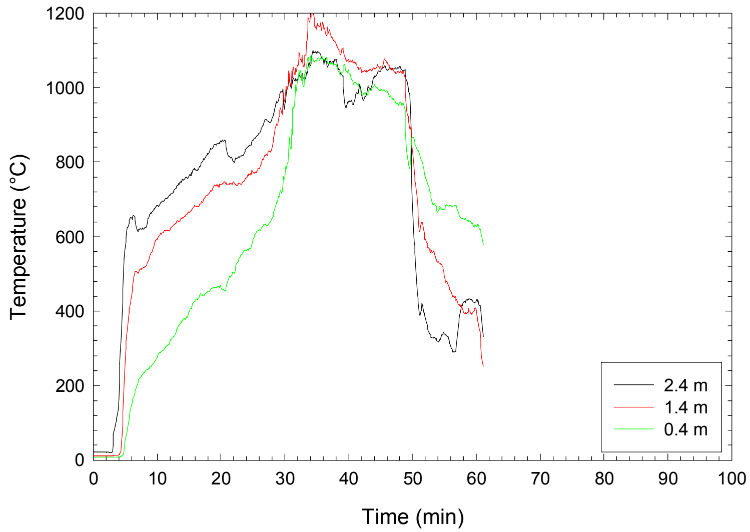


Figure 14. Temperatures south kitchen thermocouple tree.

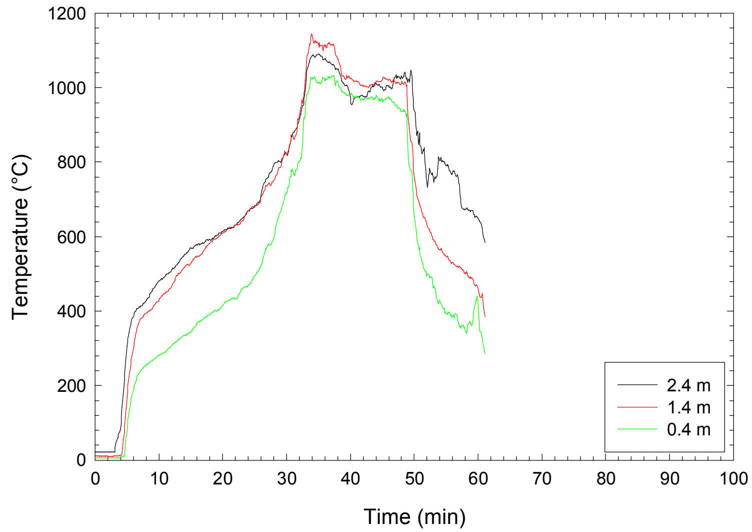


Figure 15. Temperatures entryway thermocouple tree.

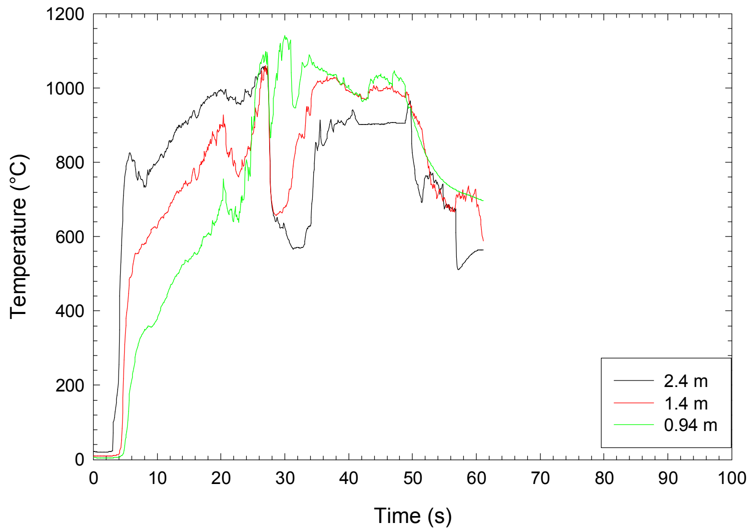


Figure 16. Temperatures center living room/kitchen thermocouple tree.

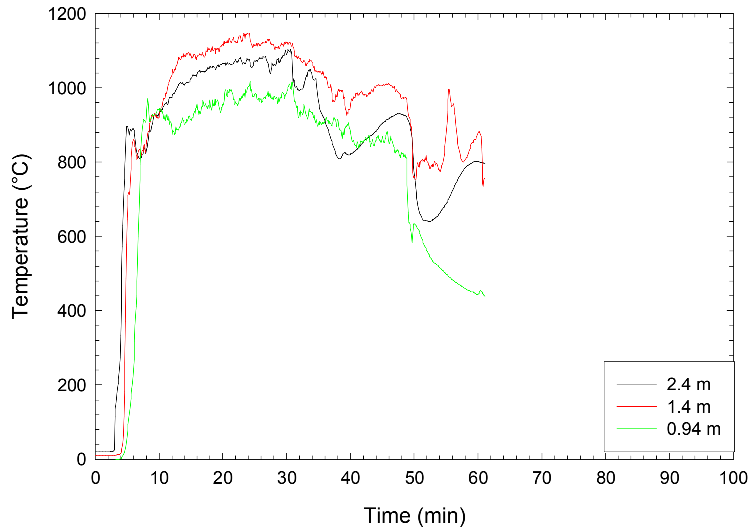


Figure 17. Temperatures north living room/kitchen thermocouple tree.

11.2 Temperatures in Wall Assemblies

Thermocouples were located in a number of cavities of all the wood stud wall assemblies on the second 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 are located only at the 1.8 m height. The thermocouples in the wall cavities were located on the unexposed side of the glass fibre insulation in the stud cavities.

11.2.1 West Bedroom Wall

The temperatures measured by the nine thermocouples located in the west bedroom wall are shown in Figure 18, Figure 19and Figure 20. Two layers of gypsum board were directly attached to the interior (fire) side of the wood stud framing. 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 stud cavities follow 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 10 - 25 min depending on the location in the room. The fastest temperature increases were typically at the 1.8 m height and the slowest at the 0.6 m height. However, the fastest temperature increase was at the 1.2 m height at the north end of the bedroom. The reason for the initial temperature increase at this location is not known.
2. There was a second phase during which the temperatures remained steady at < 100°C during the calcination of the gypsum board. This phase lasted until 39 min, 42 and 43 min at the thermocouples at the north, center and south cavity locations in the wall. (Note: these times are comparable to the 40 – 48 min measured in Test APT-LWF-1 [3].)
3. Once the gypsum board was calcined, there was a more rapid temperature increase within the caivity. However, the temperatures in the cavities were typically <300ºC until the end of the test except for the temperature measured by the thermocouple at the 0.6 m height at the south end of the wall assembly. 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 wood studs or the OSB shear panel in the cavity areas. (The potential charring of the wood studs at the gypsum board/stud interface is discussed in the next section.)
4. The encapsulation time for the two layers of gypsum board attached to the wood studs and the insulation in the stud cavities was 53 min based on a single point temperature increase of 270°C. Based on the average temperature increase for the nine thermocouples, the 250°C average temperature increase criterion was not exceeded by the end of the test. (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).)

11.2.2 Bedroom/Bathroom Partition with Regular Gypsum Board

Three thermocouples were located in the stud cavities of the partition that separates 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 cavities follow the typical pattern for heat transfer through gypsum board. The results indicate that the fire initially entered the cavity in the east end of the wall separating the bedroom from the entryway closet. The temperature at this location reached 600°C at 12 min and an initial peak temperature of approximately 1100°C at 13 min. It subsequently penetrated the wall cavity at the other two locations by 19 min.

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 temperature first exceeded 300°C at the east of the wall at 9 min. The encapsulation time for the single layer of regular gypsum board attached to the wood framing was 11 min based on the single point temperature increase criterion (270°C). Based on the average temperature increase for the three thermocouples in the joist cavities, the 250°C average temperature increase criterion was exceeded at 9 min

The fire penetration into the cavity of the nonloadbearing partition wall was earlier than for the same wall in Test APT-LWF-1 [3]. (20 min). However, the fire penetration time is comparable to those in Test APT-CLT [4] and Test APT-LSF [5} with the CLT and the lightweight steel structural assemblies, respectively. The reason for the later penetration time in Test APT-LWF-1 with the LWF assemblies is not known.

11.2.3 Interior Bedroom/Living room Wall

Six thermocouples were located in two different stud cavities 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 wood stud framing. The thermocouples were at the 0.6, 1.2 and 1.8 m heights and were located at quarter-points along the length of the wall. The temperatures measured within the stud cavities in the wall sections on the south and north side of the doorway are shown in Figure 22 and Figure 23, respectively

The temperatures followed the same general trend as those measured in the west bedroom wall with an initial temperature increase to 70 - 80°C, followed by a temperature plateau as the gypsum board calcined and a final stage with more rapid temperature increases. The temperatures measured in the wall cavities did exceed 300°C between 33 and 51 min depending on the locations indicating there would be some charring of the studs and the OSB shear panel in the cavity space.

The encapsulation time for the two layers of gypsum board attached to the wood framing and the insulation in the stud cavities was 34 min based on the single point temperature increase criterion (270°C). Based on the average temperature increase for the six thermocouples, the 250°C average temperature increase criterion was also exceeded at 41 min.

The temperatures remained under 600°C until 51 min in the south section of the wall and did not reach this temperature in the north section of the wall. This indicates that there was limited or no flames within the cavity space during the test.

11.2.4 North Exterior Wall

The north wall had two openings and represented an exterior nonloadbearing wood stud wall. A single layer of regular gypsum board was directly attached to the interior (fire) side of the wood stud framing. The temperatures were measured by twelve thermocouples located in the wood stud cavities. The thermocouples were at the 0.6, 1.2 and 1.8 m heights and 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 for the six thermocouples in the bedroom sections of the exterior wall are shown in Figure 24 and Figure 25 and in Figure 26 and Figure 27 for the thermocouples in the living room sections.

The temperature profiles in the two bedroom wall sections were similar up to approximately 20 min. However, after 20 min, there was a very rapid temperature increase in the wall section on the east side of the opening with the temperatures reaching 300°C at 21 min and exceeding 800°C at all heights by 23 min. With the burning of the wood studs, the temperatures remained high (850 - 1100°C) until the end of the test.

The temperature increases in the west section of the exterior bedroom wall was slower than in the east section. The temperatures reached 300°C between 27 and 31 min and exceeded 800°C at all heights by 38 min. The temperatures were between 800 and 900°C until approximately 49 min. After 49 min, there was a rapid decrease in temperature to approximately 750°C.

The temperature profiles in the two living room exterior wall sections were similar up to approximately 20 min. However, after 20 min, there was a rapid increase in temperatures at all heights in the wall section on the west side of the opening. The temperatures exceeded 300°C by 20 min and 800°C by 21 min. The temperatures in this section were > 900°C unit approximately 48 min, after which the temperatures decreased to 800 - 900°C.

The temperature increases in the east section of the living room exterior wall were slower than in the west section. The temperatures exceeded 300°C by 26 min and 800°C by 29 min. Subsequently, the temperatures were between 850 – 1000°C until the end of the test.

The results indicate that there was fire involvement of the wood studs in the west section of the living room exterior wall beginning at approximately 21 min and in the east section beginning at approximately 29 min. The studs were involved in the fire until the end of the test.

The encapsulation time for the one layer of regular gypsum board attached to the wood framing and insulation in the stud cavities was 20 min and 21 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 exceeded at 20 min in the living room exterior wall and at 22 min in the bedroom exterior wall.

11.2.5 East Living Room/Kitchen Wall

The temperatures were measured by nine thermocouples located in the wood stud cavities in the east living room/kitchen wall (Figure 8). Two layers of gypsum board were directly attached to the interior (fire) side of the wood stud framing. 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 are shown in Figure 28, Figure 29and Figure 30.

The temperatures followed the same general trend as those measured in the west bedroom wall with an initial temperature increase to 80 - 90°C, followed by a temperature plateau as the gypsum board calcined and a final stage with more rapid temperature increases. For all locations except at the 1.2 m height and the mid-length of the wall, the temperatures were < 100°C until 45 – 55 min and did not exceed 300°C.

The temperatures measured at the 1.2 m height at the center the wall exceeded 100°C at 34 min and 300°C at 54 min.

The temperature measurements indicate that there would be minimal or no charring of the wood studs and the OSB shear panel in the east living room wall.

The encapsulation time for the two layers of gypsum board attached to the wood framing and the insulation in the stud cavities was 60 min based on the single point temperature increase criterion (270°C). Based on the average temperature increase for the nine thermocouples in the bedroom and living room exterior walls, the 250°C average temperature increase criterion was not exceeded.

11.2.6 South Corridor Wall

The temperatures were measured by nine thermocouples located in the wood stud cavities in the south corridor wall (Figure 8). Two layers of gypsum board are directly attached to the interior (fire) side of the wood stud framing. The thermocouples are at the 0.6, 1.2 and 1.8 m heights and are located at three locations along the length of the wall (¼ and mid-lengths). The measured temperatures are shown in Figure 31, Figure 32 and Figure 33.

The temperatures followed the same general trend as those measured in the west bedroom wall with an initial temperature increase to approximately 80-90°C, followed by a temperature plateau as the gypsum board calcined and a final stage with more rapid temperature increases. For this wall, the final stage of the heat transfer process was reached only at the center thermocouple location between 50 and 55 min.

The temperatures in the wall cavities did not reach 300°C indicating there was limited or no charring of the wood studs or OSB shear panel in the corridor wall assembly.

The single point (270°C) and average temperature (250°C) were not exceeded for the nine thermocouples located in the south corridor wall assembly. This indicates that the encapsulation time for the two layers of gypsum board attached to the wood studs and the insulation in the stud cavities was longer than the test duration.

11.2.7 Interface Temperature Profiles in West Bedroom Wall

There were twelve thermocouples located at the mid-length of the west bedroom wall to measure the temperatures at each interface between materials used for the lightweight wood frame assembly. These twelve thermocouples were near the locations at which the temperatures were measured in the cavity space at the mid-length of the wall at the 1.2 and 1.8 m heights (Figure 8). The locations of the five thermocouples at each height starting in the fire area 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 wood stud assembly.
3. Interface between the base layer gypsum board and the wood stud.
4. Interface between the wood stud stud and the OSB shear panel on the unexposed (outer) side.
5. Interface between the OSB shear panel and the base gypsum board layer.
6. Interface between the base and face gypsum board layers on the unexposed (outer) side.

The temperatures measured at the 1.2 and 1.8 m heights are shown in Figure 34 and Figure 35, respectively.

There was an initial peak temperature at the exposed surface of the face layer of gypsum board at approximately 3 min. Subsequently, the temperature decreased with a minimum temperature < 600ºC at 4 min after which the temperature increased steadily exceeding 800ºC at 10 min. There was a peak with temperatures >1000°C between approximately 19 and 24 min. After 24 min, the temperatures decreased until approximately 33 min and subsequently remained relatively constant (> 900ºC) until 48 min. After 48 min, the temperatures decreased until the end of the test. These results are consistent with the temperatures measured in the bedroom (Figure 10, Figure 11, Figure 12, Figure 13), with an initial high temperature peak before 30 min followed by a decrease in temperature to a steady temperature plateau.

The temperature at the interface between the two layers of gypsum board began to increase rapidly after approximately 12 min indicating that the face layer of gypsum board was calcined in the early stages of the fire exposure. The temperatures measured at the interface between the two layers of gypsum board exceeded 300°C at approximately 20 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 18 min and the single point temperature increase exceeded 270°C at 19 min. This indicates that the face layer of gypsum board provided an encapsulation time of 18 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 50 min. This indicates that the face layer of gypsum board probably remained in place until this time.

The heat transfer through the two layers of gypsum board on the fire side of the wall showed the same general profiles as noted for the temperatures measured in the stud cavities. The steady temperature plateau with the calcination of the gypsum board ended at approximately 30 min. The temperatures measured in the cavity areas indicted that the two layers of gypsum board was calcined in 39 – 43 min. However, the thermocouples in the stud cavity were located on the non-fire side of the insulated cavity and did not measure the temperature on the base layer of gypsum board on the exposed side of the assembly. This will result in a delay in the temperature increase measured in the cavity area. Overall, the temperature results and calcinations at the two locations are consistent.

Based on the average temperature increase for the two thermocouples located at the interface between the base gypsum board layer and the wood stud, the he average temperature increase at the interface between the base layer of gypsum board and the wood exceeded 250°C at 38 min and the single point temperature increase exceeded 270°C at 38 min. This indicates that the two layers of gypsum board provided an encapsulation time of 38 min for the wood studs.

The temperature at the interface between the stud and the gypsum board reached 300°C at approximately 40 min. After this, the studs would begin to char. Since the temperatures within the cavity space generally remained below 300°C throughout the test, the charring of the studs was primarily the result of direct heat transfer from the gypsum board to the studs.

Low temperatures (<85ºC) were measured on the unexposed (outer) side of the wall assembly. The highest temperature was measured at the wood stud interface with the OSB shear layer, followed by the interface between the OSB and base layer of gypsum board base. The lowest temperature was measured at the interface between the two layers of gypsum board.

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 face layer of gypsum board on the unexposed side of the west bedroom wall. These thermocouples were at the same elevation and location as the thermocouples located in the stud cavity of the west bedroom wall (Figure 8).

The temperatures measured at the different locations are shown in Figure 36, Figure 37 and Figure 38. There was a 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 in the wall with the highest temperatures measured at the south end of the wall. The maximum temperatures at the end of the test were 20 – 30ºC. The average and single point temperature increases at the end of the test were 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 doors are shown in Figure 39 and Figure 40, respectively.

After 2.53 min, there was a rapid increase in temperature on the living room (unexposed) side of the door between the bedroom and the living room. By approximately 5 min, the temperature exceeded 600ºC indicating the living room side of the door was burning. The temperatures subsequently decreased to a minimum temperature < 400ºC at 6 min. After 6 min, the temperature increased as the door burned out and the thermocouples started to measure the temperature in the doorway.

There was a peak in the temperatures > 1000ºC measured in the doorway at approximately 37 min.

The temperature measured on the unexposed (corridor) side of the entryway door started to increase at 5 min as the temperature increased in the entryway. The temperature continued to increase to a peak temperature of 652ºC at 41 min. Subsequently, the temperature decreased to 354ºC at the end of the test.

The temperatures measured on the unexposed side of the 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 300 - 400ºC lower than the peak temperature measured in the entryway. This indicates there was substantial temperature loss at the door.

11.2.10 Summary of Temperatures in Wall Assemblies

The times at which the temperatures in the wall cavities reached 300°C are summarized in Table 1 and Table 2 for the bedroom and the living room/kitchen walls, respectively. Some general comments based on the results are as follows:

1. The temperature exceeded 300ºC in the stud cavity of the partition wall with regular gypsum board between 9 and 12 min with the earliest time at the east end of the wall.
2. The temperatures exceeded 300ºC in the east and west sections of the bedroom portion of the exterior wall (with regular gypsum board) at 21and 27min, respectively.
3. The temperatures exceeded 300ºC in the east and west sections of the living room portion of the exterior wall (with regular gypsum board) at 23 and 20 min, respectively.
4. The temperature exceeded 300ºC in the south and north sections of the interior loadbearing wall with 2 layers of 12.7 mm thick Type X gypsum board at 34 and 43 min, respectively.
5. For the other wall assemblies with 2 layers of 12.7 mm thick Type X gypsum board, the temperature did not exceed 300ºC on the unexposed side of the insulation in the stud cavities except at the 1.2 m height at the mid-length of the living room. These results indicate there was minimal or no charring of the wood and the OSB in these wall assemblies due to high temperatures in the wall cavities. Any charring was localized at the interface between the base layer of gypsum board and the studs.

The time at which the encapsulation criteria were reached in the wall assemblies are summarized in Table 3. The encapsulation times are based on an average temperature increase of 250ºC and a single point temperature increase of 270ºC. Some general observations based on the results are:

1. A single layer of 12.7 mm thick regular gypsum board provided an encapsulation time of 9 min for the nonloadbearing partition wall based on temperatures measured on the unexposed side of the insulation in the stud cavities. This encapsulation time was shorter than the 21 min determined in Test APT-LWF-1 [3] but comparable to the

encapsulation times determined in the other two apartment tests [4, 5]. The results indicate that the insulation was not as effective in reducing heat transfer to the thermocouple locations in this test versus Test APT-LWF-1.

2. The encapsulation times were 20 min for the living room portion of the exterior wall and 21 min for the bedroom portion of the exterior wall. However, these results are based on temperatures measured in the cavity space on the unexposed side of the insulation in the stud cavities and would likely be earlier if the temperature was measured between the gypsum board and the stud or directly on the gypsum board.
3. A single layer of 12.7 mm thick Type X gypsum board provided an encapsulation time of 18 min based on the temperature measurements in the bedroom wall. This is based on temperatures measured at two locations in the west wall of the bedroom.
4. The two layers of 12.7 mm thick Type X gypsum board provided an encapsulation time of 38 min based on the temperatures measured between the base layer of gypsum board and the studs in the west bedroom wall.
5. The two layers of 12.7 mm thick Type X gypsum board provided an encapsulation time of 34 min for the loadbearing interior partition wall. This time is based on the single point temperature measurement at the 1.8 m height in the south section of the wall.
6. Estimates for encapsulation times for the other wall assemblies protected by two layers of 12.7 mm thick gypsum board are provided based on the temperatures measured in the cavity space on the unexposed side of the insulation in the stud cavities. These results indicate an encapsulation time of 53 min in the west bedroom wall and 60 min in the east living room wall. These results suggest that the fire did not affect the wood elements in the stud cavity until late in the test. The wood studs would be affected earlier with the direct heat transfer through the gypsum board into the studs. The measured temperatures also indicate that there was no flaming combustion within the stud wall cavities for the duration of the test.

Table 1. Time to reach 300°C 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 38 mm x 89 mm wood studs. Temperature measured in stud cavity.	South	1.8	34
		1.2	38
		0.6	43
	North	1.8	43
		1.2	44
		0.6	51
Exterior (north) wall with a single layer of regular gypsum board directly attached to 38 mm x 141 mm wood studs. Temperature measured in stud cavity	East	1.8	21
		1.2	21
		0.6	21
	West	1.8	27
		1.2	29
		0.6	31
West wall with two layers of 12.7 mm Type X gypsum board directly attached to 38 mm x 89 mm wood studs. Temperature measured in stud cavity.	South	1.8	DNR
		1.2	DNR
		0.6	DNR
	Center	1.8	DNR
		1.2	DNR
		0.6	DNR
	North	1.8	DNR
		1.2	DNR
		0.6	DNR
Partition between bedroom and bathroom with a single layer of regular gypsum board.	East	1.8	9
	Center	1.8	12
	West	1.8	11

DNR – Did not reach 300ºC.

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

Wall Assembly	Location	TC Height (m)	Time (min)
Exterior (north) wall with a single layer of regular gypsum board directly attached to 38 mm x 141 mm wood studs. Temperature measured in stud cavity.	East	1.8 1.2 0.6	22 26 23
	West	1.8 1.2 0.6	20 20 20
East wall with two layers of Type X gypsum board directly attached to 38 mm x 89 mm wood studs. Temperature measured in stud cavity.	South	1.8 1.2 0.6	DNR DNR DNR
	Center	1.8 1.2 0.6	DNR 54 DNR
	North	1.8 1.2 0.6	DNR DNR DNR
Corridor (south) wall with two layers of Type X gypsum board directly attached to 38 mm x 89 mm wood studs. Temperature measured in stud cavity.	East	1.8 1.2 0.6	DNR DNR DNR
	Center	1.8 1.2 0.6	DNR DNR DNR
	West	1.8 1.2 0.6	DNR DNR DNR

DNR – Did not reach 300ºC.

Table 3. Encapsulation times for 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 + stud cavity insulation	9 thermocouples wall cavity	DNR	53
	1 layer 12.7 mm thick Type X GB	2 thermocouples GB_f/GB_b interface	18	19
	2 layers 12.7 mm thick Type X GB	2 thermocouples GB_b/stud interface	37	38
Interior Loadbearing Wall Bedroom/Living room	2 layers 12.7 mm thick Type X GB + stud cavity insulation on bedroom side 2 layers 12.7 mm thick Type X GB + 15.5 mm (nominal 5/8") OSB panel living room side	6 thermocouples wall cavity	41	34
North Exterior Wall Bedroom	1 layer 12.7 mm thick regular GB + stud cavity insulation	6 thermocouples wall cavity	22	21
North Exterior Wall Living room	1 layer 12.7 mm thick regular GB + stud cavity insulation	6 thermocouples wall cavity	20	20
East Living room/Kitchen	2 layers 12.7 mm thick Type X GB + stud cavity insulation	9 thermocouples wall cavity	DNR	60
South Corridor	2 layers 12.7 mm thick Type X GB + stud cavity insulation	9 thermocouples wall cavity	DNR	DNR
Partition Bedroom/Bathroom	1 layer regular GB + stud cavity insulation	3 thermocouples wall cavity	9	11

GB – Gypsum Board DNR – Did not reach temperature criteria.
GB_f – Gypsum board face layer. GB_b – Gypsum board base layer.

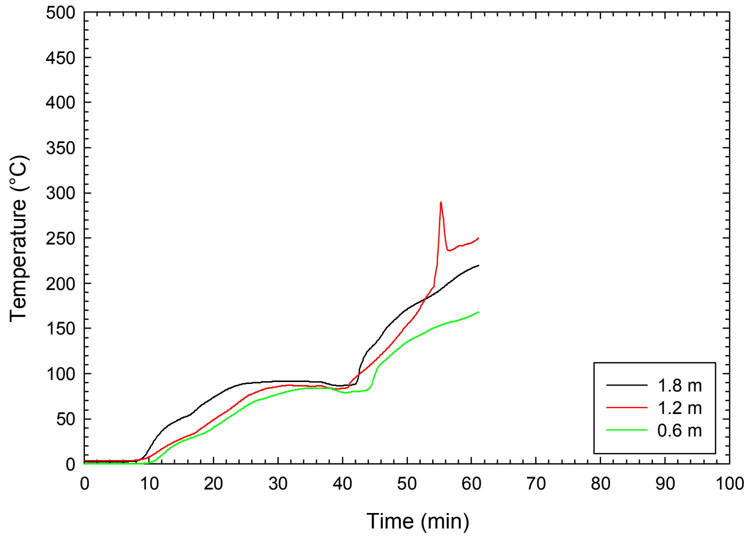


Figure 18. Temperatures west bedroom wall cavity (south).

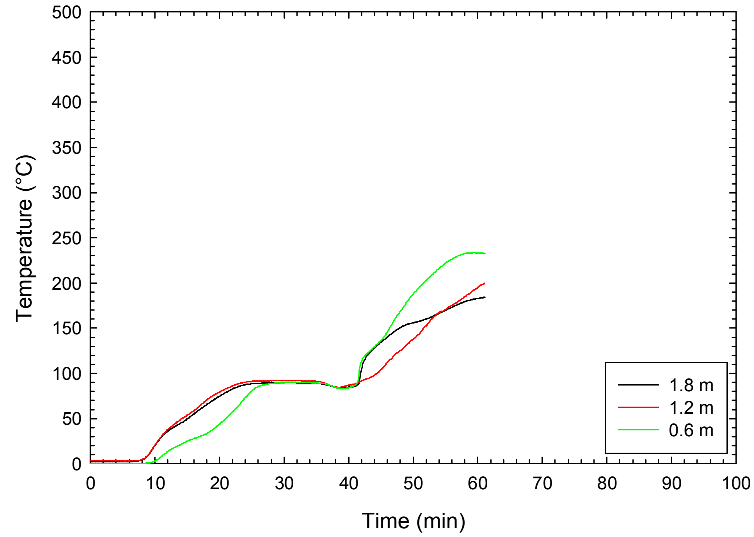


Figure 19. Temperatures west bedroom wall cavity (center).

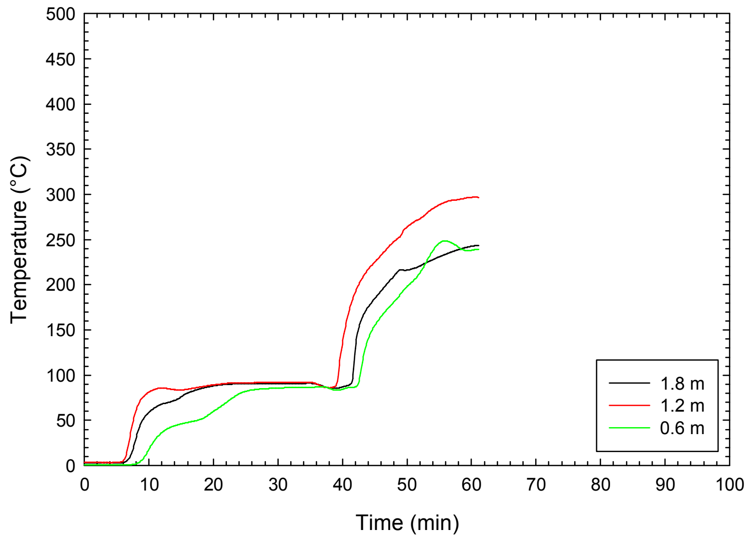


Figure 20. Temperatures west bedroom wall cavity (north).

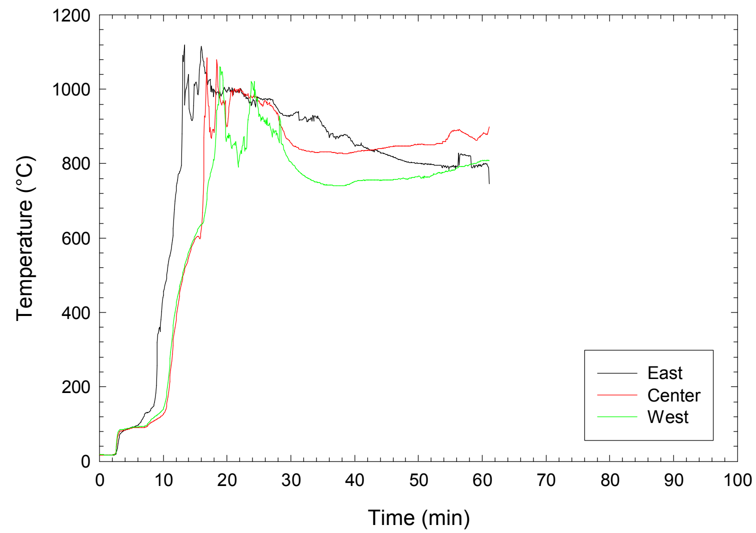


Figure 21. Temperatures in partition wall at 1.8 m height.

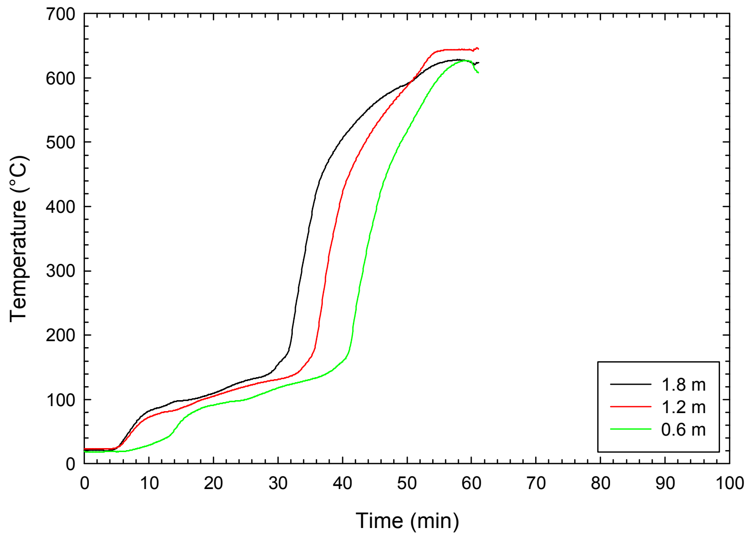


Figure 22. Temperatures interior bedroom/living room loadbearing wall cavity (south).

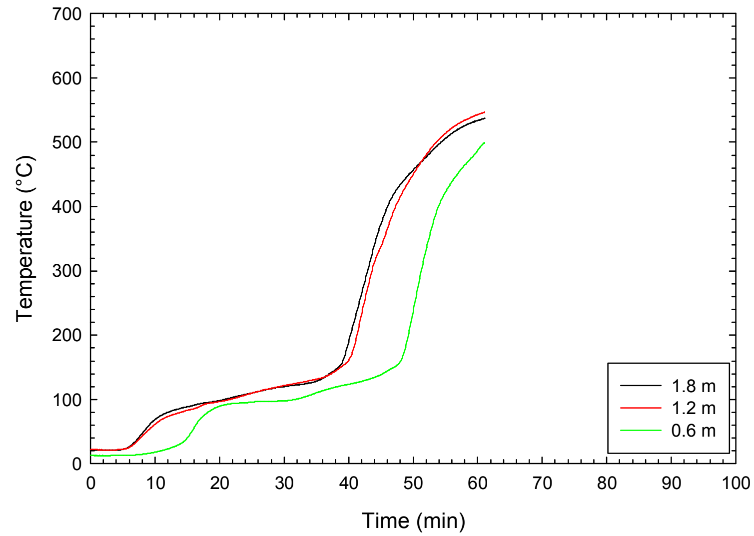


Figure 23. Temperatures interior bedroom/living room loadbearing wall cavity (north).

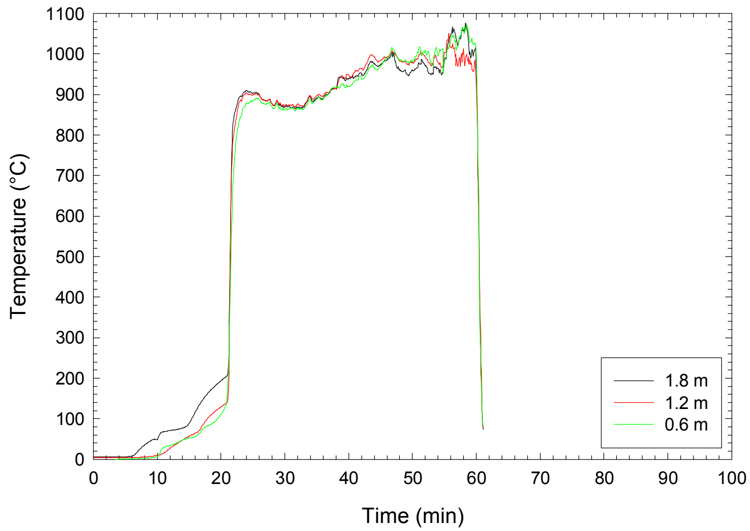


Figure 24. Temperatures exterior bedroom wall cavity (east).

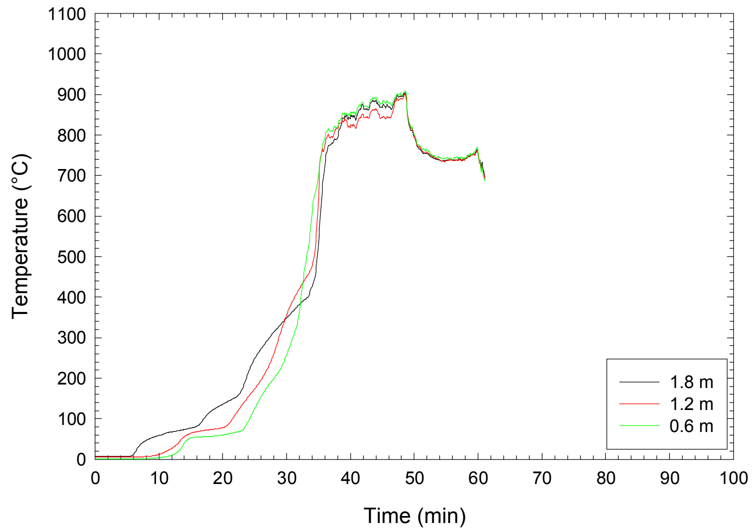


Figure 25 Temperatures exterior bedroom wall cavity (west).

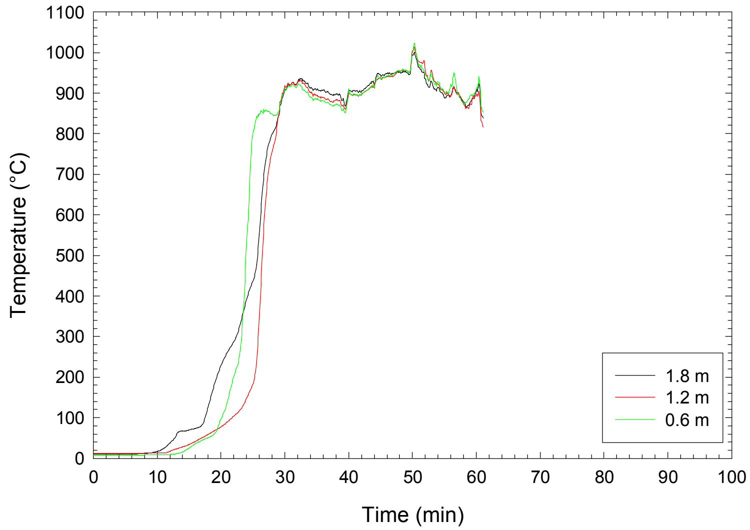


Figure 26. Temperatures exterior living room wall cavity (east).

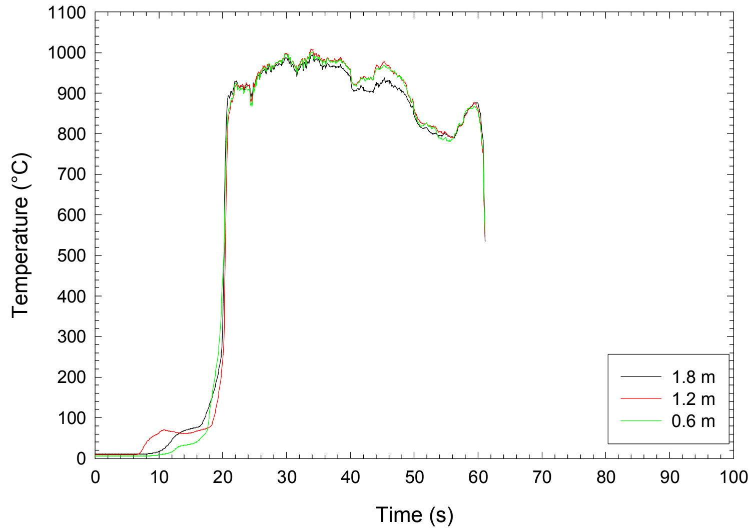


Figure 27. Temperatures exterior living room wall cavity (west).

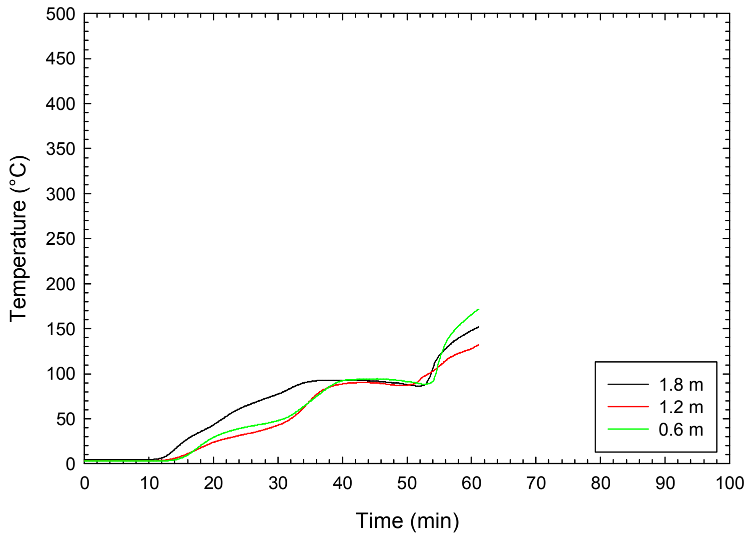


Figure 28. Temperatures east living room/kitchen wall cavity (south).

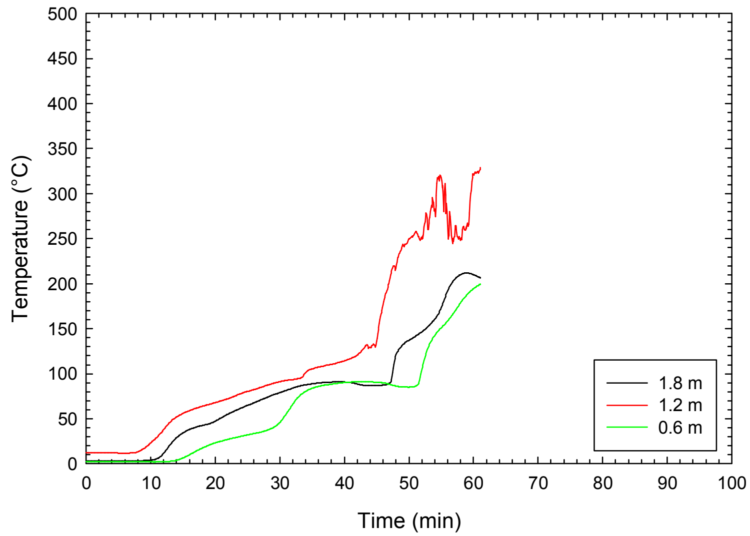


Figure 29. Temperatures east living room/kitchen wall cavity (center).

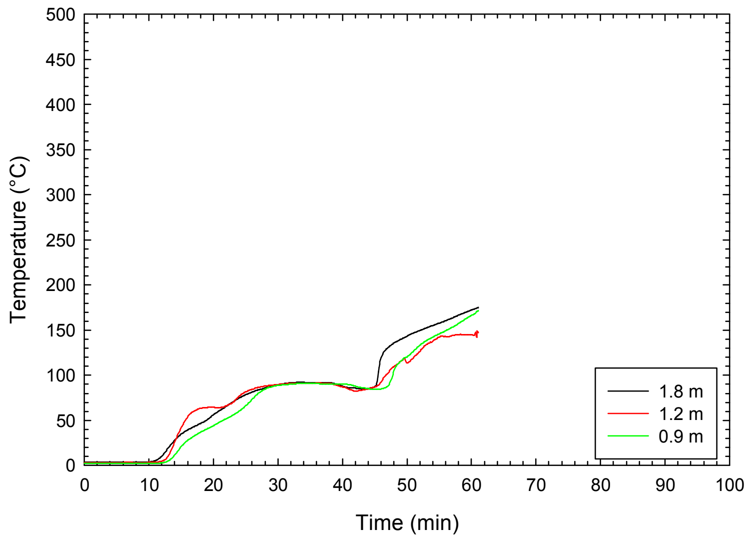


Figure 30. Temperatures east living room/kitchen wall cavity (north).

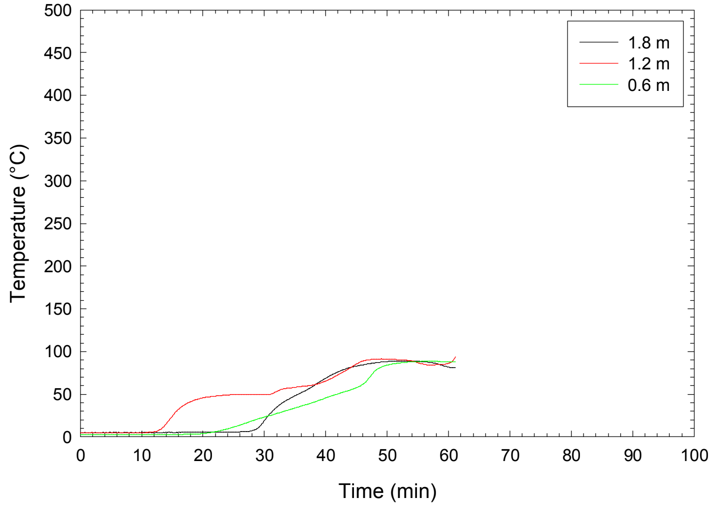


Figure 31. Temperatures south corridor wall cavity (east).

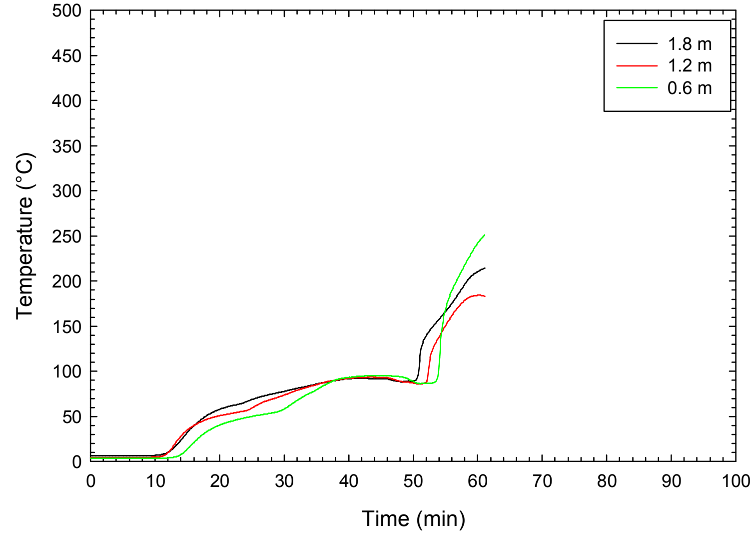


Figure 32. Temperatures south corridor wall cavity (center).

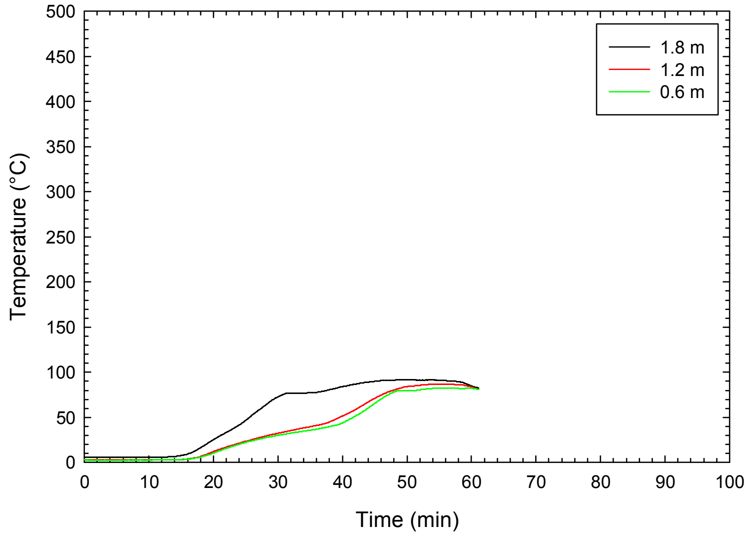


Figure 33. Temperatures south corridor wall cavity (west).

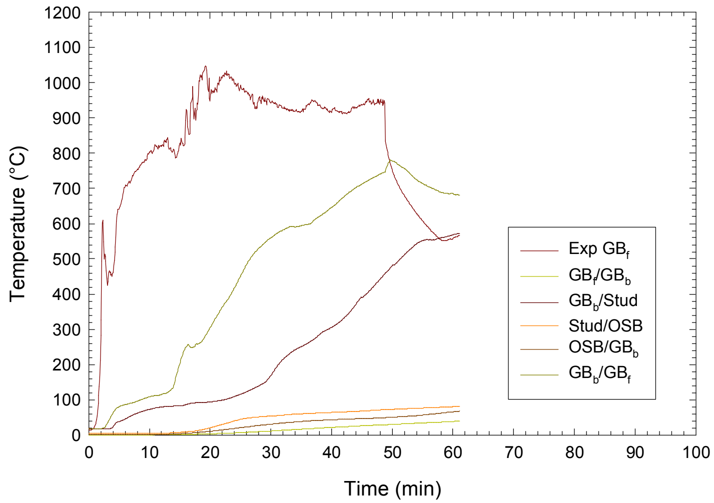


Figure 34. Temperature profiles at 1.2 m height in west bedroom wall.

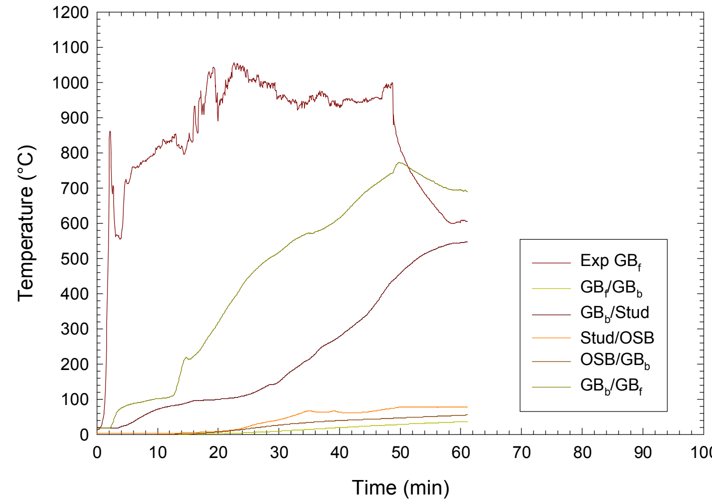


Figure 35. Temperature profiles at 1.8 m height in west bedroom wall.

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/Stud	Interface between base layer of gypsum board and wood stud.
Stud/OSB	Interface between wood stud and OSB shear panel on the unexposed (outer) side of the wall assembly.
OSB/GB_b	Interface between OSB shear panel and base layer of gypsum board on unexposed (outer) side of the wall assembly.
GB_b/GB_f	Interface between the base and face layers of gypsum board on the unexposed side of the wall assembly.

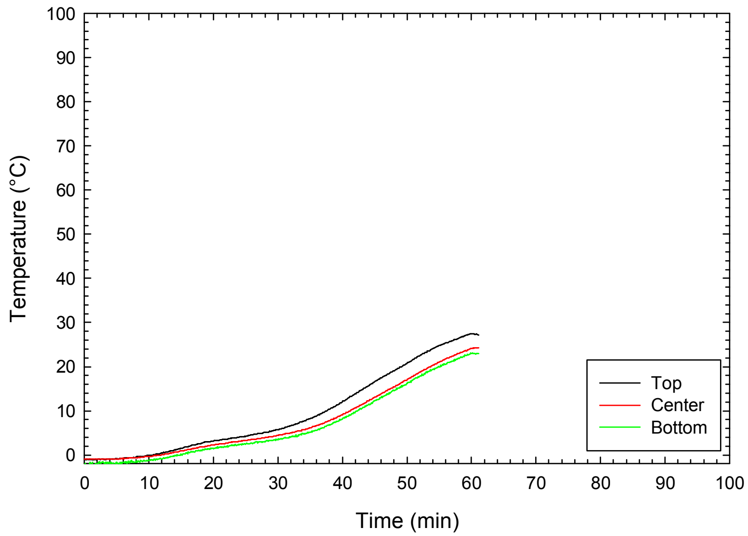


Figure 36. Temperatures unexposed side of west bedroom wall (south).

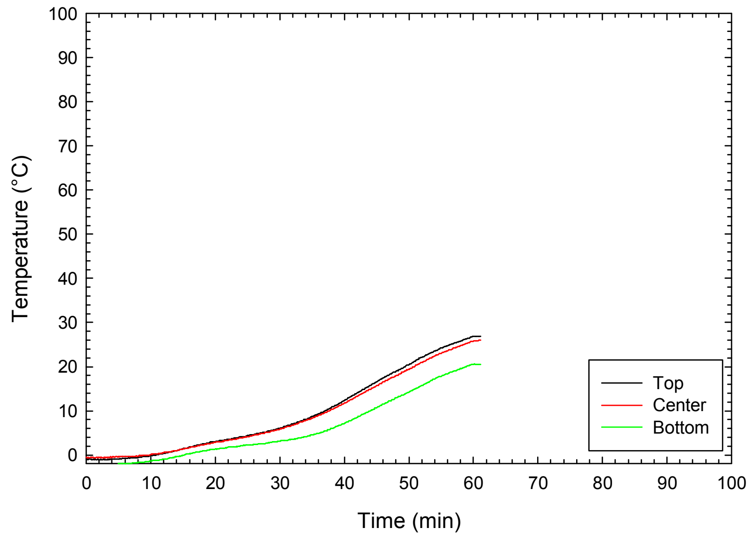


Figure 37. Temperatures unexposed side of west bedroom wall (center).

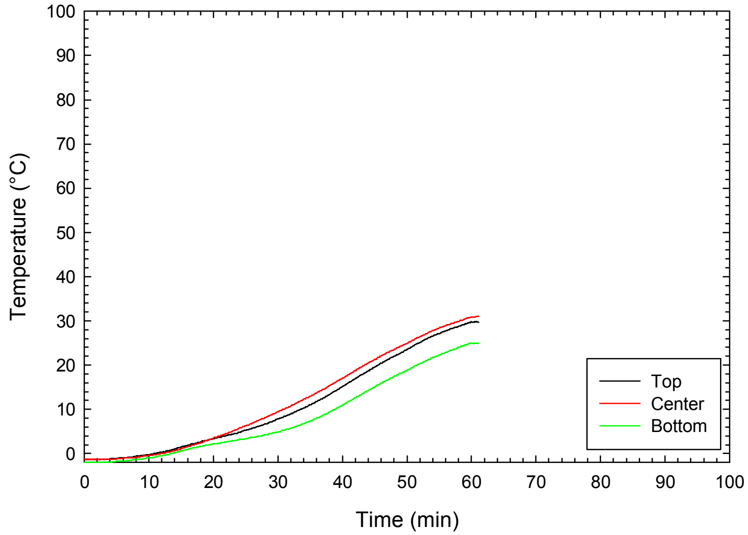


Figure 38. Temperatures unexposed side of west bedroom wall (north).

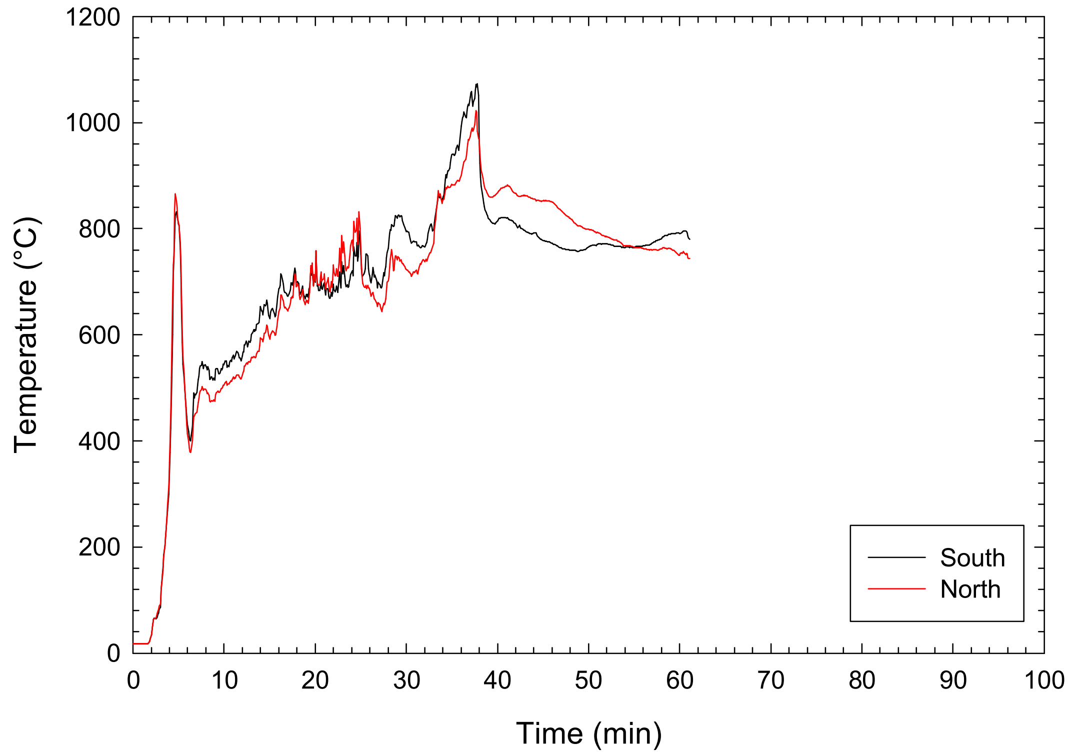


Figure 39. Temperatures on unexposed side of living room/bedroom door.

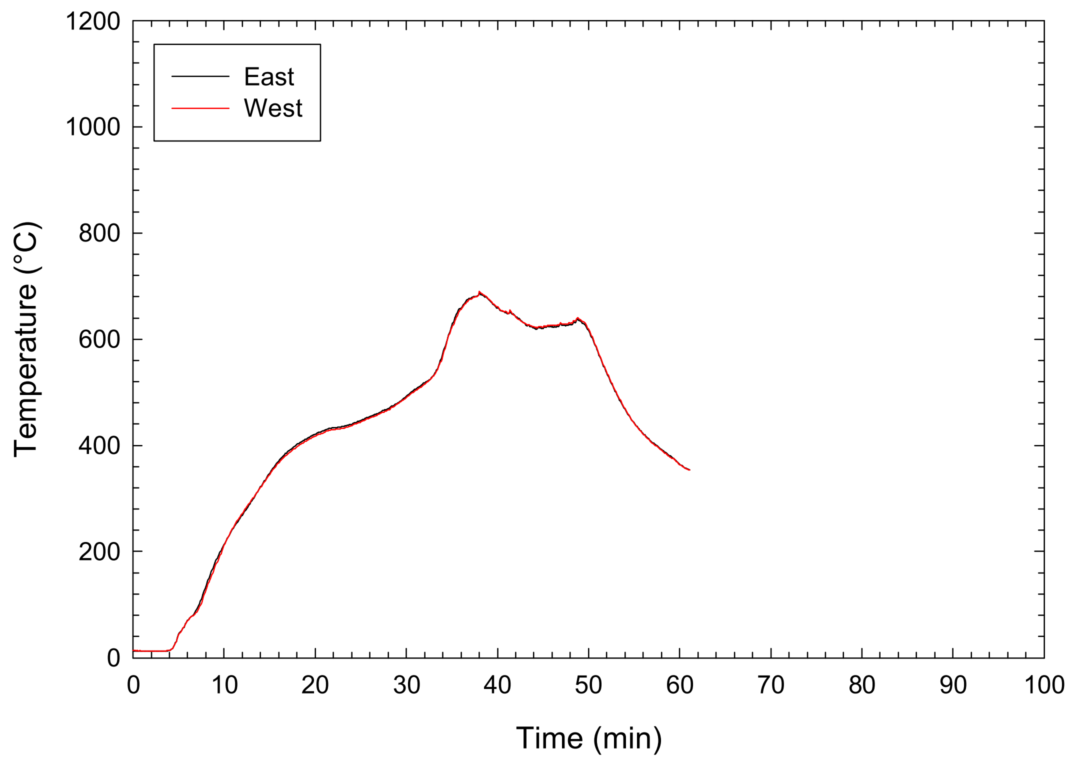


Figure 40. Temperatures on unexposed side of corridor door.

11.3 Temperatures in Ceiling/Floor Assemblies

For both of the floor/ceiling assemblies in the test structure, two layers of 12.7 mm thick Type X gypsum board were attached to the wood I-joists using resilient metal channels (RMCs). Thermocouples were located in the I-joist cavities of the floor assemblies both above and below the bedroom and the living room/kitchen areas. The approximate location of thermocouples in the joist cavities in the ceiling/floor assemblies on both storeys (levels) are shown in the sketch in Figure 9. For the ceiling assemblies above the middle (fire) floor, the thermocouples were located on the unexposed side of the insulation in the joist cavities.

11.3.1 Ceiling Assembly in Bedroom

Nine thermocouples were located in the I-joist cavity of 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.

The measured temperatures are shown in Figure 41, Figure 42 and Figure 43. The temperatures followed the same general trend as those measured in the west bedroom wall with an initial temperature increase, followed by a temperature plateau as the two layers of gypsum board calcined and a final stage with a more rapid temperature increase.

The time at which the steady temperature stage ended depended on the location in the bedroom. The thermocouples in the joist cavity at the southeast and south center locations indicated a rapid temperature increase at approximately 22 min and 24 min, respectively. A similar rapid temperature increase in the other joist cavities occurred at the center and north ends of the bedroom with the steady stage temperature stage ending at approximately 28 – 30 min.

The temperature increases in the bedroom ceiling joist cavity was generally earlier than in the first test. There was also no transition period between the steady temperature phase and the third temperature increase phase as normally occurred with heat transfer through gypsum board. The thermocouples located at the southeast and center-east locations were close to the partition wall at the south end of the bedroom and the hot gases from the bedroom may have entered the joist cavity through the openings to the ceiling cavity produced with the fall-off the gypsum board on the partition wall. In addition, there may have been hot air leakage into the joist space cavity once the fire penetrated into the exterior wall cavity space.

The time at which the temperature reached 300ºC at the nine thermocouple locations in the joist cavities is summarized in Table 4. The time at which the temperatures exceeded 300ºC depended on the location of the thermocouple. The earliest time (23 min) was at the southeast room quarter point and the temperature exceeded 300ºC at all other locations by 30 min. These times were 10 - 15 min earlier than in first test with LWF assemblies (Test APT-LWF-1 [3]).

Based on the temperatures measured by the nine thermocouples in the ceiling joist cavities above the insulation in the joist cavities, the encapsulation time for the two layers of 12.7 mm thick Type X gypsum board plus the insulation in the ceiling above the bedroom was 23 min based on a single point temperature increase of 270°C. Based on the average temperature increase for the nine thermocouples, the 250°C average temperature increase criterion was exceeded at 28 min.

The temperatures in the bedroom joist cavity exceeded 700ºC between 30 and 36 min depending on the location indicating the fire had penetrated into the joist space. Steady temperatures > 800ºC were subsequently measured until approximately 50 min at which time the temperatures decreased with the failure of the floor system.

11.3.2 Ceiling Assembly in Living Room/Kitchen Area

Nine thermocouples were located in the I-joist cavity of the ceiling/floor assembly above the living room and kitchen areas. The thermocouples were located at the quarter- and mid-widths and lengths of the living room/kitchen area. The measured temperatures are shown in Figure 44, Figure 45 and Figure 46. The time at which the temperature reached 300ºC at the nine thermocouple locations is summarized in Table 5.

The earliest times (32 – 35 min) to reach 300ºC in the I-joist cavity space in the living room and kitchen areas were at the thermocouple locations at the mid-length and north end of the living room area. The temperatures in the joist cavity in the kitchen area exceeded 300ºC by 40 min.

Based on the temperatures measured by the nine thermocouples in the ceiling joist cavities above the insulation in the joist cavities, the encapsulation time for the two layers of 12.7 mm thick Type X gypsum board plus the insulation in the ceiling above the living room/kitchen area was 32 min based on a single point temperature increase of 270°C.. Based on the average temperature increase for the nine thermocouples, the 250°C average temperature increase criterion was exceeded at 34 min.

The temperatures in the joist cavities exceeded 700ºC between 35 and 42 min depending on location in the living room and kitchen. The earliest times were at the mid-length of the living room and kitchen area and the longest time at the west side of the kitchen.

The temperatures subsequently increased to peak temperatures between 950 – 1000ºC at approximately 48 min. After 48 min, the temperatures decreased with the collapse of the floor.

11.3.3 Interface Temperature Profiles in Bedroom Ceiling Assembly

Seven thermocouples were located at the center of the bedroom to measure the temperature at each interface between the various materials used in the construction of the wood I-joist ceiling/floor assembly above the fire area. The temperatures measured using these seven 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 seven 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 layers of gypsum board on the exposed (fire) side of the wood I-joist ceiling/floor assembly.
3. Interface between the base layer of gypsum board and the cavity space.
4. Interface between the resilient metal channel and the wood I-joist.
5. Interface between the wood I-joist and OSB subfloor
6. Interface between the OSB and base layer of cement board on the unexposed (upper) side of the ceiling/floor assembly
7. Interface between the base and face layers of cement board on the unexposed (upper) side of the ceiling/floor assembly

The temperatures measured at each interface in the ceiling assembly are shown in Figure 47.

General comments regarding the temperatures measured at each interface between the various materials in the wood I-joist ceiling assembly above the bedroom are as follows:

1. **Exposed surface of the face layer of gypsum board.** There was a rapid increase in the temperature measured on the exposed surface of the face layer of gypsum board with an initial peak temperature of 700ºC at 3 min followed by short dip in temperature. The temperature subsequently increased reaching 1160ºC at 16 min. Starting at 18 min, there were rapid fluctuations in the temperature with a decrease to 544ºC at 18 min followed by an increase to 1200ºC. These fluctuations corresponded to the fall-off the face layer of gypsum board at the center of the bedroom ceiling. After the fall-off of the gypsum board, the exact location of the thermocouple in the bedroom is not known.
2. **Interface between the face and base layers of gypsum board on the exposed (fire) side of the assembly**. The temperature reached 300ºC at the interface between the two layers of gypsum board at 17 min. The temperature increase at this location exceeded 270°C at 16 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 in temperature between 18 and 19 min. At 19 min the temperature exceeded 1000ºC with the fall-off of the face layer of gypsum board at the center of the bedroom ceiling.
3. **Interface between the base layer of gypsum board and the cavity space.** The temperature reached 300ºC at the interface between the base gypsum board layer and wood I-joist cavity at 25 min. The temperature increase at this location exceeded 270°C at 25 min providing an estimate for the encapsulation time based on a single point measurement. Subsequently, there was a steady increase to temperature > 800ºC at 28 min indicating falloff of the base layer of gypsum board.
4. **Interface between the resilient metal channel and the wood I-joist.** The temperatures measured at the interface between the resilient metal channel and the joist lagged the temperature measured at the gypsum board/cavity interface. The temperature reached 300ºC at 26 min. Subsequently, there was a rapid increase in temperature to > 800ºC at 27 min indicating falloff of the base layer of gypsum board. The temperature increase at this location exceeded 270°C at 26 min providing an estimate for the encapsulation time for the two layers of 12.7 mm thick Type X gypsum board and the resilient channel.
5. **Interface between the wood I-joist and OSB subfloor**. The temperature at the interface between the joist and the OSB subfloor was < 100ºC until 35 min. Subsequently, there was a rapid increase to > 800ºC indicating flaming combustion at this location.
6. **Interface between the OSB and base layer of cement board on the unexposed (upper) side of the ceiling/floor assembly.** The temperature at the interface between the OSB and the cement board was < 100ºC until 41 min. Subsequently, there was a rapid increase to > 800ºC by 46 min indicating flaming combustion at this location..
7. **Interface between the base and face layers of cement board on the unexposed (upper) side of the ceiling/floor assembly.** The temperature at the interface between the two layers of cement board was < 100ºC until 45 min. Subsequently, there were rapid fluctuations in temperature with an initial peak at approximately 48 min with the collapse of the floor assembly indicating flaming combustion at this location..

11.3.4 Temperatures Measured on Unexposed Side of Ceiling Assembly Above Bedroom

Nine thermocouples covered with the pads used in standard fire resistance tests [9] were located on exposed surface (top) of the face layer of cement board of the ceiling/floor assembly above the bedroom on the fire floor. 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 cavity shown in Figure 9. The measured temperatures are shown in Figure 48, Figure 49 and Figure 50.

There was a gradual increase in the temperatures at the nine thermocouple locations until approximately 49 min with the measured temperature < 80ºC. Between 49 and 53 min, there was a rapid increase in the temperatures with the failure of the floor assembly.

11.3.5 Summary Temperatures in Ceiling Assembly of the Second Storey (Fire Floor)

The encapsulation times for the ceiling/floor 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 (16 min). This time is based on a single measurement at the center of 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 thick Type X gypsum board fastened to resilient metal channels varied depending on the measurement used. The shortest time was based on the 9 thermocouples located in the bedroom joist cavity with the single point temperature increase exceeded at 23 min at the southeast thermocouple location. The encapsulation time based on the average of the 9 thermocouples was 28 min which is comparable to the encapsulation time determined using the measurements at the center of the bedroom with 25 min at the gypsum board interface with the resilient channel and 26 min at the interface between the resilient channel and the joist.
3. The encapsulation time for the two layers of 12.7 mm thick Type X gypsum board fastened to resilient metal channels in the living room ceiling was 32 min based on the 9 thermocouples located in the joist cavity. The earliest time to reach a temperature increase of 270ºC was at the thermocouple location on the west side of the living room at its mid-length. The encapsulation time determined in the living room is comparable to the time at which there was a rapid increase in temperature in the wood I-joist cavity indicating that the base layer of gypsum board was falling off.

The results of the measurements in the ceiling assembly of the second storey (fire floor) indicate:

1. There were high temperature gases in the joist cavities of the ceiling in the southeast section of the bedroom at approximately 22 min. (Hot gases may have entered the joist space in the area around the top plates for the partition wall separating the bedroom and entryway/bathroom.)
2. The falloff of the face layer of gypsum board in the bedroom occurred at approximately 19 min.
3. The two layers of gypsum board limited the temperature at the joist to < 300ºC until approximately 25 min.
4. There was a rapid increase in temperatures in the joist cavities in the bedroom area after 27 min indicating falloff of the base layer of gypsum board.

5. There was a rapid increase in temperatures in the joist cavities in the living room and kitchen area after 32 min indicating falloff of the base layer of gypsum board.
6. The temperatures at the interfaces for the materials in the floor portion of the ceiling floor assembly were <100ºC until 35 min. Subsequently, there was a rapid increase in the temperature measured at the interfaces in the floor portion of the assembly with the progressive collapse of the floor system (Figure 47).

Table 4. Time temperature reached 300ºC in bedroom ceiling joist cavity.

Thermocouple Location	Time (min)
Southeast	23
South-center	30
Southwest	35
Center-east	25
Center	30
Center-west	30
Northeast	30
North-center	29
Northwest	28

Table 5. Time temperature reached 300ºC in living room/kitchen ceiling joist cavity.

Thermocouple Location	Time (min)
Southeast	36
South-center	39
Southwest	40
Center-east	32
Center	34
Center-west	33
Northeast	35
North-center	34
Northwest	34

Table 6. Encapsulation times based on measurements in ceiling assembly of the second 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	16
	2 layers 12.7 mm thick Type X GB	9 thermocouples joist cavity	28	23
	2 layers 12.7 mm thick Type X GB	1 thermocouple GB_b/cavity interface	NA	25
	2 layers 12.7 mm thick Type X GB +RMC	1 thermocouple RMC/joist interface	NA	26
Living room/Kitchen	2 layers 12.7 mm thick Type X GB	9 thermocouples joist cavity	34	32

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

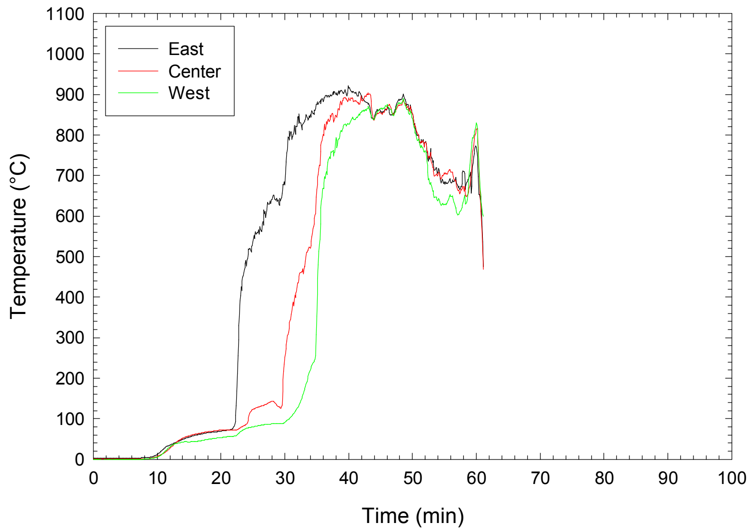


Figure 41. Temperatures bedroom ceiling joist cavity (south).

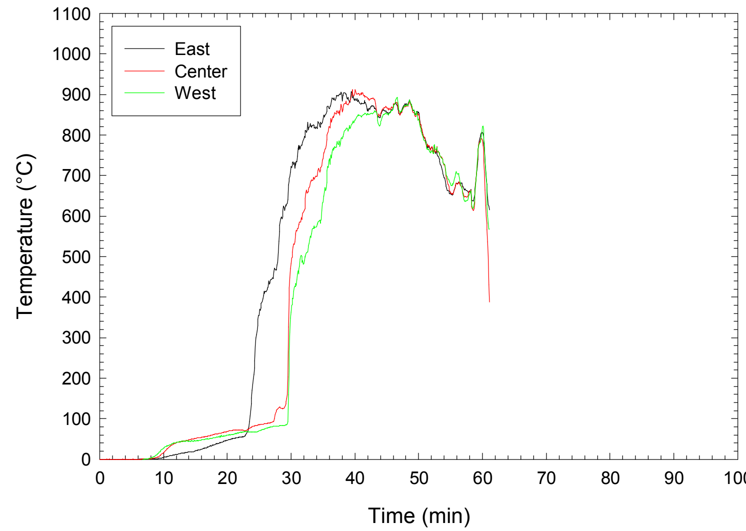


Figure 42. Temperatures bedroom ceiling joist cavity (center).

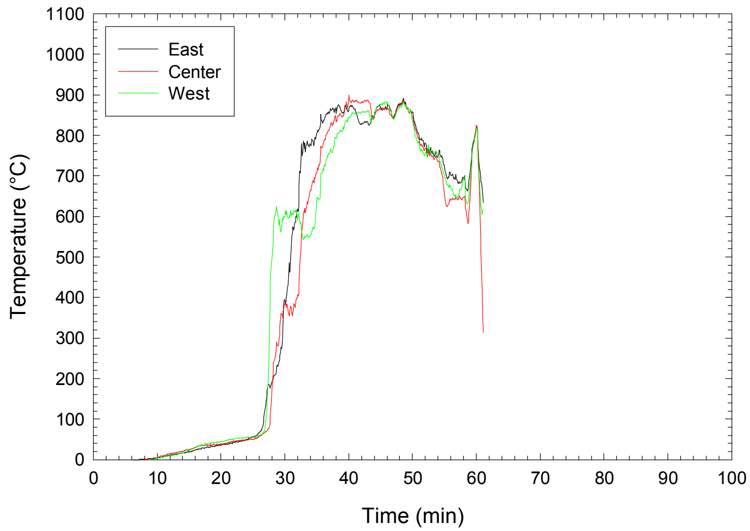


Figure 43. Temperatures bedroom ceiling joist cavity (north).

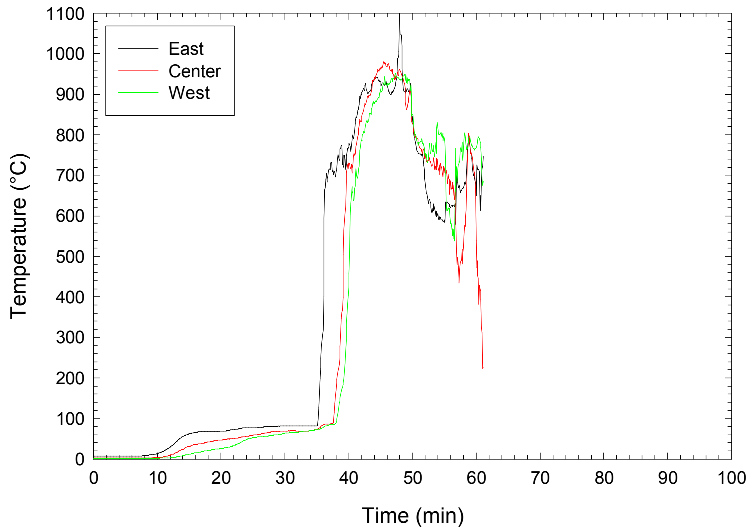


Figure 44. Temperatures living room/kitchen ceiling joist cavity (south).

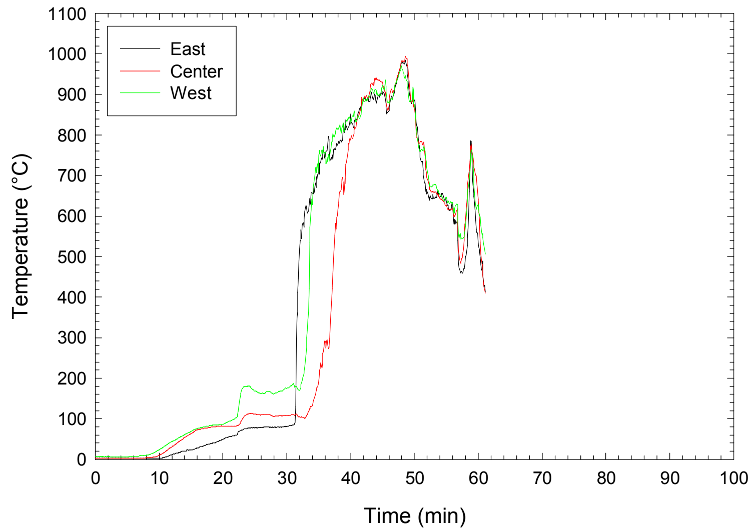


Figure 45. Temperatures living room/kitchen ceiling joist cavity (center).

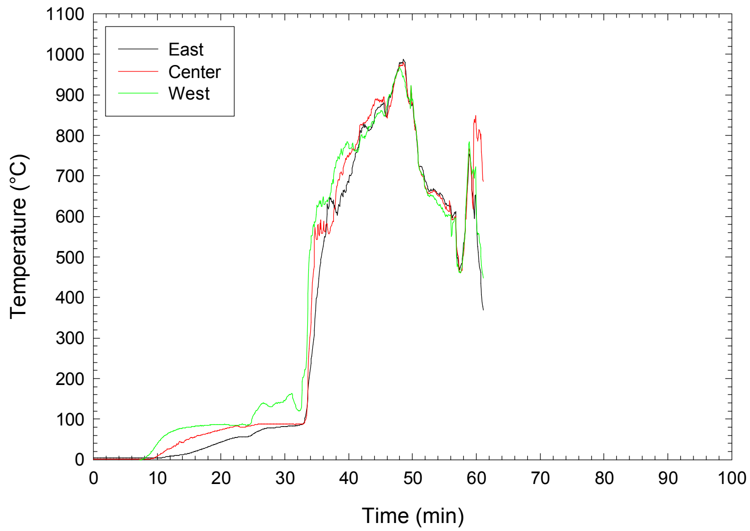


Figure 46. Temperatures living room/kitchen ceiling joist cavity (north).

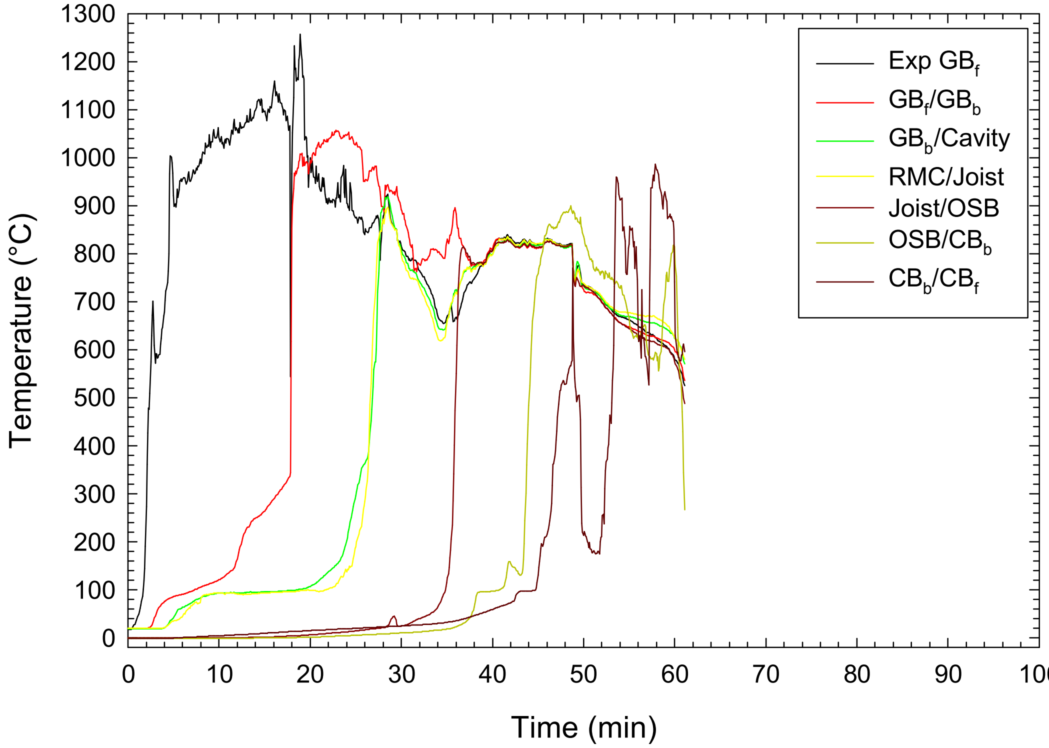


Figure 47. Temperature profiles in ceiling/floor assembly at center of the bedroom.

Exp GB_f	Exposed surface of the face layer of gypsum board.
GB_f/GB_b	Interface between the face and base layers of gypsum board on the exposed (fire) side of the wood I-joist ceiling/floor assembly.
GB_b/Cav	Interface between the base layer of gypsum board and the I-joist cavity.
RMC/Jst	Interface between the resilient metal channel and the wood I-joist.
Jst/OSB	Interface between the wood I-joist and OSB subfloor.
OSB/CB_b	Interface between the OSB subfloor and base layer of cement board on the unexposed (upper) side of the ceiling/floor assembly.
CB_b/CB_f	Interface between the base and face layers of cement board on the unexposed (upper) side of the ceiling/floor assembly.

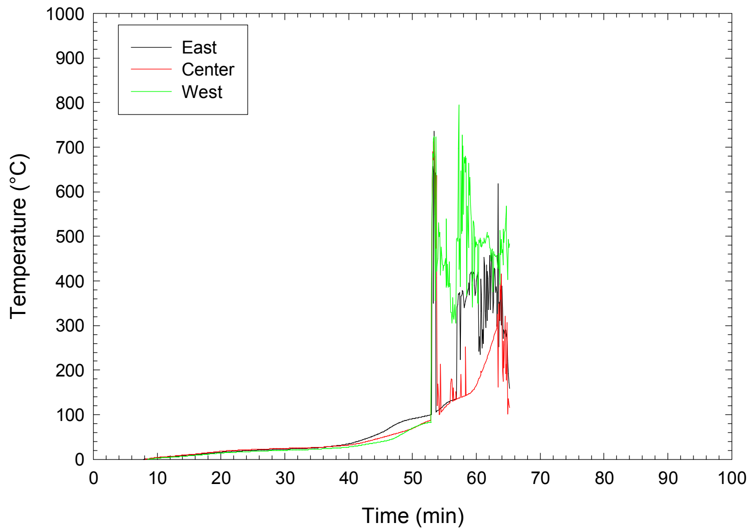


Figure 48. Temperatures floor on third storey bedroom (south).

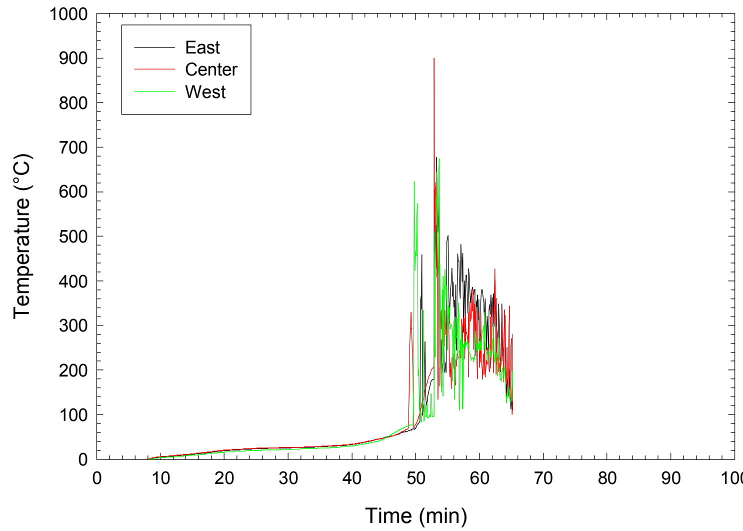


Figure 49. Temperatures floor on third storey bedroom (center).

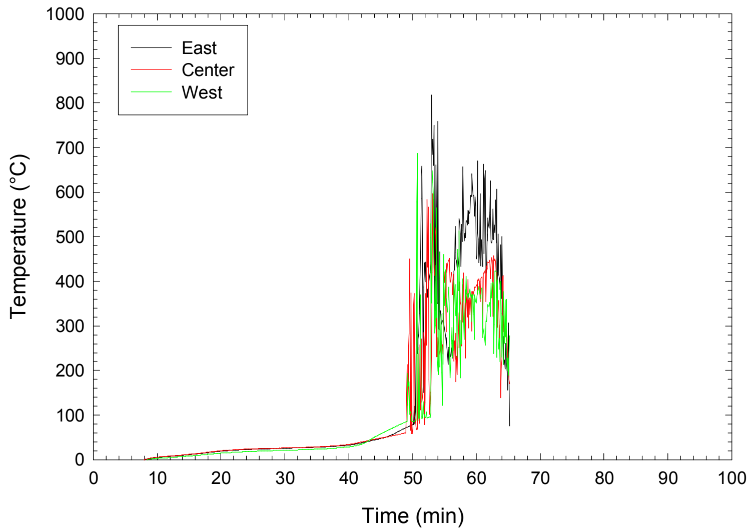


Figure 50. Temperatures floor on third storey bedroom (north).

11.4 Temperatures in the Floor Assembly of the Fire Floor

For both of the floor/ceiling assemblies in the test structure, two layers of 12.7 mm thick Type X gypsum board were attached to the wood I-joists using resilient metal channels (RMCs). Thermocouples were located in the I-joist cavities of the floor assemblies both above and below the bedroom and the living room/ kitchen areas The approximate location of thermocouples in the joist cavities in the ceiling/floor assemblies are shown in the sketch in Figure 9.

11.4.1 Floor Assembly in Bedroom

Nine thermocouples were located in the I-joist cavities below the bedroom. The thermocouples were located at the quarter- and mid-widths and lengths of the bedroom area excluding the closet.

The measured temperatures are shown in Figure 51, Figure 52 and Figure 53. The temperatures in the I-joist remained at or near ambient until approximately 22 min. After 22 min, there was a gradual increase in temperature until the end of the test. The maximum temperature (57ºC) was measured in the northeast section of the bedroom. The maximum temperatures at the other locations were between 26 and 50ºC.

11.4.2 Floor Assembly in Living Room

Nine thermocouples were located in the I-joist cavities for the floor/ceiling assembly below the living room/kitchen area. The thermocouples were located at the quarter- and mid-widths and lengths of the area.

The measured temperatures are shown in Figure 54, Figure 55 and Figure 56. The temperatures remained at or near ambient until after 25 min. The earliest temperature increases were at the north end of the living room near the ventilation opening in the exterior wall. The maximum temperatures at this location were between 37 and 53ºC at the end of the test.

There was minimal or no temperature increase at the center and south end of the living room/kitchen area with the maximum temperatures <26ºC.

The maximum temperatures in the floor joist cavities were well below 300ºC throughout the tests and the floor joists would not be affected by the fire.

11.4.3 Interface Temperatures in Bedroom Floor Assembly on OSB Subfloor

In addition to the temperatures measured at nine different locations in the floor joist cavities in the floor/ceiling assembly between the middle (second) and lowest (first) storeys, nine thermocouples were also located at the interface between the OSB subfloor and the acoustic membrane used between the cement board and the subfloor. The measured temperatures are shown in Figure 57, Figure 58 and Figure 59.

There was an initial temperature increase to 60 – 80ºC followed by a steady temperature plateau as the water in the cement board was driven off. Subsequently, there was a faster increase in temperatures. The times for the temperatures to reach approximately 100ºC are summarized in Table 7. The earliest time (26 min) was at the northeast thermocouple location. However, after 25 min, the temperature profile was not consistent with those at the other locations indicating thermocouple may have failed or been located at a joint in the cement board.

At the other thermocouple locations, the temperature exceeded 100ºC after 55 min and at several locations did not reach this temperature.

The temperatures remained under 300ºC throughout the test. These results indicate that the fire had minimal or no effect on the bedroom subfloor. The temperature criteria for encapsulation materials were not exceeded during the duration of the test.

11.4.4 Interface Temperature Profiles in Bedroom Floor Assembly

Nine thermocouples were located at the center of the bedroom to measure the temperature at each interface between materials used in the construction of the wood I-joist floor/ceiling assembly between the first and second stories. The temperatures measured using these thermocouples are shown in Figure 60.
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 face and base layers of cement board.
3. Interface between the base layer of cement board and acoustic membrane used between subfloor and the base layer of cement board.
4.
5. Interface between the OSB subfloor and the acoustic membrane used between the subfloor and the base layer of cement board.
6. Interface between the OSB subfloor and wood I-joist.
7. Interface between the resilient metal channel (ceiling) in the lowest storey and the wood I-joist.
8. Interface between the base layer of gypsum board and the joist cavity.
9. Interface between the face and base layer of gypsum board (ceiling) in the lowest (first) storey.
10. Unexposed surface of the face layer of gypsum board.

General comments regarding the temperatures measured at each interface in the assembly are as follows:

1. **Temperature exposed face of hardwood flooring.** There was an initial peak temperature of 738ºC at 3 min followed by short dip in temperature. Subsequently, the temperature increased to > 700ºC by 4 min and remained above this temperature until 53 min. Temperatures > 900ºC were measured between 18 and 33 min.
2. **Interface between the face and base layers of cement board.** Temperature reached 100ºC at 22 min and 300ºC at 30 min. Subsequently, there was a gradual increase in temperature to a maximum of 408ºC at 51 min.
3. **Interface between the cement board and the acoustic membrane used between the subfloor and the cement board.** Temperature reached 100ºC at 35 min. Subsequently, there was a gradual temperature increase in temperature until approximately 49 min after which there was a more rapid increase in temperature. The temperature at the end of the test was 241ºC.
4. **Interface between the OSB subfloor and the acoustic membrane used between the subfloor and the base layer of cement board.** There was a gradual increase in temperature starting at approximately 20 min unit 50 min. After 50 min, there was a more

rapid increase in temperature. The maximum temperature at the end of the test was 137ºC.

5. **Interface between the OSB subfloor and wood I-joist**. Gradual temperature increase throughout the test to a maximum temperature of 30ºC.
6. **Interface between the resilient metal channel and wood I-joist**. There was a minimal temperature increase (< 1ºC).
7. **Interface between the base layer of gypsum board and the joist cavity**. There was a minimal temperature increase (< 1ºC).
8. **Interface between the face and base layer of gypsum board.** There was a minimal temperature increase (< 1ºC).
9. **Unexposed surface of the face layer of gypsum board**. There was a minimal temperature increase (< 1ºC).

11.4.5 Summary of Temperatures in Floor Assembly of the Second Storey (fire floor)

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

1. The temperature increase at the interface between the face and base layer of cement board reached 270ºC at 30 min (Table 8). This provides an estimate for the encapsulation time provided by the hardwood floor, acoustic membrane and the face layer of cement board based on a single measurement at the center of the bedroom.
2. The temperatures measured at the interface of the OSB subfloor with the acoustic membrane material indicate that the temperatures did not exceed 300ºC. Therefore, the fire had minimal effect or no effect on the subfloor and the acoustic membrane material.
3. The temperature increase at the interface between the OSB subfloor and the acoustic membrane did not reach 270ºC (Table 8) and the average temperature increase did not reach 250ºC. Based on these results, the hardwood flooring plus the two layers of cement board provided an encapsulation time of at least 61 min (test duration).
4. The maximum temperatures measured in the I-joist cavities below the bedroom floor and the living room/kitchen area were 57ºC and 53ºC, respectively. Based on these temperatures the fire had no effect on the joists.
5. There was minimal temperature increase in either of the two layers of gypsum board on the unexposed (lower) side (< 1ºC) of the floor assembly.

Table 7. Time temperature reached 100ºC at interface between OSB and acoustic membrane in bedroom floor.

Thermocouple Location	Time (min)
Southeast	DNR
South-center	DNR
Southwest	DNR
Center-east	59
Center	56
Center-west	DNR
Northeast	26
North-center	56
Northwest	DNR

Table 8. Encapsulation times for floor/ceiling assembly.

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	30
	Hardwood floor + acoustic membrane + 2 layers of cement board + acoustic membrane	1 thermocouple AM/OSB interface	NA	DNR
	Hardwood floor + acoustic membrane + 2 layers of cement board + acoustic membrane	9 thermocouple AM/OSB interface	DNR	DNR

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

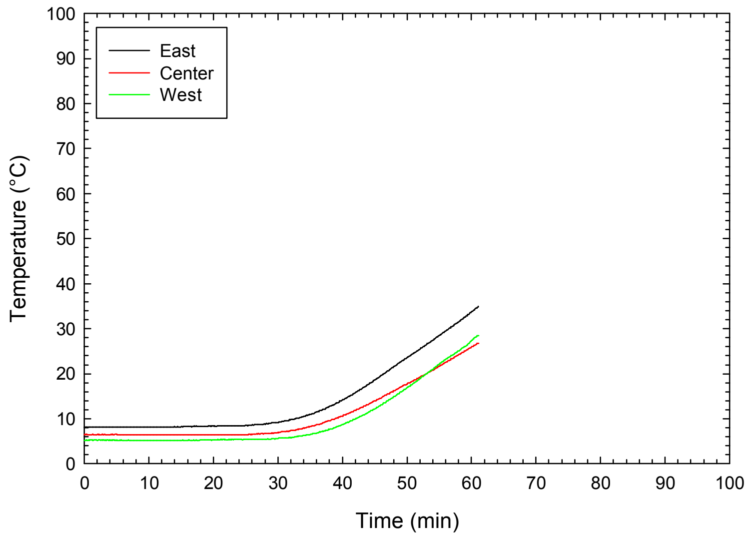


Figure 51. Temperatures bedroom floor joist cavity (south).

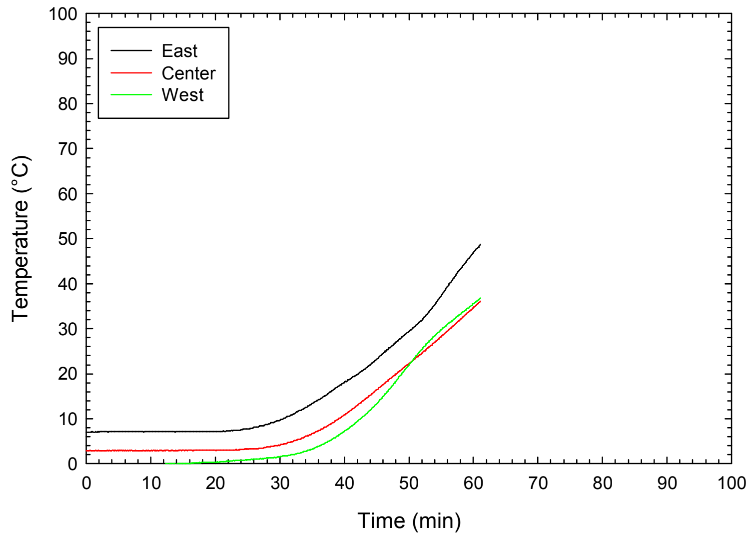


Figure 52. Temperatures bedroom floor joist cavity (center).

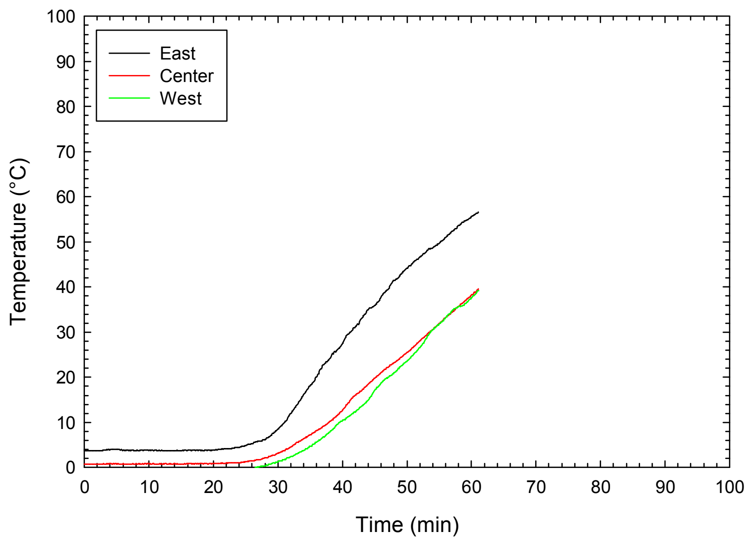


Figure 53. Temperatures bedroom floor joist cavity (north).

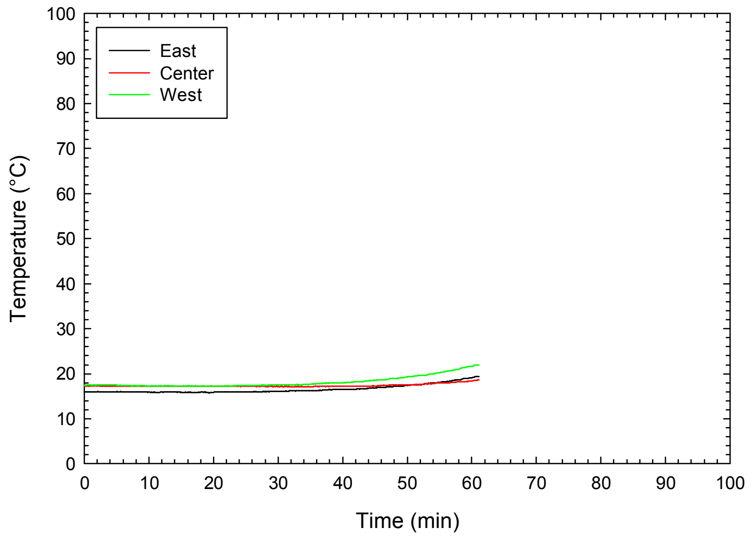


Figure 54. Temperatures living room/kitchen floor joist cavity (south).

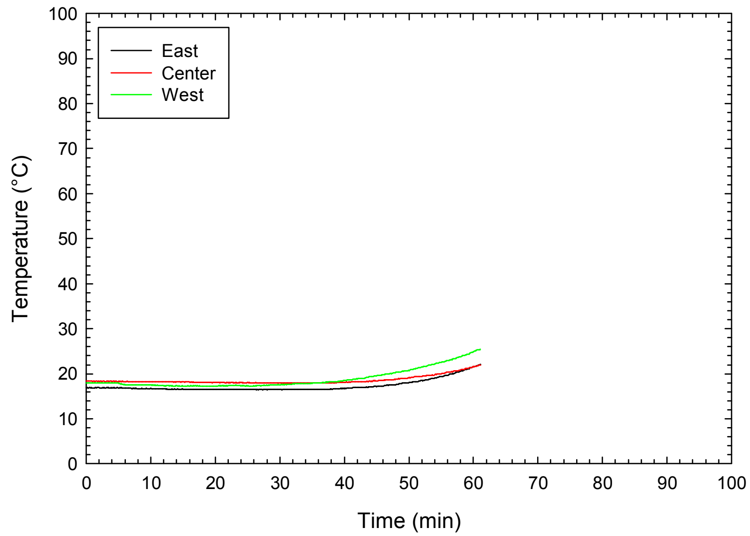


Figure 55. Temperatures living room/kitchen floor joist cavity (center).

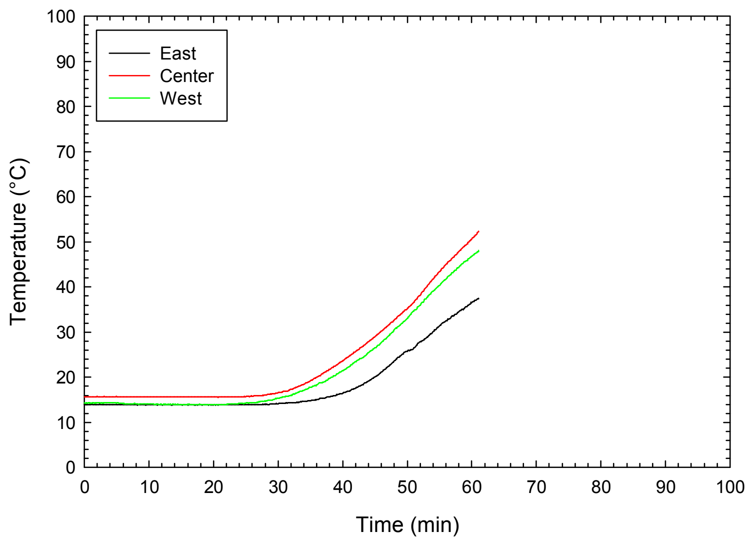


Figure 56. Temperatures living room/kitchen floor joist cavity (north).

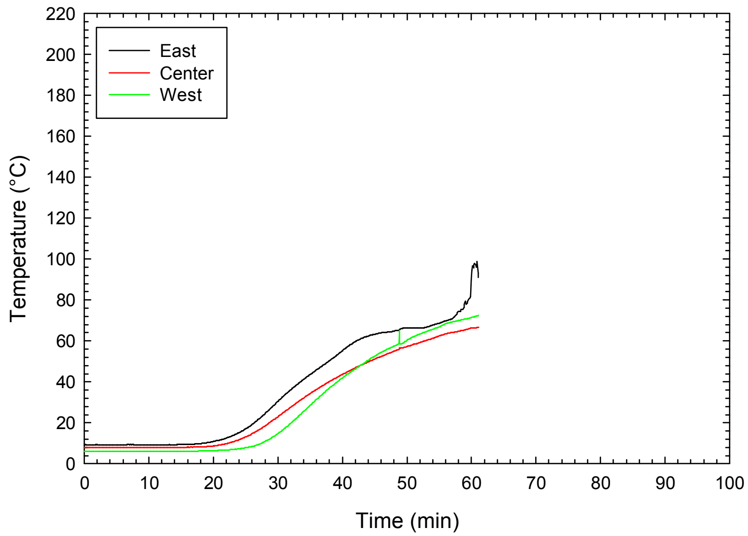


Figure 57. Temperatures cement board/OSB interface bedroom floor (south).

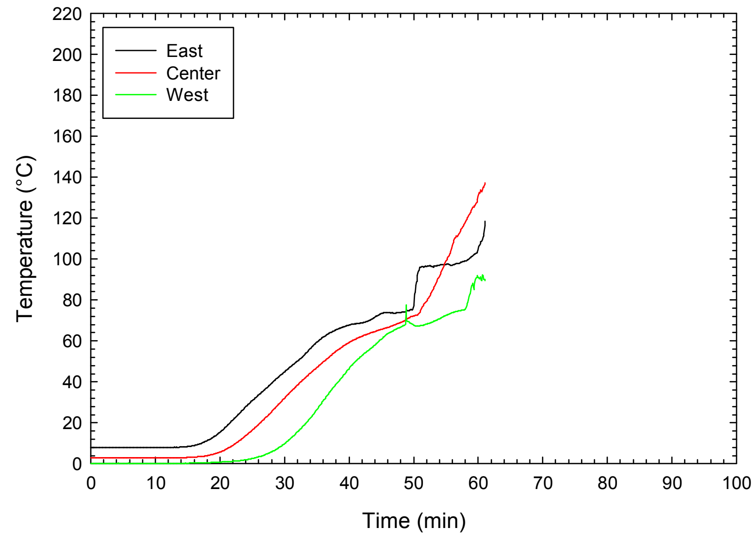


Figure 58. Temperatures cement board/OSB interface bedroom floor (center).

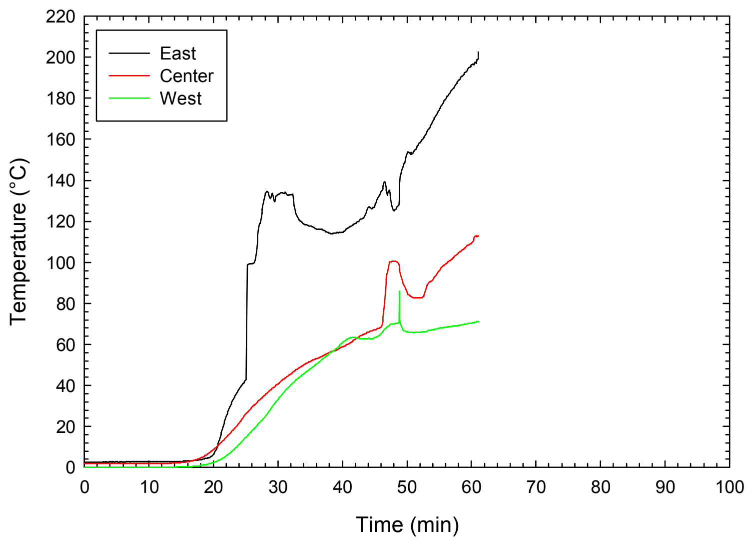


Figure 59. Temperatures cement board/OSB interface bedroom floor (north).

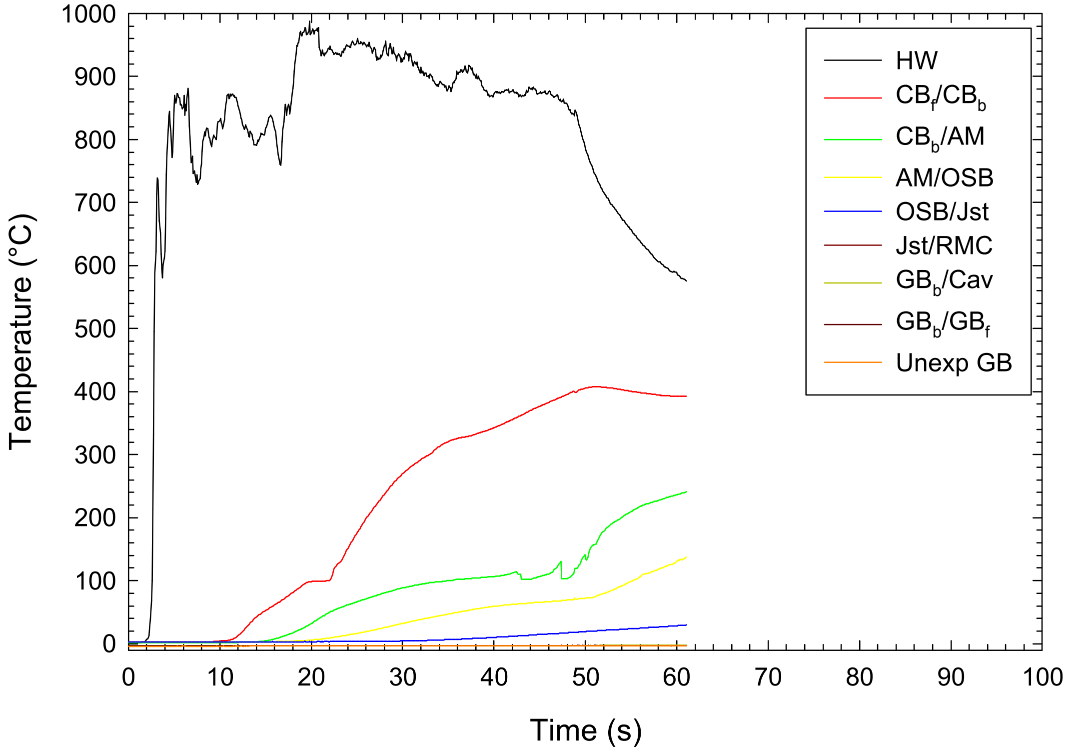


Figure 60. Temperature profiles in floor assembly at center of the bedroom.

HW	Exposed surface of hardwood floor.
CB_f/CB_b	Interface between face and base layer of cement board.
CB_b/AM	Interface between cement board and acoustic insulation.
AM/OSB	Interface between acoustic insulation and OSB.
OSB/Jst	Interface between joist and OSB.
Jst/RMC	Interface between joist and resilient channel.
GB_b/Cav	Base layer interface with joist cavity.
GB_b/GB_f	Interface between face and base gypsum board layers.
Unexp GB	Surface of face layer of gypsum board.

11.5 Temperatures Measured in the Third Storey

The third storey portion of the test arrangement that was used in the first test with LWF assemblies, as well as the test with the LSF assemblies and the CLT assemblies was not included in this test. There were no thermocouple trees used to measure temperatures in the third storey.

11.6 Heat Fluxes to the Exterior Wall Façade

Since the third storey portion of the test arrangement that was used in the first test with LWF assemblies, as well as the test with the LSF assemblies and the CLT assemblies was not included in the test setup for the second LWF assemblies, there was only a short height of exterior wall façade above the top of the openings in the bedroom and living room in this test. As a result, the heat fluxes to the exterior wall façade could not be measured in the second LWF test.

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 61 and Figure 62, respectively.

There was a rapid increase in the heat fluxes measured for the bedroom opening coinciding with flashover in the bedroom with an initial peak heat flux of 8.5 and 25.6 kW/m^2 at 4 min at the 4.8 and 2.4 m distance, respectively. Subsequently, the heat flux decreased before beginning to increase to a second peak. The heat flux at the 2.4 m distance was > 25 kW/m^2 between 10 and 15 min. The maximum heat flux was 29.2 kW/m^2, which occurred just after 12 min. After 15 min, the heat flux steadily decreased until 34 min before increasing with the burning of the joists and the subfloor in the ceiling/floor assembly above the fire floor. Also, the exterior wall section above the opening was fully open by this time increasing the field of view of the fire inside 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 from the opening.. The heat flux at the 4.8 m distance was > 5 kW/m^2 until approximately 34 min. The maximum heat flux was 9.3 kW/m^2 just after 12 min. There was a gradual increase in the measured heat flux after 34 min. This corresponds to the burning of the joists and the subfloor in the ceiling/floor assembly above the fire floor and the increased size of the opening in the exterior wall.

There was an initial heat flux measured by the heat flux meters located in front of the living room opening at approximately 4 min coinciding with the flashover in the bedroom with an initial peak heat flux of 3.4 kW/m^2 at the 4.8 m distance. After 8 min, there was a rapid increase in the heat flux coinciding with the flashover of the living room/kitchen area.

For the meter located 2.4 m from the opening, the heat flux was > 12.5 kW/m^2 between 8 and 50 min. A peak heat flux of 25.2 kW/m^2 was measured just after 15 min.

For the meter located 4.8 m from the opening, the heat flux was > 5 kW/m^2 between 7 and 49 min. A peak heat flux of 10.1 kW/m^2 was measured at approximately 14 min.

There was an increase in the measured heat fluxes at both distances in front of the opening in the living room exterior wall after approximately 34 min coinciding with the burning of the joists and subfloor in the ceiling above the fire floor and the increased opening size in the exterior wall.

The relatively steady heat fluxes measured for the living room opening are consistent with the progression of the fire from the living room to the kitchen and the eventual exposure and burning of the joists and subfloor above the fire floor.

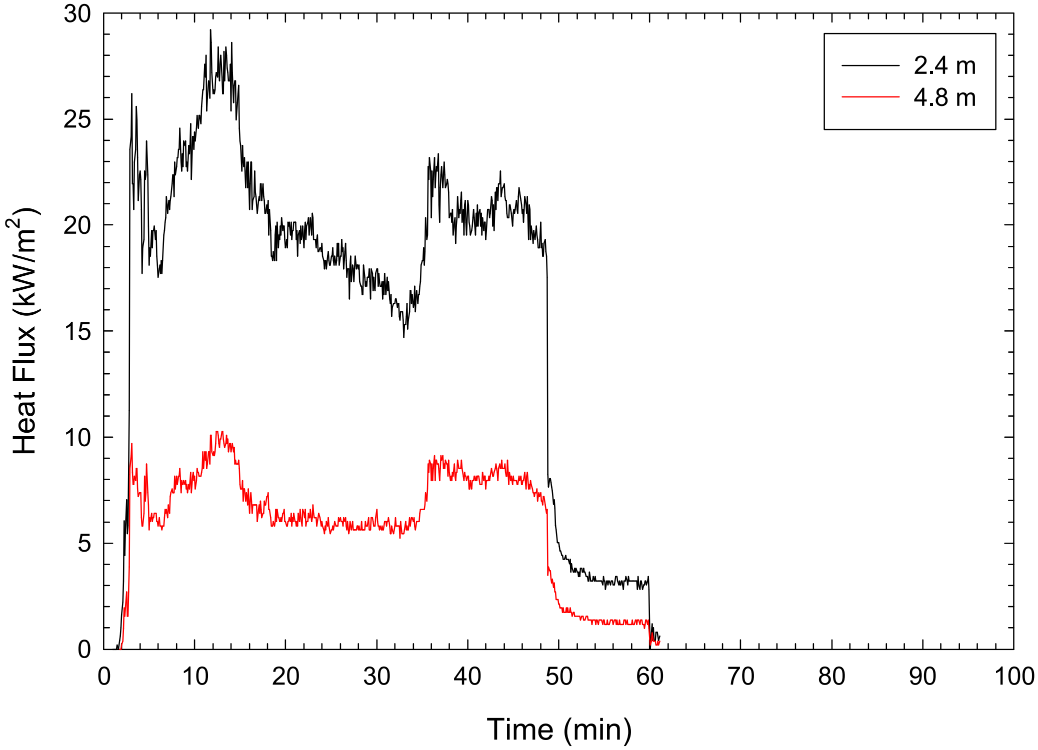


Figure 61. Heat flux from bedroom opening.

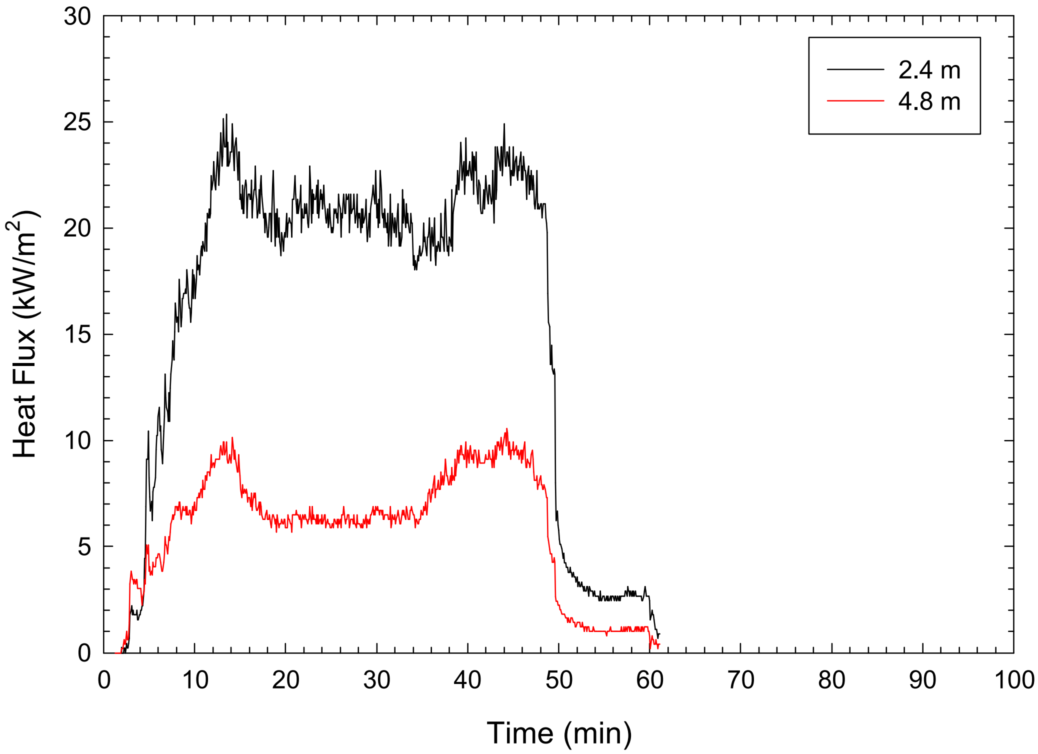


Figure 62. Heat flux from living room opening.

11.8 Duct Measurements

The smoke hot gases produced by the fire were 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 the duct. The volumetric and mass flow rates are shown in Figure 63.

The initial mass flow rate in the exhaust duct was 23 – 25 kg/s. As the temperature of the smoke increased (Figure 64) the mass flow rate was reduced but was > 18 kg/s until approximately 34 min. After 34 min, the temperature in the duct increased with the burning of the floor joists and the subfloor resulting in a further decrease in the mass flow rate. The minimum mass flow rate was 16.1 kg/s at 40 min.

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 65 and the O_2 concentration is shown in Figure 66.

There was an initial peak/minimum in the CO_2 and O_2 concentrations at approximately 3 min. This corresponds to the flashover of the bedroom. After the initial peak, there was a decrease in the CO_2 concentration and increase in the O_2 concentrations until 4 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 18.7%, respectively, at approximately 19 min.

After 19 min, there was a slow decrease in the CO_2 concentration and a slow increase in the O_2 concentration until approximately 29 min, after which, there was an increase in the concentrations as the fire size increased with the increased burning of the floor joists and the subfloor. The maximum CO_2 and minimum O_2 concentrations were 1.7% and 17.5%, respectively, at approximately 40 min. Subsequently, there was a decrease in the CO_2 concentration and increase in the O_2 concentration with the decay of the fire.

The CO concentration had an initial peak concentration (0.40%) at 3 min. This corresponds to the flashover of the bedroom. After the initial peak, there was a decrease in the CO concentration followed by a second peak concentration (0.25%) at approximately 7 min. Subsequently, the concentrations decreased but were between 0.1 and 0.18% for the remainder of the test.

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 67. 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 [16].

There was an initial peak heat release rate of 9.4 MW at 3 min based on the raw data and 8.7 MW using the time-averaged results. This peak heat release rate corresponds to the flashover of 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.

After the initial peak, the heat release rate decreased to 6.5 MW at 6 min. The heat release rate subsequently increased to between 7.0 and 7.5 MW until 25 min. After 25 min, it remained steady at 7.0 MW or lower until 30 min when it began to increase with the burning of the joists and subfloor in the ceiling assembly above the fire floor. The maximum heat release rate was approximately 10.5 MW at approximately 40 min. However, there was smoke buildup in the test facility in the later stages of the test indicating all the smoke was not collected in the exhaust system. As such, the heat release rate may be higher during this stage of the test.

The smoke obscuration was also measured in the exhaust duct. The results are shown in Figure 68.

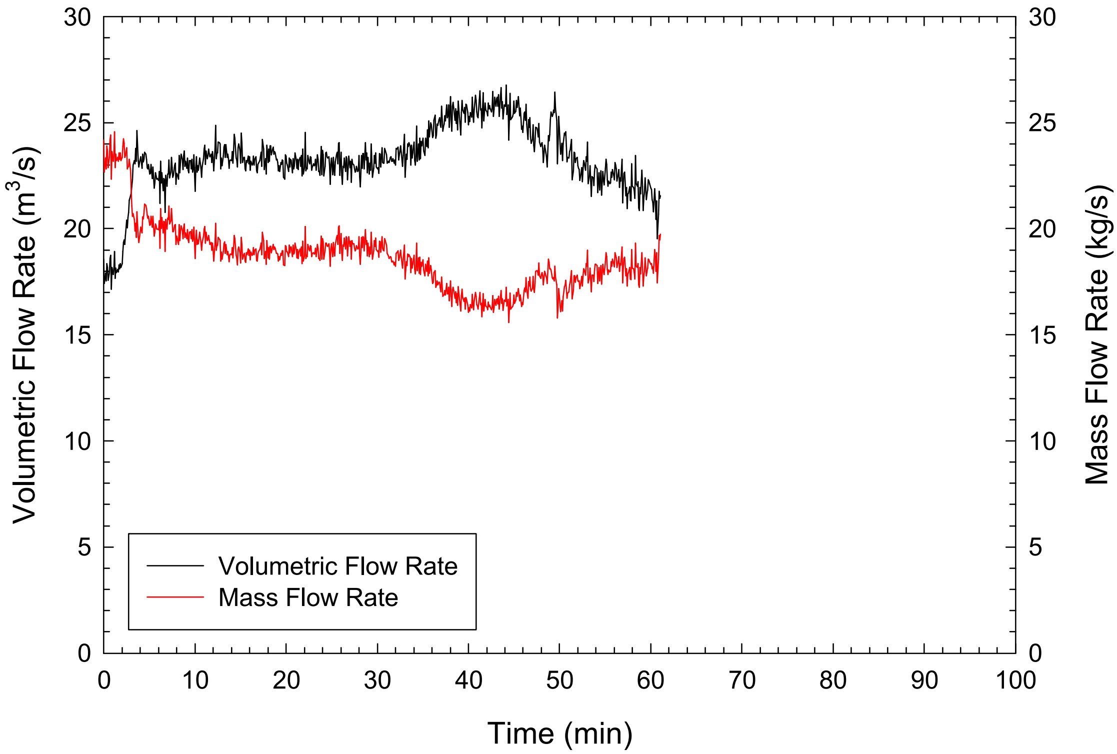


Figure 63. Volumetric and mass flow rate in exhaust duct.

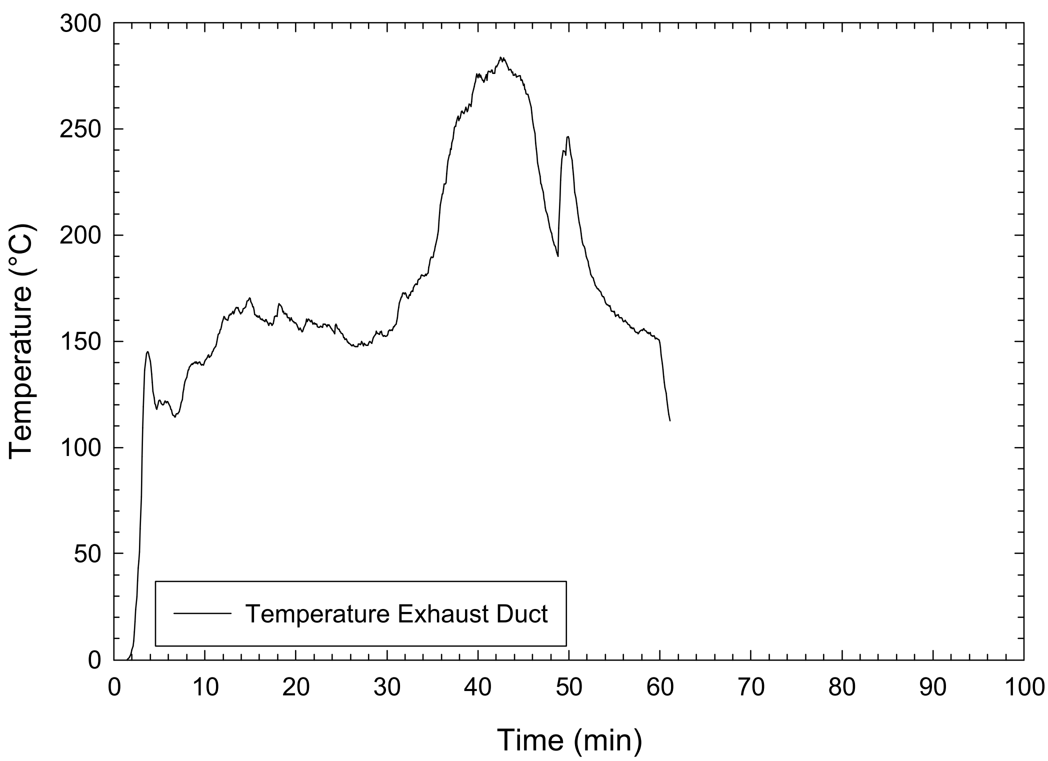


Figure 64. Temperature in exhaust duct.

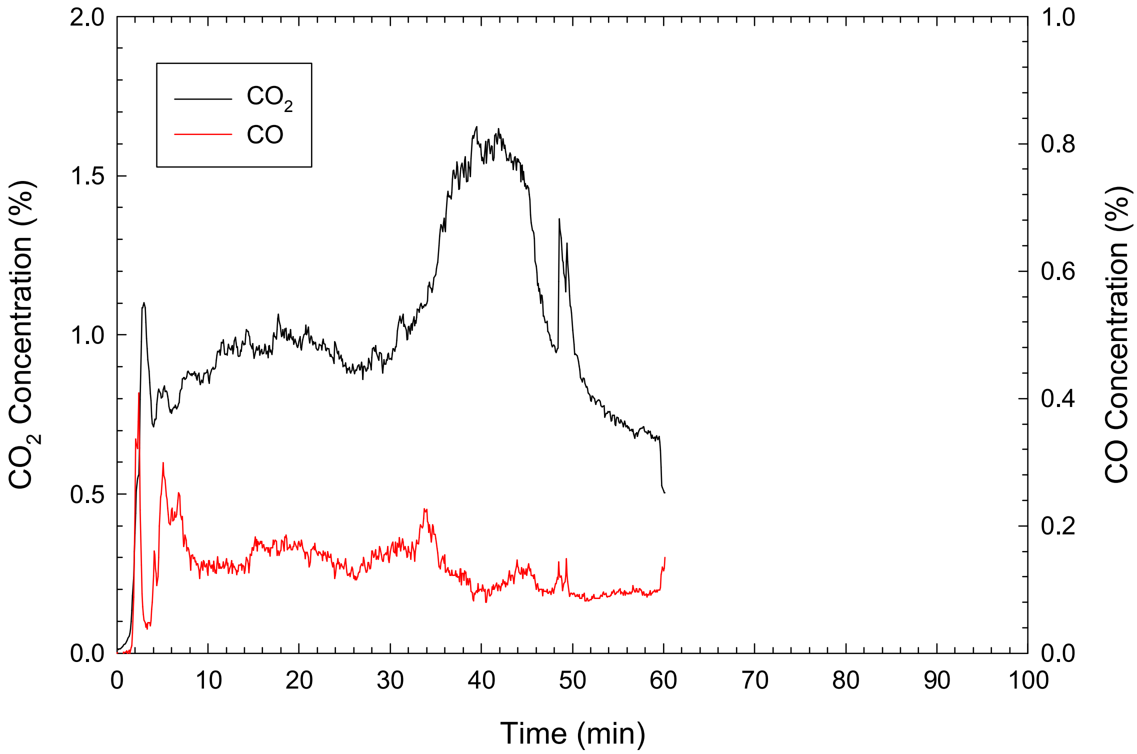


Figure 65. CO and CO_2 concentrations in the exhaust duct.

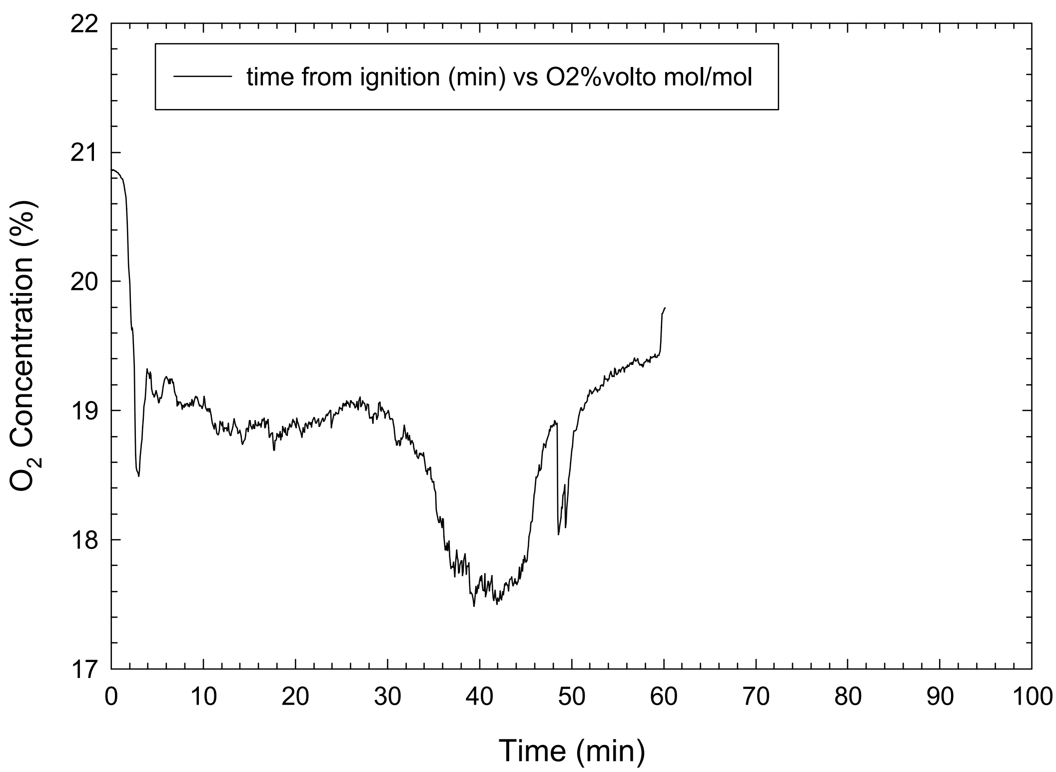


Figure 66. Oxygen concentration in the exhaust duct.

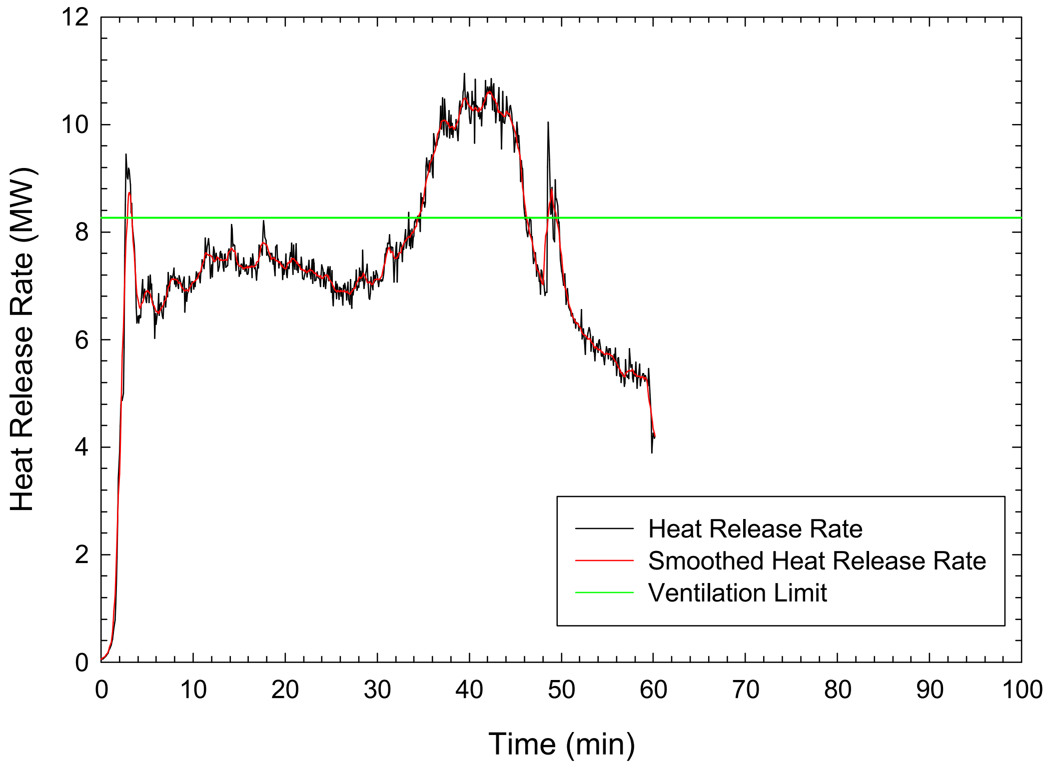


Figure 67. Heat release rate.

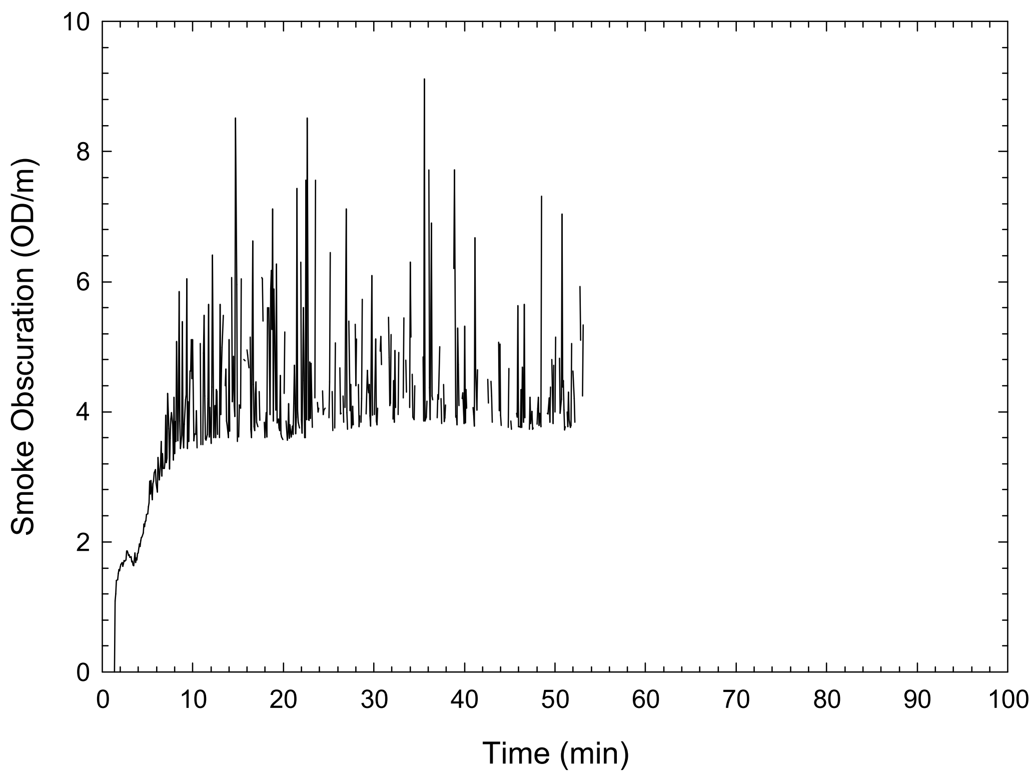


Figure 68. Smoke obscuration measured in the exhaust duct.

12 DISCUSSION AND TIMELINE

Figure 69 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 fire resistance tests [9]. Observations based on the plots shown in Figure 69 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 the bedroom.
2. The temperatures shown in the maximum temperature plots were consistently higher than the average temperatures indicating there were hotter regions in the bedroom.
3. The fuel load used in Test PMF-03 was similar to that used in the apartment. However, there were some variations in the average temperature profiles:
    a. Higher temperatures were measured in the LWF apartment fire test between 6 and 10 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.
    b. At approximately 11 min, the average temperature in the apartment bedroom decreased. This corresponds to the time at which the fire penetrated into the cavity space of the nonloadbearing partition wall.
    c. At approximately 25 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 was not protected by cement board in PMF-03 (15.5 mm thick (nominal 5/8") OSB) providing additional fuel load for the fire.
    d. After 30 min, the temperatures measured in PMF-03 decreased until the end of the test. In the apartment test, the temperatures in the bedroom decreased until approximately 35 min and subsequently remained steady until the end of the test. This corresponds to the period during which the wood studs in the exterior wall and the wood I-joists and subfloor in the ceiling/floor assembly were contributing to the fire.
4. The standard time-temperature curve used in fire resistance tests is also shown in Figure 69. During the initial 35 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 testing. After approximately 35 min, the wood structural elements in the exterior wall and the floor/ceiling assembly began to contribute to the fire. However, since the fire involving the room contents was in the decay phase, the temperatures remained relatively steady and were slightly higher but comparable to the temperatures in the standard time-temperature curve.

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 in the bedroom developed rapidly with flashover at approximately 4 min
2. The highest temperatures were between 6 and 25 min.
3. After 25 min, there was a general decrease in temperature until approximately 35 min followed by a temperature plateau with temperatures > 900°C that lasted until 48 min.
4. The temperature plateau between 35 and 48 min corresponded to the fall-off of the base layer of gypsum board on ceiling/floor assembly and corresponded to the burning of the floor joists and the OSB subfloor in the ceiling assembly above the fire floor.
5. There was also an increase in the radiant flux from the opening with the temperature plateau between 35 and 48 min.

Figure 70 shows the maximum and average temperatures at the three thermocouple trees 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 70 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 throughout the test indicating there were hotter 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 71. 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 but comparable to the standard time-temperature curve until 30 min (Figure 70). Between 30 and 48 min the average temperatures increased with the burning of the joists and the subfloor and were up to 150°C higher than the standard time-temperature curve.
4. The temperature averaged over the entire area does not give the best indication of the fire severity and its impact on the room boundaries. As shown in Figure 71, the average temperature at the north end of the living room was significantly higher than the standard time-temperature between 6 and 40 min. However, the temperatures in the entryway only exceeded the standard time-temperature curve for a short period between 30 and 48 min.

Table 10 shows the times at which the main fire events occurred in the living room and kitchen. A summary of the main fire events in the living room and kitchen area are:

1. Initial temperature increases were observed in the living room area between 3 and 4 min.
2. By 5 min, the temperatures in the living room were > 600°C in the living room indicating flashover in this area.
3. The temperatures did not reach 600°C until 11 min in the kitchen area.
4. The temperatures varied depending on location in the kitchen/living room area with maximum temperature occurring at the north end of the living room prior to 30 min and in the kitchen and entryway at approximately 34 min.
5. After 30 min, the temperatures decreased in the living room area until 35 min followed by a steady temperature plateau until the floor collapsed at approximately 48 min.

6. The maximum temperatures in the kitchen and entryway were at approximately 34 min. The temperatures subsequently decreased until approximately 40 min followed by a steady temperature plateau until the floor collapsed at approximately 48 min
7. With the sustained burning of the fuel load in the living room and kitchen, the radiant flux through the opening remained high throughout the test.
8. After 48 min, there was a rapid decrease in temperatures at all heights and locations.

A primary objective of the 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 regular gypsum board will provide limited protection (9 min on the bedroom/bathroom nonloadbearing partition wall and approximately 20 min on the exterior walls). The encapsulation times were estimated based on temperatures measured in the wood stud cavities rather than at the interface between the gypsum board and the wood stud.
2. The encapsulation time for the two layers of 12.7 mm thick Type X gypsum board used on the bedroom ceiling was 23 min based on the temperatures measured in the joist cavity and 26 min based on the temperatures measured at the interface of the gypsum board with the I-joist at the center of the ceiling. The earlier time based on measurements in the joist cavity indicate there was leakage of hot air into the joist cavity.
3. The encapsulation time for the two layers of gypsum board used on the ceiling in the living room/kitchen was 32 min based on temperatures measured in the joist cavity.
4. The encapsulation time for the two layers of 12.7 mm thick Type X gypsum board on the loadbearing partition wall was 34 min based on temperatures measured in the cavity space. This wall was subjected to fire exposure on both sides of the assembly.
5. The encapsulation time for the two layers of 12.7 mm thick Type X gypsum board on the west bedroom wall was 38 min based on temperatures measured at the interface between the base layer of gypsum board and the studs.
6. Extended encapsulation times were determined using the temperature measurements in the wall stud spaces (> 53 min). This suggests that the initial effects of the fire will be at the interface between the base layer of gypsum board and the studs. Longer times are required before the temperatures in the stud cavities will affect the structural elements.
7. The combination of the hardwood flooring and the cement board provided extended encapsulation time for the floor assembly below the bedroom (> 60 min).

Table 9. Summary of fire events bedroom.

Time (min)	Description
0	Bed ignited using propane burner
0.3	Smoke alarm responded within 20 s
4	Flashover in bedroom
12	Decrease in temperature with fire penetration into partition wall
6 - 25	Sustained high temperatures
10 -15	Peak in radiant flux from opeing.
25 - 35	Decreasing temperatures
35 - 50	Temperature plateau – temperature > 900°C. Increased radiant flux from opening.
48	Collapse of ceiling/floor assembly
> 48	Decreasing temperatures

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

Time (min)	Description
3 – 4	Initial temperature increase at ceiling
5	Temperature living room areas > 600°C indicating flashover
8 - 48	High heat flux (>12.5 kW/m^2) through exterior wall opening
18	Fall-off face layer of gypsum board.
30	Maximum temperature in living room.
>32	Fall-off of base layer of gypsum board on ceiling.
34	Maximum temperature in kitchen and entryway.
35 - 48	Temperature plateau – temperature > 800°C.
48	Collapse of ceiling/floor assembly
> 48	Decreasing temperatures

Table 11. Summary of encapsulation times.

Time (min)	Encapsulation/Location
9	Single layer 12.7 mm thick regular gypsum board based on temperatures measured in stud cavity of nonloadbearing partition wall.
16	Single layer 12.7 mm thick Type X gypsum board center bedroom ceiling
18	Single layer 12.7 mm thick Type X gypsum board based on temperatures measured at the interface between the base and face layer of gypsum board on the west bedroom wall.
20	Single layer 12.7 mm thick regular gypsum board based on temperatures measured in stud cavity of living room exterior wall.
21	Single layer 12.7 mm thick regular gypsum board based on temperatures measured in stud cavity of bedroom exterior wall.
23	Two layers of 12.7 mm thick Type X gypsum board bedroom ceiling based on temperatures measured in joist cavity at southeast quarter point of room.
25	Two layers of 12.7 mm thick Type X gypsum board bedroom ceiling based on temperatures measured between base layer of gypsum board and resilient channel at center of bedroom.
26	Two layers of 12.7 mm thick Type X gypsum board and resilient channel in bedroom ceiling based on temperatures measured between resilient channel and joist at center of bedroom.
27	Fall-off of base layer of gypsum board on bedroom ceiling.
30	Harwood flooring, acoustic insulation and a layer of 12.7 mm thick cement board based on temperature measured at center of bedroom floor.
32	Two layers of 12.7 mm thick Type X gypsum board on ceiling of living room/kitchen area based on temperatures measured in the joist cavity.
34	Two layers of 12.7 mm thick Type X gypsum board on loadbearing partition wall.
38	Two layers of 12.7 mm thick Type X gypsum board west bedroom wall based on temperatures measured between base layer and stud.
>53	Two layers of 12.7 mm thick Type X gypsum board based on temperatures measured in the cavities of east living room wall, west bedroom wall and South corridor wall.
>60	Harwood flooring and two layers of 12.7 mm thick cement

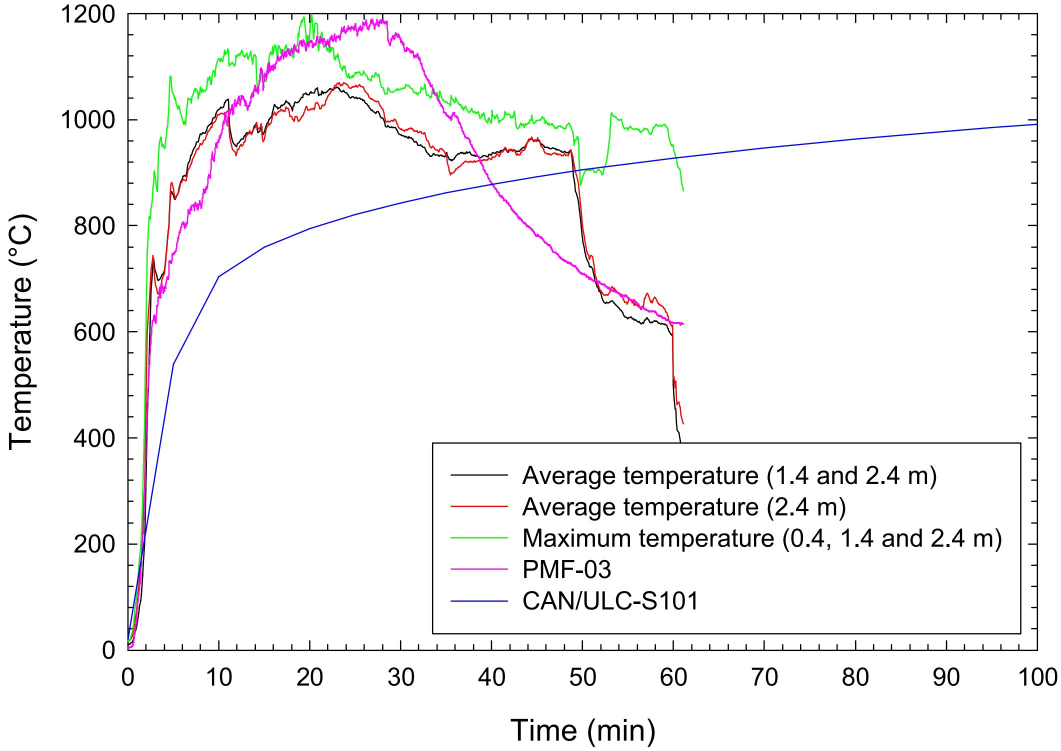


Figure 69. Maximum and average temperatures in bedroom.

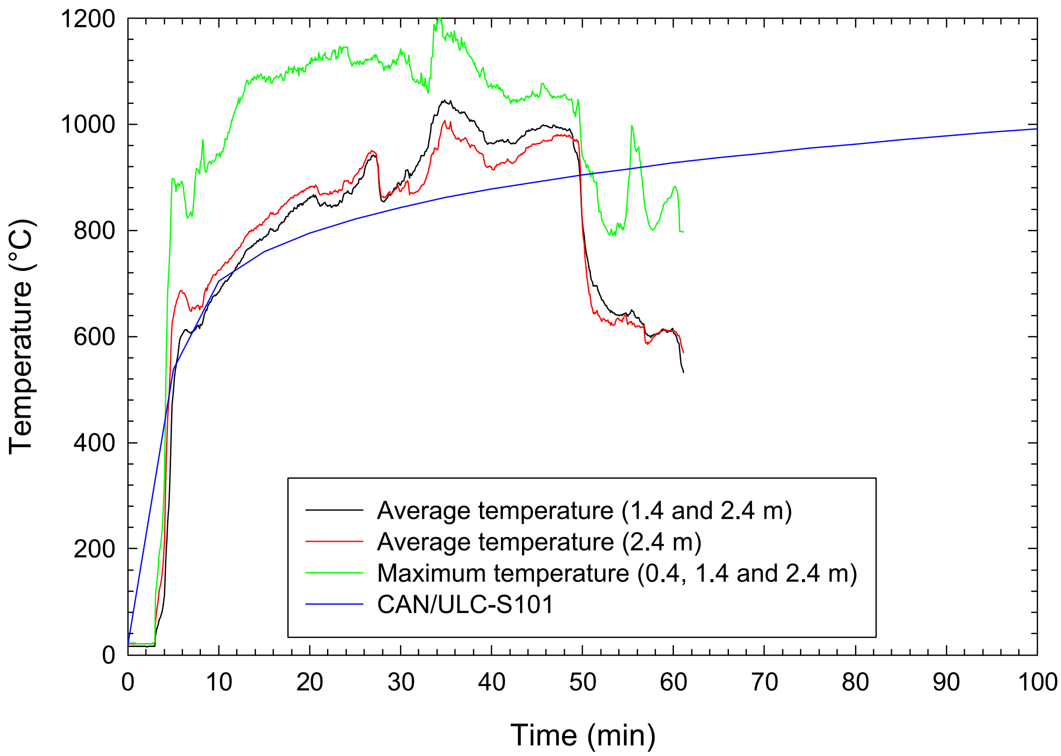


Figure 70. Maximum and average temperatures in living room/kitchen.

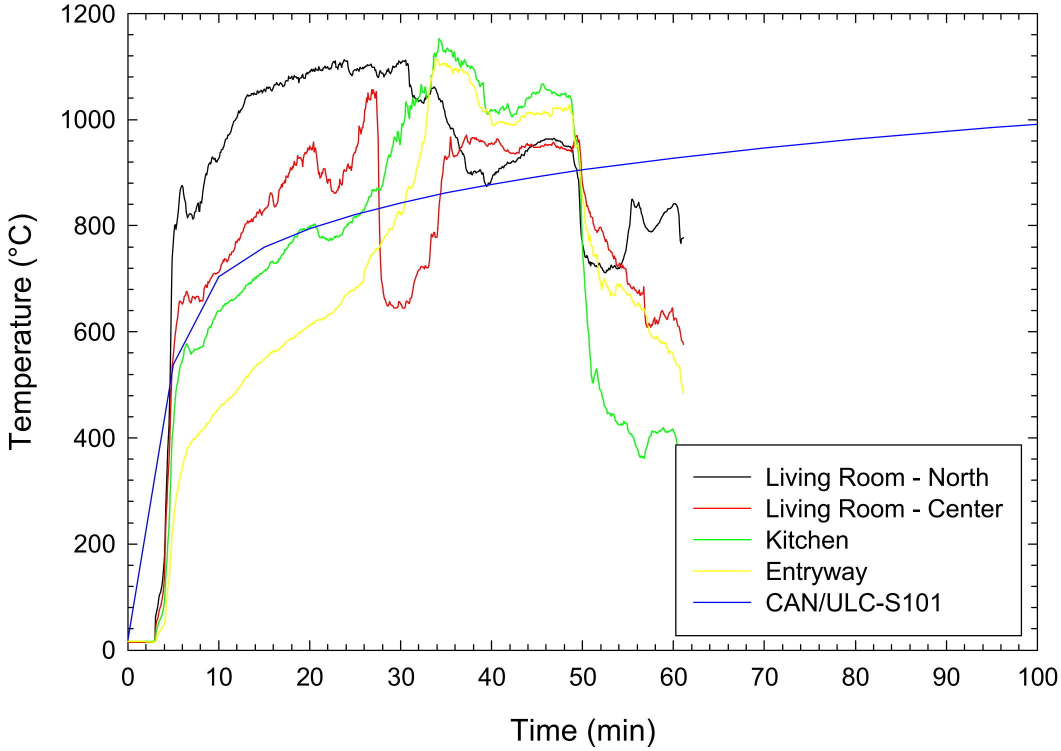


Figure 71. Average temperatures at thermocouple trees in living room/kitchen (1.4 and 2.4 m heights).

13 SUMMARY

A project, Wood and Wood-Hybrid Midrise Buildings, was undertaken to develop information for an alternative solution for mid-rise 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 (LSF) system. Each experiment involved construction of a test set-up consisting of an apartment unit, representing a portion of a six-storey mid-rise building.

The intent was to provide the opportunity for comparison of the fire performance of the encapsulated LWF and CLT systems to that of the LSF system. However, after the initial 15 min, there were differences in the fire conditions within the apartment in the test of the LSF system that made this comparison difficult. As a result of these differences, it was decided to conduct a second test with a LWF system. For this test, the construction of the exterior wall for the apartment was changed so that is more similar to the exterior wall assembly used in the LSF apartment test.

In all three of the original test apartment designs (LWF, LSF and CLT), the exterior wall assembly with openings did not support an assembly that was required to have a fire-resistance rating. As a result, it was not required to be designed to have a 1-h fire resistance rating. However, in the first LWF test, the interior side of the wood studs in the exterior wall was protected using two layers of 12.7 mm thick Type X gypsum board, to encapsulate the wood members, even though they were not supporting the floor/ceiling assembly of the storey above. For the second LWF test, the interior side of the studs was sheathed with a single layer of 12.7 mm thick regular gypsum board as was done in the code-conforming noncombustible LSF test arrangement. This report provides the results of the second test with an encapsulated LWF setup.

14 ACKNOWLEDGMENTS

Financial and in-kind support for the project provided by the following organizations is gratefully acknowledged:

- Canadian Wood Council
- National Research Council Canada

Extensive technical input by Rodney McPhee and Ineke Van Zeeland, Canadian Wood Council is also gratefully acknowledged:

15 REFERENCES

1. 2010 NBC, National Building Code of Canada, National Research Council, Ottawa, Ontario, 2010.
2. Su, J., Gover, B., Lougheed, G., Benichou, N., Swinton, M., Schoenwald, S., Lacasse, M., Di Lenardo, B., Mostafaei, H. and Pernica, G., Wood And Wood-Hybrid Mid-Rise Buildings, Phase 1: Scoping Study, B4726.1, National Research Council, Ottawa, Ontario, 2011.
3. Taber, B.C., Lougheed, G.D., Su, J.Z. and Benichou, N., Solutions for Mid-Rise Wood Construction: Apartment Fire Test with Encapsulated Lightweight Wood Frame Construction (Test APT-LWF-1), Report A1-100035-01.9, National Research Council, Ottawa, 2014.

4. Taber, B.C., Lougheed, G.D., Su, J.Z. and Benichou, N., Solutions for Mid-Rise Wood Construction: Apartment FIRE Test with Encapsulated Cross laminated timber Construction (Test APT-CLT), Report A1-100035-01.10, National Research Council, Ottawa, 2014.
5. Lougheed, G.D. and Su, J.Z., Solutions for Mid-Rise Wood Construction: Full-Scale Apartment Fire Test with Lightweight Steel Frame Construction (Test APT-LSF), Report A1-100035-01.11, National Research Council, Ottawa, 2014.
6. CAN/ULC-S134, Fire Test of Exterior Wall Assemblies, Underwriters Laboratories of Canada, Ottawa, Ontario, 2012.
7. Gibbs, E., Taber, B.C., Lougheed, G.D., Su, J.Z., Benichou, N., Alternative Solution for Mid-Rise Wood Construction: Full-scale Fire Test for Exterior Wall Assembly using Lightweight Wood Frame Construction with Gypsum Sheathing, Report A1-100035-01.5, National Research Council, Ottawa, 2013.
8. Bijloos, M., Lougheed, G.D., Su, J.Z., Benichou, N., Alternative Solution for Mid-Rise Wood Construction: Cone Calorimeter Tests for Acoustic Insulation Materials, Report A1-100035-01.13, National Research Council, Ottawa, 2013.
9. CAN/ULC-S101, Standard Methods of Fire Endurance Tests of Building Construction and Materials Underwriters Laboratories of Canada, Ottawa, Ontario, 2007
10. Bwalya, A., Gibbs, E., Lougheed, G. Kashef, A., Characterization of Fires in Multi-Suite Residential Dwellings - Part 1: A Compilation of Post-Flashover Room Fire Test Data, Research Report, National Research Council, Ottawa, Ontario, 2013.
11. Alex Bwalya, Gary Lougheed, Ahmed Kashef and Hamed Saber, Survey Results of Combustible Contents and Floor Areas in Canadian Multi-Family Dwellings, Fire Technology, Vol.46, No.1, p.1-20, 2010.
12. Bwalya, Alex, Lougheed, Gary, and Kashef, Ahmed, 2010. "Characterization of Fires in Multi-Suite Residential Dwellings: Phase 1 - Room Fire Experiments with Individual Furnishings", *Institute for Research in Construction, National Research Council Canada*, *Research Report*, IRC-RR-302, Ottawa, Canada.
13. Janssens, M. and Parker, W, Oxygen Consumption Calorimetry, in Heat Release in Fires, edited by Babrauskas, V. and Grayson, S.J., Elesevier Science Publishing Co. Ltd, N.Y., N.Y.
14. Babrauskas, V, Ignition Handbook, Fire Science Publishers, Issaquah, WA, 2003.
15. Berzins, R., Lafrance, P-S., Leroux, P., Lougheed, G.D., Su, J.Z. and Bénichou, N., Solutions for Mid-Rise Wood Construction: Intermediate-Scale Furnace Tests with Encapsulation Materials, CLIENT REPORT A1-100035-01.2, National Research Council, Ottawa, Ontario, 2014.
16. Drysdale, D., An Introduction to Fire Dynamics, Wiley, Mississauga, 2011.