Solutions for mid-rise wood construction: intermediate-scale furnace tests with encapsulation materials: report to Research Consortium for Wood and Wood-Hybrid Mid-Rise Buildings

Berzins, R.; Lafrance, P.-S.; Leroux, P.; Lougheed, G. D.; Su, J. Z.; Bénichou, N.

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

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SOLUTIONS FOR MID-RISE WOOD CONSTRUCTION: INTERMEDIATE-SCALE FURNACE TESTS WITH ENCAPSULATION MATERIALS

R. Berzins, P-S. Lafrance, P. Leroux, G.D. Lougheed, J.Z. Su and N. Bénichou

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.

Three materials were selected for investigation as encapsulation materials for combustible structural elements: Type X gypsum board (12.7 mm thick and 15.9 mm thick), cement board (12.7 mm thick) and gypsum-concrete (25 mm thick and 39 mm thick). This report documents the results of intermediate-scale furnace tests conducted to investigate the performance of the three encapsulation materials.

2 TEST METHOD AND SETUP

Intermediate-scale furnace tests were conducted to evaluate each encapsulation material. The test method used for these tests was based on CAN/ULC-S124 [3], which is used to evaluate protective covers for use with foamed plastic insulation. The objective of these tests was to provide comparative data for the three encapsulation materials, applying the same test arrangement and time-temperature exposure as found in CAN/ULC-S124.

The primary measurement in the tests was the temperature rise values at the interface between the encapsulation material and a plywood substrate.

2.1 Intermediate-scale Furnace

The intermediate-scale fire experiments were conducted using a 1.33 m by 1.94 m horizontal furnace. The furnace is oriented in the east-west direction with the exhaust stack located at the east end. A full description of the intermediate-scale furnace facility is provided by Sultan *et al.* [4].

Four dual-element Chromel-Alumel K-type thermocouple probes were used to measure the temperature inside the furnace chamber. These furnace thermocouples were located approximately 150 mm below the underside of the test assembly. The average temperature measured using these four thermocouples was used to control the furnace. For the majority of the experiments discussed in this report, the temperature in the furnace followed the standard time-temperature curve given in CAN/ULC-S101 [5]. Two additional tests were conducted using a non-standard time-temperature curve based on temperatures measured in full-scale fully furnished bedroom fire tests [6].

2.2 Test Assembly

The test assembly consisted of a support structure constructed using 2x4 wood studs spaced at 406 mm on center (o.c.). Gypsum board (12.5 mm thick Type X) was mounted on the unexposed side of the test assembly. For all except one test, two layers of 15.9 mm thick plywood were mounted on the exposed side of the test frame as a substrate for the encapsulation material to be tested. In the other test, a single layer of 15.9 mm thick plywood was used as the substrate for the encapsulation material. The different encapsulation materials were then mounted on top of the plywood on the exposed side of the test frame.

Two initial tests were conducted using 12.7 mm thick Type X Gypsum Board as the encapsulation material with a single layer of 15.9 mm thick plywood used as the substrate in one test and a double layer of plywood in the second test to provide data upon which to base a decision as to the substrate thickness to be used for the remainder of the tests. An increase of the temperature rise values at the interface between the gypsum board and the plywood substrate occurred earlier in the test with the double layer of plywood. As a result, a double layer of 15.9 mm thick plywood was used for all the other tests with encapsulation materials.

The test assemblies and test conditions are summarized in Table 1.

Table 1. Test assemblies.

Test	Encapsulation Material	Thickness (mm)	Number of Layers	Ambient Temperature# (ºC)	Time-Temperature Curve
IS-1	Type X Gypsum Board	12.7	1	20.11	CAN/ULC-S101
IS-2*	Type X Gypsum Board	12.7	1	21.49	CAN/ULC-S101
IS-3	Cement Board	12.7	1	21.63	CAN/ULC-S101
IS-4	Type X Gypsum Board	15.9	1	22.04	CAN/ULC-S101
IS-5	Type X Gypsum Board	12.7	2	21.17	CAN/ULC-S101
IS-6	Gypsum-concrete	39.0	1	18.87	CAN/ULC-S101
IS-7	Gypsum-concrete	25.0	1	25.57	CAN/ULC-S101
IS-8	Cement Board	12.7	2	22.10	CAN/ULC-S101
IS-9	Type X Gypsum Board	15.9	2	23.67	CAN/ULC-S101
IS-10	Type X Gypsum Board	15.9	1	23.81	non-standard
IS-11	Type X Gypsum Board	12.7	2	24.86	non-standard

*Test assembly with a single layer of 15.9 mm thick plywood substrate.
#Average temperature at the interface between the encapsulation material and plywood substrate prior to the commencement of the test. (“Ambient temperatures” are the value used to “normalize” the temperature rise values presented in this report.)

2.3 Test Assembly Instrumentation

The primary measurements used a set of 9 thermocouples located at the interface between the encapsulation material and the plywood substrate. The thermocouples were located at the quarter- and mid-lengths along the centerlines of the width and length of each test assembly. In addition, thermocouples were located at the quarter points of the assembly.

Thermocouples were also installed at the following locations:

1. A thermocouple was attached at the center of the exposed surface for all encapsulation materials except the gypsum-concrete.
2. For the tests with two layers of an encapsulation material, 9 thermocouples were located at the interface between the two layers. The arrangement was the same as that used for

the thermocouples located at the interface of the encapsulation material with the plywood.

3. For the tests with two layers of plywood as the substrate, 9 thermocouples were located at the interface between the two layers of plywood. The arrangement was the same as that used for the thermocouples at the interface of the encapsulation material with the plywood.
4. A thermocouple was attached at the center of the plywood at the interface with the cavity formed by the wood studs.
5. A thermocouple was located at the center of the unexposed side of the gypsum board on the unexposed side of the test assembly.

The thermocouple numbering and locations are shown in the figures of the drawings for the test assemblies (Figures 1, 2, 3, 13, 14, 22, 23 and 31).

3 ENCAPSULATION

Encapsulation is frequently used to protect structural elements to increase their fire resistance performance. For example, steel columns and beams can be encapsulated using materials with low thermal conductivity to increase the fire resistance performance of the structural elements. Also, encapsulation is used in lightweight wood- and steel-frame structural assemblies, to delay the effects of the fire on the structural elements to provide the required fire-resistance rating.

In Europe, the protection of combustible materials by means of encapsulation of building elements to delay the contribution of combustible building elements to a fire has proved successful [7]. The building elements and other combustible materials (e.g. insulation) are protected with a protective cover such as gypsum board or other lining material, which encapsulates the building elements and delays their ignition.

In Europe, it is assumed that a protective cover will be effective as long as the average temperature rise value over the exposed surface of the protected building element is limited to 250ºC, and the maximum temperature rise value at any point on that surface does not exceed 270ºC. This is based on a charring temperature for structural timber of 300ºC [7].

In this report, the European set of criteria for evaluating the performance of the three encapsulation materials is one of three sets of criteria investigated (Criteria 3). The other two sets of criteria are based on temperature rise criteria used in CAN/ULC-S101 [5] and CAN/ULC-S124 [3]:

1. Criteria 1. The average temperature rise value over the exposed surface of the protected building element is limited to 140ºC, and the maximum temperature rise value at any point on that surface does not exceed 180ºC.
2. Criteria 2. The average temperature rise value over the exposed surface of the protected building element is limited to 195ºC, and the maximum temperature rise value at any point on that surface does not exceed 250ºC.

The times at which the temperature rise values at the interface between the encapsulation material and the plywood substrate exceeded each of the three sets of criteria were determined for each test. In addition, the times at which the three sets of temperature rise criteria were met or exceeded at other interfaces in the assembly were also determined. This included the times at the interface between layers of the encapsulation materials, as well as the times at the interface between the two layers of plywood substrate.

4 RESULTS OF INTERMEDIATE-SCALE FURNACE TESTS WITH ENCAPSULATION MATERIALS USING THE STANDARD TIME-TEMPERATURE CURVE

The results for the 9 tests with encapsulation materials and the standard time-temperature curve are provided in this section. The following information and results are provided for each test:

1. Drawings showing the details for the test assembly, including the location of the fasteners and the thermocouples.
2. A plot showing the temperature rise values measured by the nine thermocouples located at the interface between the encapsulation material and the plywood substrate. The three single-point temperature rise criteria are also shown in these plots. The labeling for the thermocouples in the plot legend corresponds to those on the drawings for the test assembly.
3. A plot showing the temperature rise values at the plywood/plywood interface for all tests except Test IS-2 (for which the test assembly included only one layer of plywood). The three single-point temperature rise criteria are also shown in these plots. The labeling for the thermocouples in the plot legend corresponds to those on the drawings for the test assembly.
4. For the tests with two layers of encapsulation material, a plot is provided showing the temperature rise values measured by the nine thermocouples at the interface between the two layers of encapsulation material. The three single-point temperature rise criteria are also shown in these plots. The labeling for the thermocouples in the plot legend corresponds to those on the drawings for the test assembly.
5. A plot showing the average furnace temperature values and the temperature values on the exposed surface of the encapsulation material on the exposed side of the assembly.
6. A plot showing the average temperature rise values at each interface in the test assembly, and the temperature rise values at the plywood/cavity interface and on the unexposed surface of the of the gypsum board on the unexposed side of the assembly.

The three average temperature rise criteria are also shown. The nomenclature used in the legend for the plots is as follows:

a. Fur Avg — average furnace temperature values;
b. Exp GB — temperature values measured on exposed surface of gypsum board on exposed side of assembly;
c. Exp CB — temperature values measured on exposed surface of cement board on exposed side of assembly;
d. GB-GB Avg — average temperature rise values at interface between two layers gypsum board;
e. CB-CB Avg — average temperature rise values at interface between two layers cement board;
f. GB-Ply Avg — average temperature rise values at interface between gypsum board and plywood;
g. CB-Ply Avg — average temperature rise values at interface between cement board and plywood;
h. GC-Ply Avg — average temperature rise values at interface between gypsum-concrete and plywood;
i. Ply-Ply Avg — average temperature rise values at interface between two layers of plywood;
j. Ply-Cav — temperature rise values on plywood at interface with cavity; and

k. Unexposed temperature rise values on unexposed surface of gypsum board on unexposed side of assembly.

4.1 Results - 12.7 mm Thick Type X Gypsum Board

Three tests were conducted using 12.7 mm thick Type X gypsum board as the encapsulation material, using the standard time-temperature curve:

1. Test IS-1. A single layer of gypsum board with two layers of 15.9 mm thick plywood as the substrate.
2. Test IS-2. A single layer of gypsum board with one layer of 15.9 mm thick plywood as the substrate.
3. Test IS-5. Two layers of gypsum board with two layers of 15.9 mm thick plywood as the substrate.

The drawings for the test assemblies are shown in Figure 1, Figure 2 and Figure 3, respectively.

4.1.1 Results for Test IS-1

The results for Test IS-1 with a single layer of 12.7 mm Type X gypsum board and two layers of 15.9 mm thick plywood as the substrate are shown in Figure 4, Figure 5, Figure 6 and Figure 7. The temperature rise profiles measured by the thermocouples at the interface between the two layers of plywood and at the interface between the gypsum board and the plywood are shown in Figure 4 and Figure 5, respectively. The furnace temperature and the temperature measured at the exposed gypsum board surface are shown in Figure 6. The average temperature at each interface and the temperature rise values at the plywood/cavity interface and on the unexposed surface of the gypsum board on the unexposed side of the assembly are shown in Figure 7.

At the interface between the gypsum board and plywood substrate, there was an initial rapid increase of temperature rise values to approximately 60 – 65°C within approximately 5 min (Figure 5). Subsequently, there was a second phase, with a slower rate of increase of temperature rise values during calcination and vaporization of the water in the gypsum board. The average temperature rise value at that interface reached 100°C at approximately 16.5 min (Figure 7).

After 16.5 min, there was a third phase for the temperature rise values measured at the interface between the gypsum board and plywood substrate, with a higher rate of increase of temperature rise values. The temperature rise values reached approximately 500°C at approximately 38 min, at which time the gypsum board fell off, resulting in direct exposure of the plywood substrate to the furnace environment.

There was minimal variation in the temperature rise values measured by the nine thermocouples at the interface between the gypsum board and plywood substrate until the later stage of Phase 2. However, after approximately 13 min, there was an increasing variation in the measured temperature rise values, with the highest variations during Phase 3. The fastest rates of increase of temperature rise values during Phase 3 were measured by TC 16 and TC 17 (Figure 5). These thermocouples were at the same locations in the assembly (in a different plane) as TC 7 and TC 8 (Figure 4), which had the fastest rates of increase of temperature rise values at the interface between the two layers of plywood during Phase 3. The slowest rate of increase of temperature rise values was measured by TC 3 (Figure 4), located at the center of the northeast quadrant of the test assembly.

There was a steady increase of temperature rise values at the interface between the two layers of plywood beginning at approximately 5 min after the start of the test (Figure 4). Initially, there was minimal variation in the temperature rise values measured by the 9 thermocouples at that interface. However, after 25 min, there were increasing differences in the measured temperature rise values, with the fastest rates of increase of temperature rise values measured by TC 7 and TC 8. Both thermocouples were located at the mid-length of the assembly with TC 7 at the center of the assembly and TC 8 at the center point of the southern half of the assembly.

Beginning at approximately 38 min, there was a rapid increase of temperature rise values at the interface between the two layers of plywood, and by 42 min all thermocouples at that interface reached temperatures equivalent to the furnace temperature. This indicated burn through of the initial plywood layer and extensive burning of the second plywood layer.

The average furnace temperature and the temperature measured on the exposed surface of the gypsum board on the exposed side of the assembly (TC 21) are shown in Figure 6. The temperature measured on the exposed surface of the exposed gypsum board lagged the furnace temperature until 28.6 min. The average temperature at the gypsum board and plywood interface was 378°C at that time. Subsequent to this, the higher temperature measured on the exposed surface of the exposed gypsum board compared to the average furnace temperature would suggest that burning in the furnace of pyrolysis gases from the plywood was being recorded by the TC located at the exposed surface of the gypsum board from that point in time onwards.

4.1.2 Results for Test IS-2

The results for Test IS-2 with a single layer of 12.7 mm Type X gypsum board and one layer of 15.9 mm thick plywood as the substrate are shown in Figure 8, Figure 9 and Figure 10. The temperature rise profiles measured by the thermocouples at the interface between the gypsum board and the plywood are shown in Figure 8. The furnace temperature and the temperature measured at the exposed gypsum board surface are shown in Figure 9. The average temperature at each interface and the temperature rise values at the plywood/cavity interface and on the unexposed surface of the gypsum board on the unexposed side of the assembly are shown in Figure 10.

At the interface between the gypsum board and plywood substrate (Figure 8), the temperature rise values followed the same general trend as those measured in Test IS-1. There was an initial rapid increase of temperature rise values to approximately 60 – 65°C within approximately 5 min. Subsequently, there was a second phase, with a slower rate of increase of temperature rise values during calcination and vaporization of the water in the gypsum board. The average temperature rise value at that interface reached approximately 100°C at approximately 17 min (Figure 10).

After 17 min, there was a third phase for the temperature rise values measured at the interface between the gypsum board and plywood substrate, with a faster rate of increase. The average temperature rise value reached approximately 500°C at approximately 41 min, at which time the gypsum board fell off, resulting in direct exposure of the plywood substrate to the furnace environment.

There was minimal variation in the temperature rise values measured by the nine thermocouples at the interface between the gypsum board and plywood substrate until the later stage of Phase 2. However, after approximately 13 min there was an increasing variation in the measured temperature rise values, with the highest variations during Phase 3. However, the temperature rise values' variations were less than those in Test IS-1.

The fastest rates of increase of temperature rise values during Phase 3 were measured by TC 4 and TC 10 (Figure 8). These thermocouples were located on the centerline at the east and west ends of the assembly. The slowest rate of increase of temperature rise values during Phase 3 was measured by TC 7 located at the centre of the test assembly.

The average furnace temperature and the temperature measured on the exposed surface of the gypsum board on the exposed side of the assembly (TC 12) are shown in Figure 9. The temperature measured on the exposed surface of the exposed gypsum board lagged the furnace temperature until 30.3 min. The average temperature at the gypsum board and plywood interface was 371°C at that time. Subsequent to this, the higher temperature measured on the exposed surface of the exposed gypsum board relative to the average furnace temperature would suggest that burning in the furnace of pyrolysis gases from the plywood was being recorded by the TC located at the exposed surface of the gypsum board from that point in time onwards.

The rates of increase of the temperature rise values measured at the interface between the gypsum board and plywood were slower in Test IS-2 than in Test IS-1. However, the rates of increase of temperature rise values measured on the plywood at the interface with the cavity (TC 2) and on the unexposed surface of the gypsum board on the unexposed side of the assembly (TC 1) were faster in Test IS-2 than in Test IS-1, with temperature rise values at the end of the test of 172°C and 50°C measured in Test IS-2 at the two locations, respectively, compared with 50°C and 14°C in Test IS-1. This indicates there was less heat loss into the assembly cavity and subsequently from the unexposed side of the assembly in Test IS-1. Since the test with two layers of plywood substrate decreased the heat loss into the cavity compared to the test with only one layer, a double layer of plywood was used as the substrate for all the subsequent tests of the encapsulation materials.

4.1.3 Results for Test IS-5

The results for Test IS-5 with two layers of 12.7 mm Type X gypsum board and two layers of 15.9 mm thick plywood as the substrate are shown in Figure 11, Figure 12, Figure 13, Figure 14 and Figure 15. The temperature rise profiles measured by the thermocouples at the interface between the two layers of plywood, at the interface between the gypsum board and the plywood and at the interface between the two layers of gypsum board are shown in Figure 11, Figure 12 and Figure 13, respectively. The furnace temperature and the temperature measured at the exposed gypsum board surface are shown in Figure 14. The average temperature at each interface and the temperature rise values at the plywood/cavity interface and on the unexposed surface of the gypsum board on the unexposed side of the assembly are shown in Figure 15.

At the gypsum board/gypsum board interface (Figure 13), the temperature rise values followed the same general trend as those measured at the first interface in Test IS-1(the interface between the single layer of gypsum board and the plywood substrate). There was an initial rapid increase of temperature rise values to approximately 50°C at 5 min. Subsequently, there was a second phase, with a slower rate of increase of temperature rise values during calcination and vaporization of the water in the gypsum board. The average temperature rise value at the gypsum board/gypsum board interface reached 100°C at approximately 17.5 min (Figure 15).

After 17.5 min, there was a third phase, with a higher rate of increase of the temperature rise values. The average temperature rise value reached approximately 670°C at approximately 68 min, at which time the gypsum board fell off, resulting in direct exposure of the base layer of gypsum board to the furnace environment.

There was minimal variation in the temperature rise values measured by the nine thermocouples at the gypsum board/gypsum board interface until Phase 3. However, after approximately 18 min, there was an increasing variation in the measured temperature rise values. The fastest rates of increase in temperature rise values during Phase 3 were measured by TC 22, TC 23 and TC 26 (Figure 13). TC 22 and TC 23 were at the east end of the test assembly with TC 22 on the centerline and TC 23 at the center of the southeast quadrant of the assembly. TC 26 was located at mid-length on the south side of the test assembly.

At the interface between the gypsum board and plywood substrate (Figure 12), there was a gradual increase of temperature rise values beginning at approximately 5 min. There was not a distinct initial phase with fast rates of increase of temperature rise values as was found in the tests with a single layer of gypsum board. However, the rates of increase of temperature rise values slowed down during calcination and vaporization of the water in the gypsum board. The average temperature rise value at the interface reached 100°C at approximately 46 min (Figure 15). Subsequently, there were faster rates of increase of temperature rise values. The average temperature rise value reached approximately 310°C at approximately 71 min, at which time the base layer of gypsum board fell off, resulting in faster rates of increase of temperature rise values at the interface between the gypsum board and the plywood.

There was minimal variation in the temperature rise values measured by the nine thermocouples at the interface between the gypsum board and the plywood until the later stage of Phase 1. However, after approximately 46 min there was an increasing variation in the measured temperature rise values, with the highest variations during Phase 2. The fastest rate of increase of temperature rise values during Phase 3 was measured by TC 16 (Figure 12) located at the center of the test assembly.

There was a steady increase of temperature rise values at the interface between the two layers of plywood beginning at approximately 12 min after the start of the test (Figure 11). There was minimal variation in the temperature rise values measured by the 9 thermocouples at that interface until near the end of the test. The test was stopped at 79.8 min before any of the temperature rise criteria were exceeded. However, the average temperature rise value was 136°C, and it can be estimated that the average temperature rise value for Criteria 1 would have been exceeded at approximately 80 min, since at the end of the test, only a 3 - 5 mm thickness of the first layer of plywood remained uncharred.

The average furnace temperature and the temperature measured on the exposed surface of the gypsum board on the exposed side of the assembly are shown in Figure 14. The temperature measured on the exposed surface of the exposed gypsum board initially lagged the furnace temperature; during the later stages of the test it was comparable to the furnace temperature. There was no indication of burning of the plywood until the base layer of gypsum fell off at approximately 77 min.

The increase in temperature rise value was minimal on the plywood in the cavity (TC 2: 55°C) and on the unexposed surface of the gypsum board on the unexposed side of the assembly (TC 1: 23°C) by the end of the test. This indicates there was limited heat loss through the back portion of the test assembly.

4.1.4 Discussion and Summary - 12.7 mm Thick Type X Gypsum Board

Three tests were conducted using 12.7 mm thick Type X gypsum board as the encapsulation material: 2 tests with a single layer and 1 test with a double layer of gypsum board. The times at which the temperature rise values measured at the interface between the gypsum board and plywood and at the interface between the two layers of gypsum board exceeded the temperature rise criteria are shown in Table 1.

For the face layer of gypsum board, the temperature rise value profiles followed the same trend or phases in all tests:

1. Phase 1. Initial fast increase of temperature rise values to 60°C.
2. Phase 2. Relatively steady but slower increase of temperature rise values during the calcination and subsequent vaporization of water in the gypsum board.
3. Phase 3. Rapid increase of temperature rise values to high values.

There was minimal variation in the temperature rise values measured by the nine thermocouples at the interface behind the gypsum board face layer until the end of Phase 2 and the beginning of Phase 3 in all three tests.

The fall-off times for the gypsum board face layers were 38 and 41 min in Tests IS-1 and IS-2, respectively. In Test IS-3, the fall-off time for the face layer was 68 min.

The increases in temperature rise values at the gypsum board/plywood interface in Test IS-5 had three phases similar to Tests IS-1 and IS-2. However, the initial phase in Test IS-5 was not as distinct as in the other two tests, with the temperature rise values showing a relatively steady increase until approximately 100°C.

In Tests IS-1 and IS-5, the temperature rise values at the plywood/plywood interface showed a steady increase until near the end of the test. In Test IS-1, there was a rapid increase of the temperature rise values once the face layer of plywood was completely charred.

For Test IS-1, the average temperature rise criteria were exceeded first for Criteria 1 and 2 and the single-point temperature rise criteria were exceeded first for Criteria 3 at the gypsum board/plywood interface. The differences in time between reaching the average and single-point criteria were 0.25, 1.09 and 1.34 min for Criteria 1, 2 and 3, respectively. The increasing difference between the average and single-point times is consistent with the temperature rise value profiles shown Figure 5, which show a faster rate of increase of the temperature rise values measured by TC 16 and TC 17 than at the other 7 locations.

With the rapid increase of the temperature rise values at the interface between the two plywood layers near the end of Test IS-1, all the temperature rise criteria were exceeded within a short time interval (between 39.83 and 40.92 min). For all three sets of criteria, the single-point temperature rise value was exceeded before the average temperature rise value.

For Test IS-2, the average temperature rise criteria were exceeded first for all three sets of temperature criteria at the gypsum board/plywood interface. The differences in time between reaching the average and single-point temperature rise criteria were 0.84, 1.25 and 0.25 min for Criteria 1, 2 and 3, respectively. The lower differences between the average and single-point criteria times in Test IS-2 relative to Test IS-1 are consistent with the decreased variation in the temperature rise values measured at the 9 locations in the two tests.

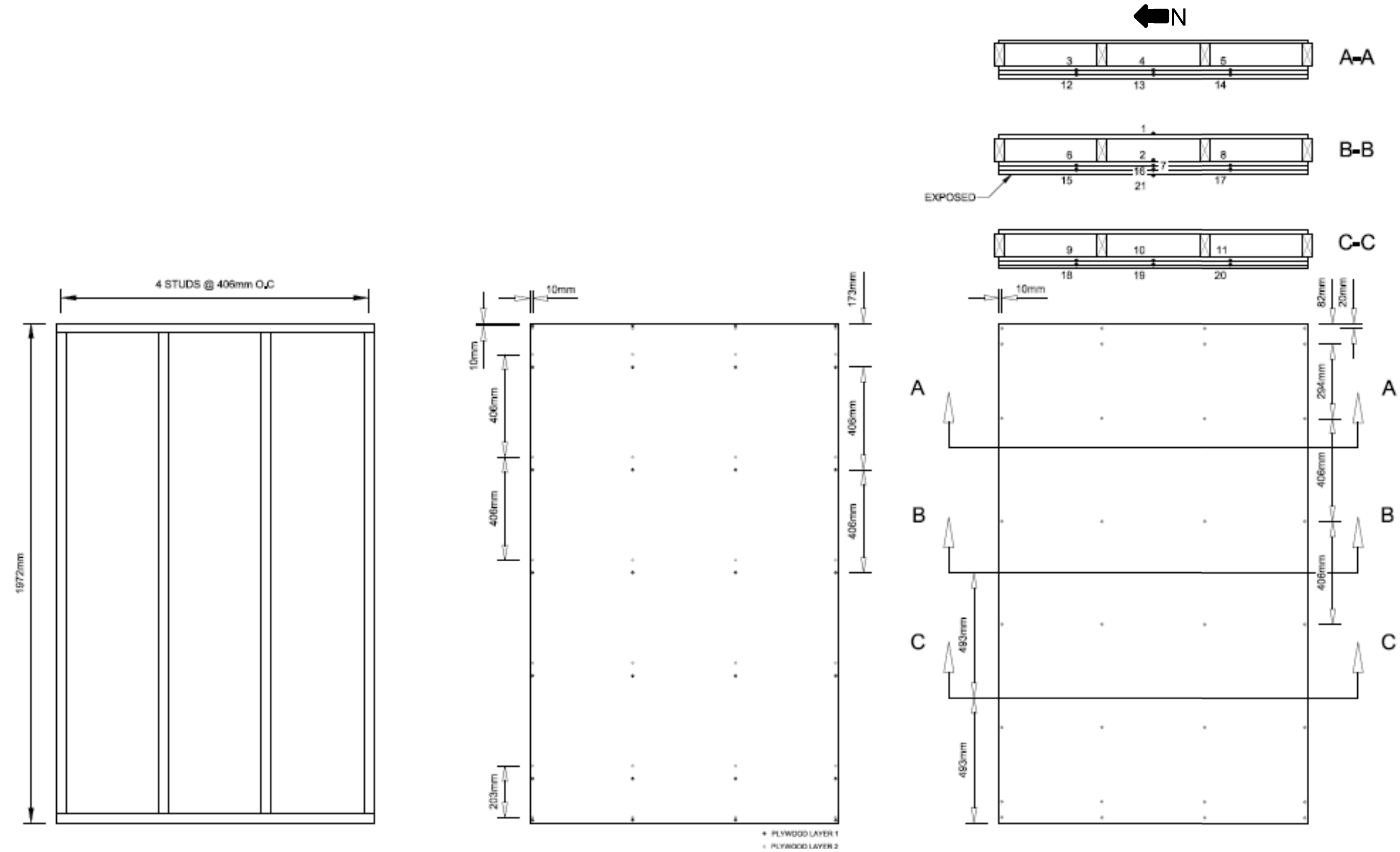
For Test IS-5, the average temperature rise criteria were exceeded first for Criteria 1 and 2 and the single-point temperature rise criteria were exceeded first for Criteria 3 at the gypsum board/plywood interface. The differences in time between reaching the average and single-point criteria were 0.33, 1.75 and 2.75 min for Criteria 1, 2 and 3, respectively. The increasing difference between the average and single-point times is consistent with the temperature rise value profiles shown Figure 12, which show a faster rate of increase of the temperature rise values measured by TC 16 than at the other 8 locations.

Test IS-5 was stopped before the temperature rise values measured at the interface between the two plywood layers exceeded the temperature rise criteria. However, the average temperature rise value measured at this location was approaching Criteria 1. There was only a 3 - 5 mm thickness of the first layer of plywood not charred and it can be estimated that all criteria would be exceeded within a short time if the test had continued.

Table 2. Times at which temperature rise values exceeded the average and single-point temperature rise criteria for tests with 12.7 mm thick Type X gypsum board.

Test	Number of Layers	Interface	Time ΔT Exceeded					
			Average ΔT (ºC)			Single-Point ΔT (ºC)		
			140 (min)	195 (min)	250 (min)	180 (min)	250 (min)	270 (min)
IS-1	1	Gypsum board-Plywood	17.92	19.83	22.92	18.17	20.92	21.58
		Plywood-Plywood	40.08	40.42	40.92	39.83	40.25	40.25
IS-2	1	Gypsum board-Plywood	18.58	21.67	24.08	19.42	22.92	24.33
IS-5	2	Gypsum board-Gypsum board	18.67	20.67	24.00	19.50	21.83	21.92
		Gypsum board-Plywood	50.67	55.33	61.50	51.00	57.08	58.75
		Plywood-Plywood	80.0*	NA	NA	NA	NA	NA

*Test terminated at 80 min with temperature rise value at 136ºC. It was estimated that only 3 - 5 mm of the first layer of plywood was not charred at that time.



Wood Frame | Plywood Base Layer | Gypsum Board

Figure 1. Drawings for the assembly used for Test IS-1 with a single layer of 12.7 mm thick Type X gypsum board.

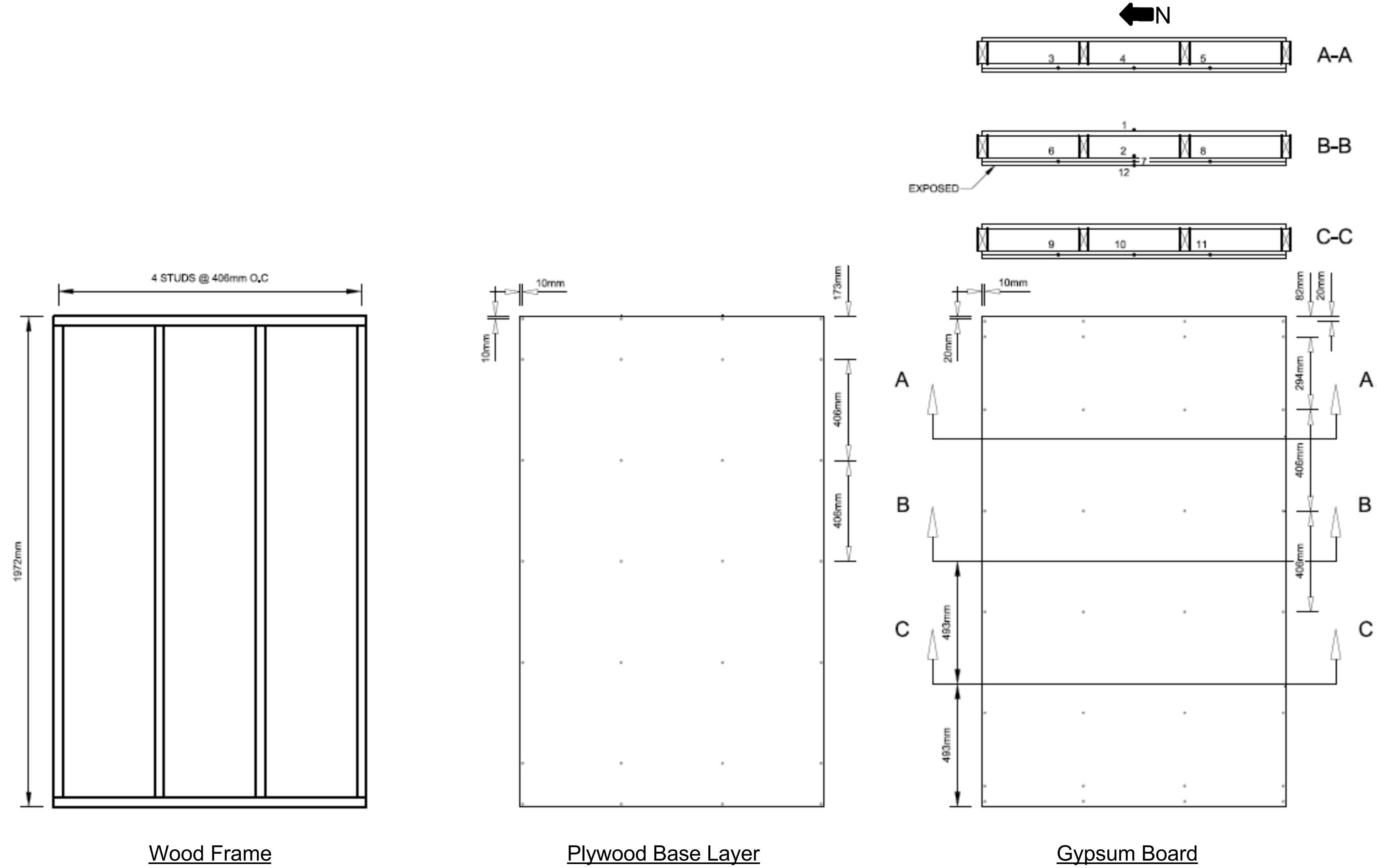
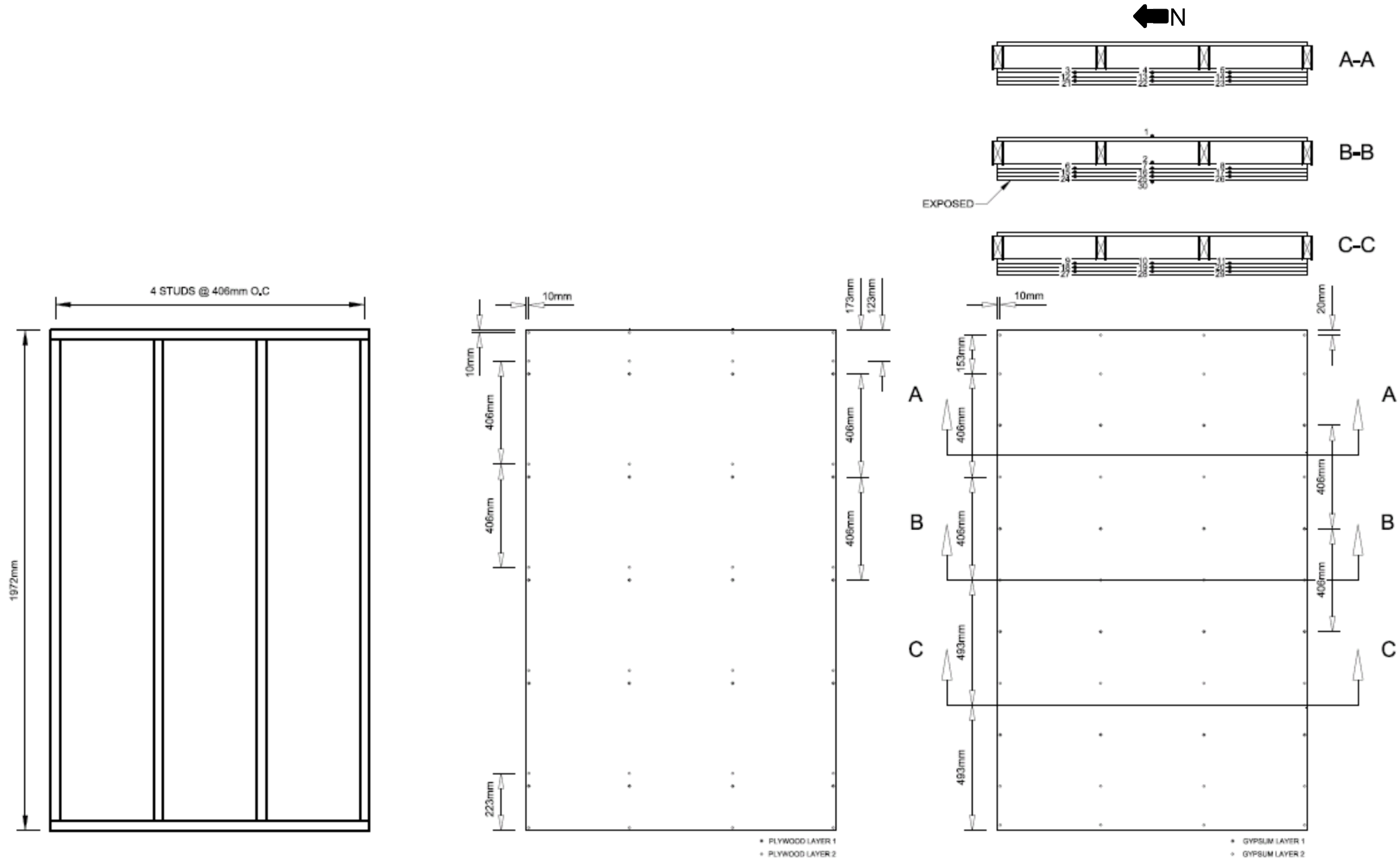


Figure 2. Drawings for the assembly used for Test IS-2 with a single layer of 12.7 mm thick Type X gypsum board.



Wood Frame Plywood Base Layer Gypsum Board

Figure 3. Drawings for the assemblies used for Test IS-5 and Test IS-11 with two layers of 12.7 mm thick Type X gypsum board.

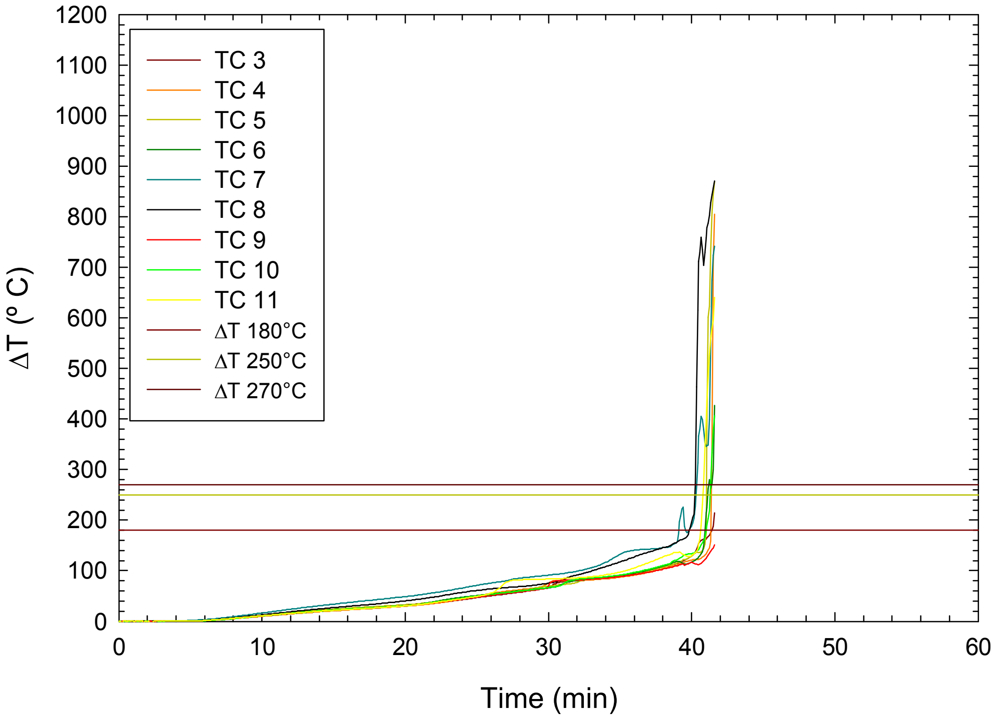


Figure 4. Temperature rise value profiles at Ply-Ply interface for Test IS-1 with 1 layer 12.7 mm Type X gypsum board.

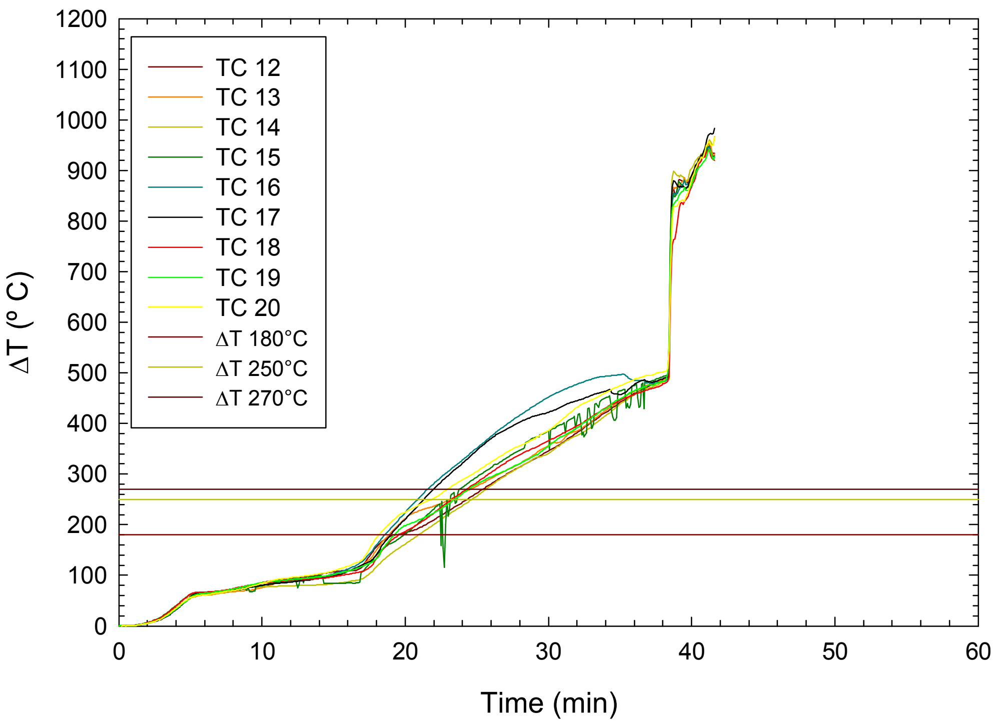


Figure 5. Temperature rise value profiles at GB-Ply interface for Test IS-1 with 1 layer 12.7 mm Type X gypsum board.

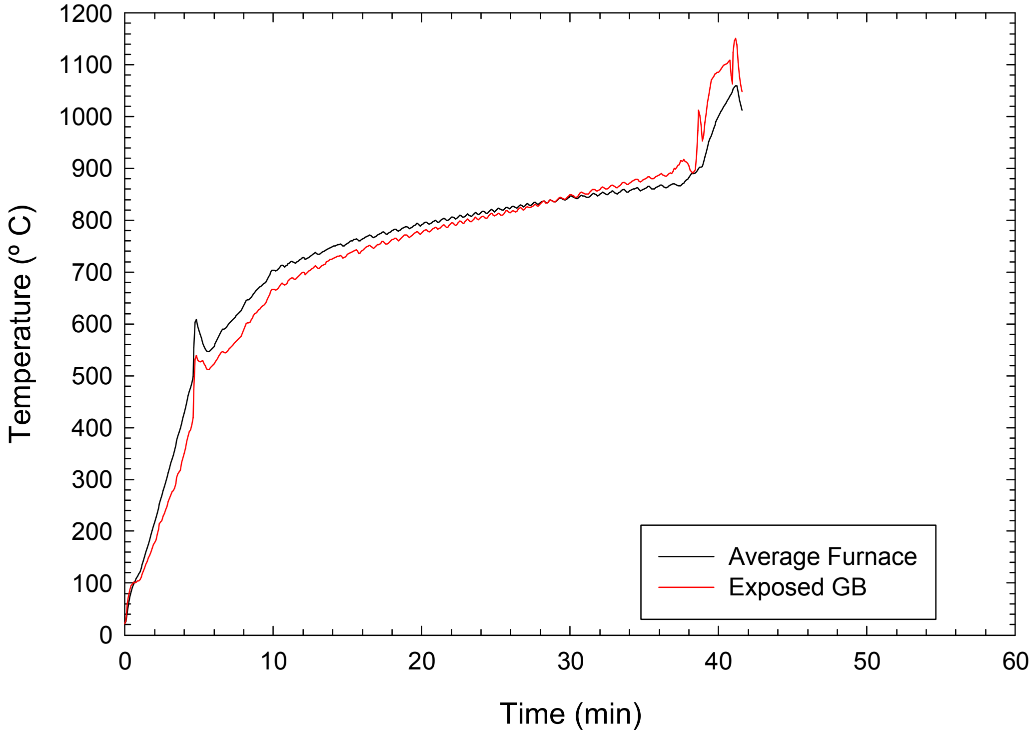


Figure 6. Temperature profiles for Test IS-1 with 1 layer 12.7 mm Type X gypsum board.

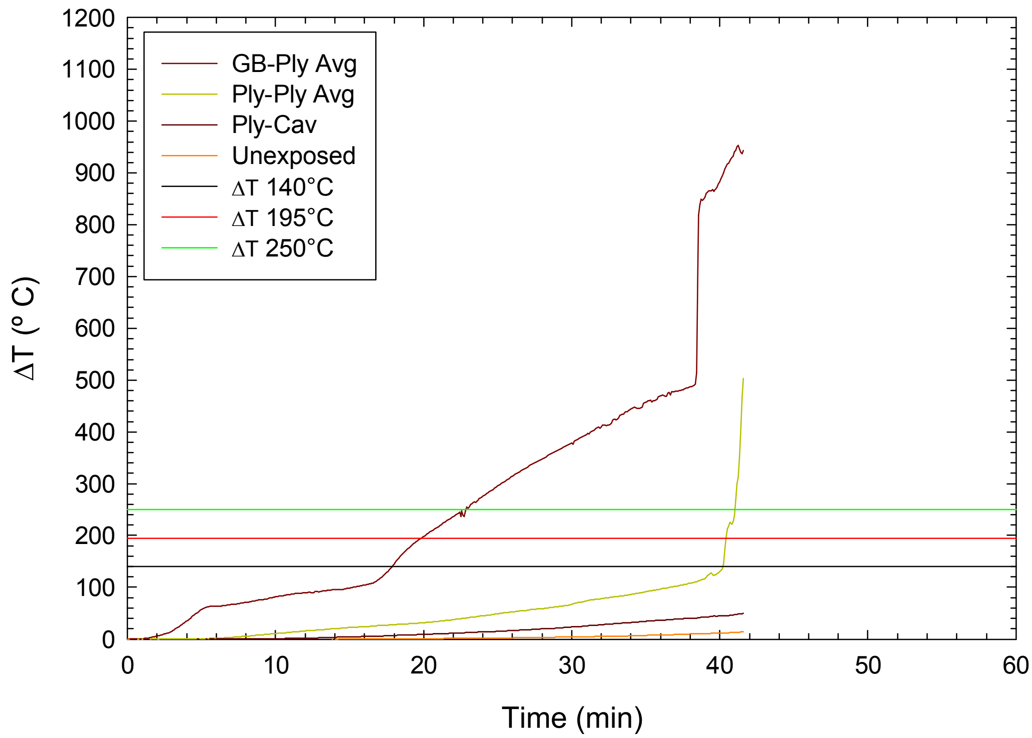


Figure 7. Temperature rise profiles for Test IS-1 with 1 layer 12.7 mm Type X gypsum board.

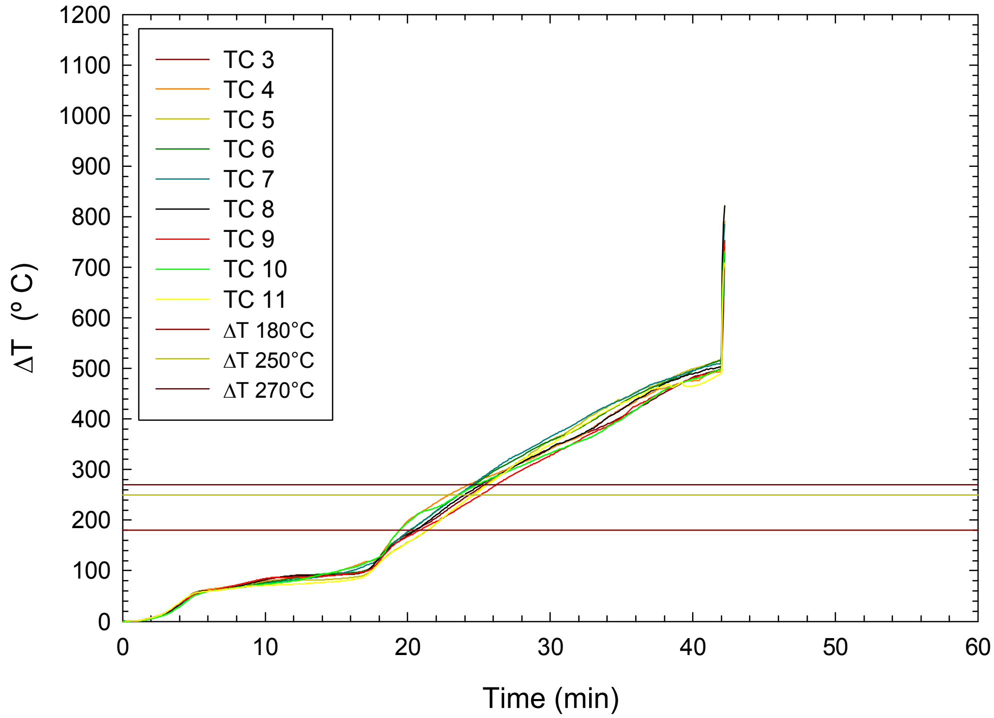


Figure 8. Temperature rise value profiles at GB-Ply interface for Test IS-2 with 1 layer 12.7 mm Type X gypsum board.

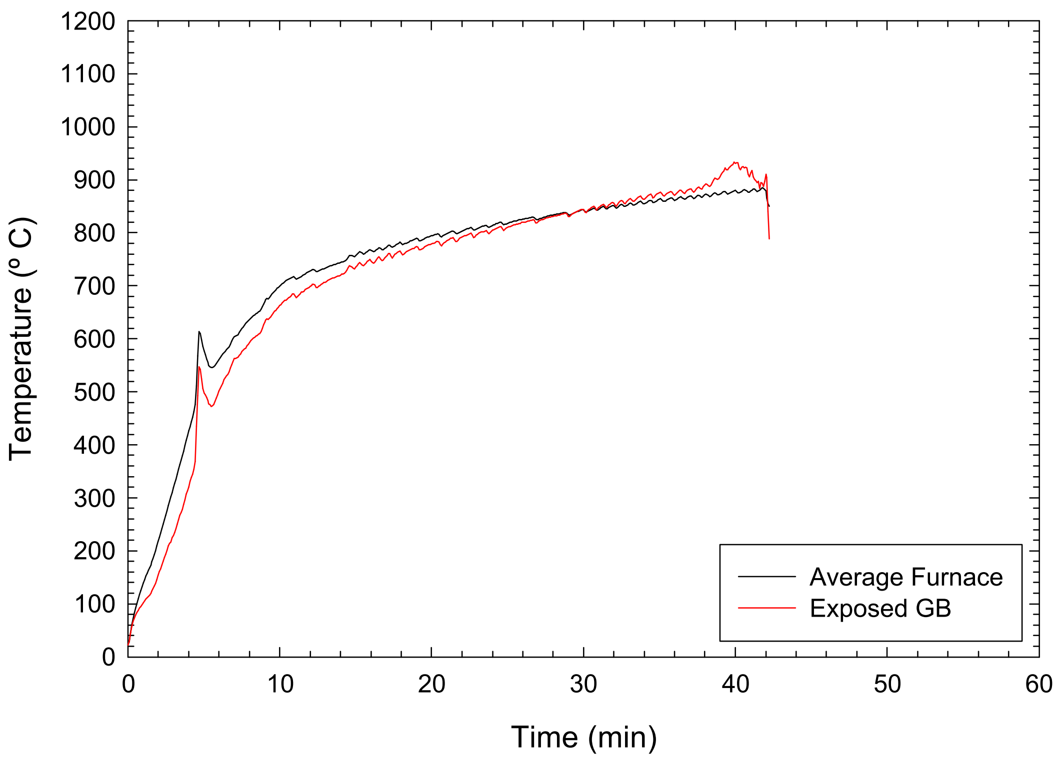


Figure 9. Temperature profiles for Test IS-2 with 1 layer 12.7 mm Type X gypsum board.

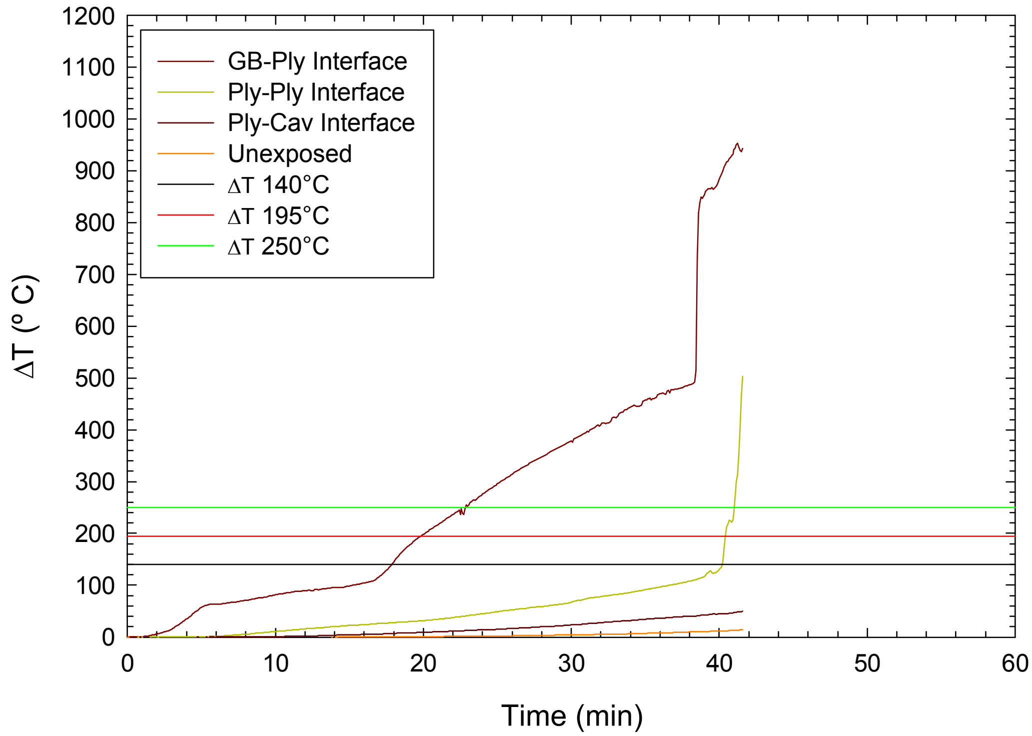


Figure 10. Temperature rise value profiles for Test IS-2 with 1 layer 12.7 mm Type X gypsum board.

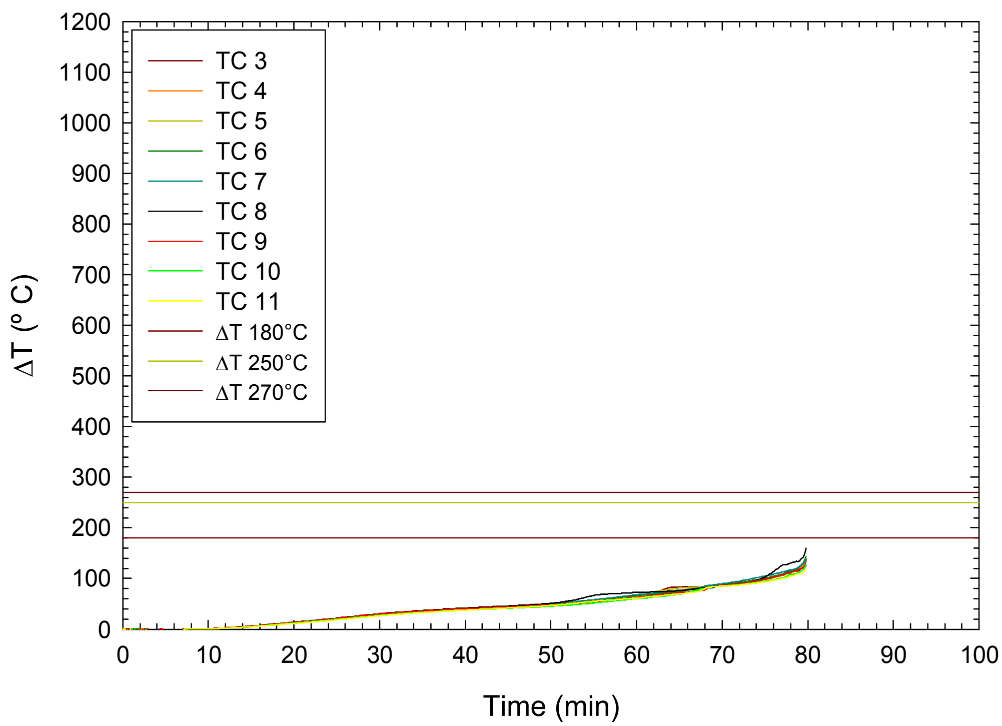


Figure 11. Temperature rise value profiles at Ply-Ply interface for Test IS-5 with 2 layers 12.7 mm Type X gypsum board.

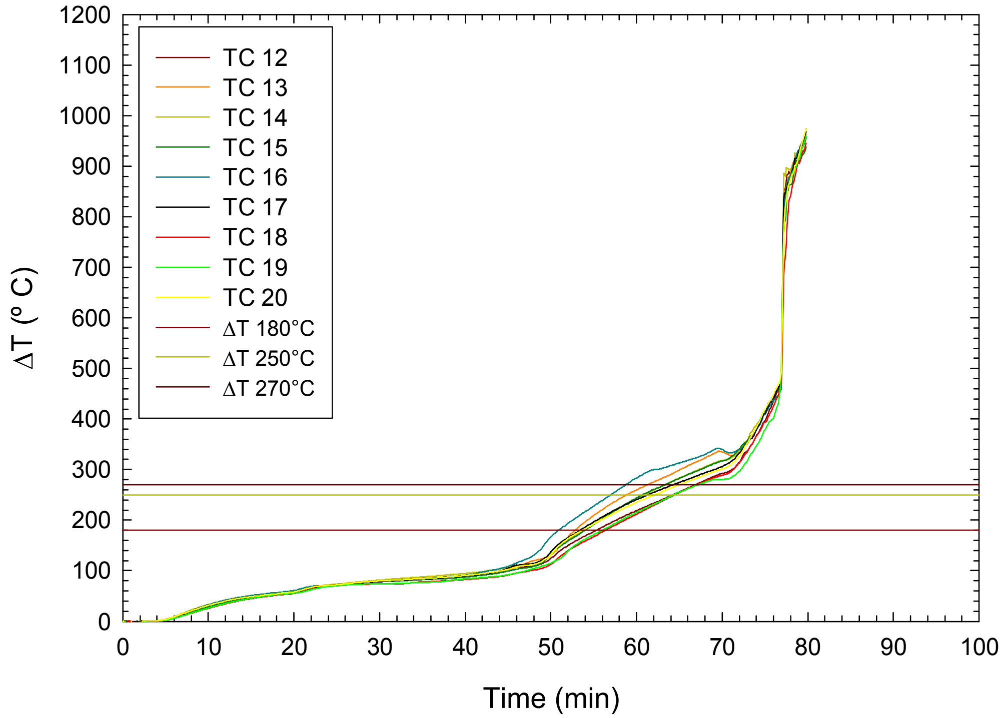


Figure 12. Temperature rise value profiles at GB-Ply interface for Test IS-5 with 2 layers 12.7 mm Type X gypsum board.

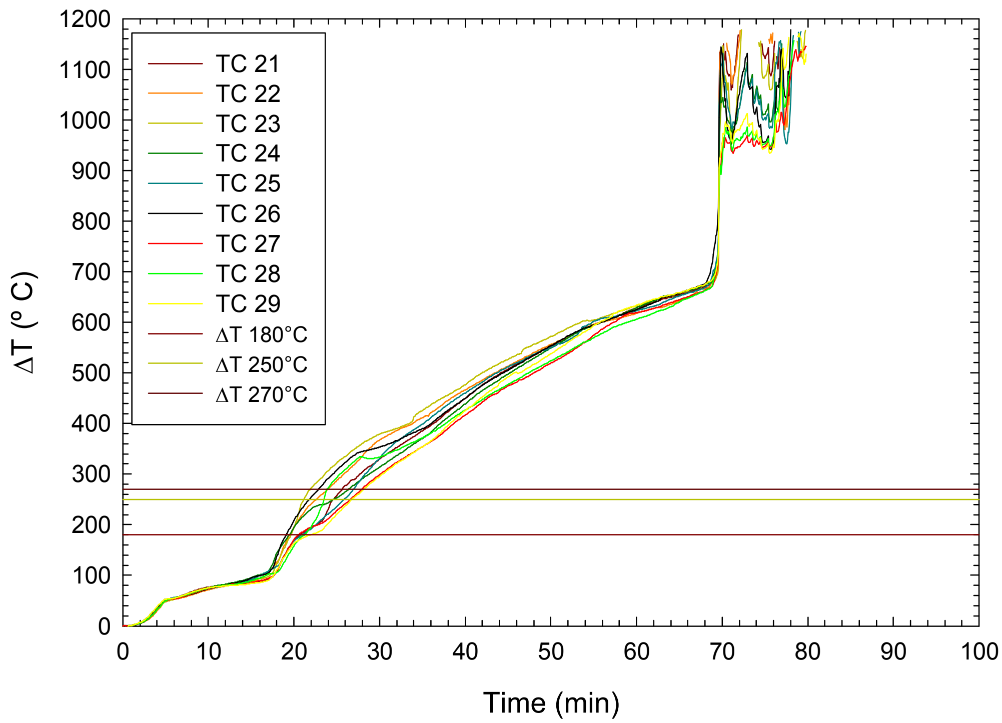


Figure 13. Temperature rise value profiles at GB-GB interface for Test IS-5 with 2 layers 12.7 mm Type X gypsum board.

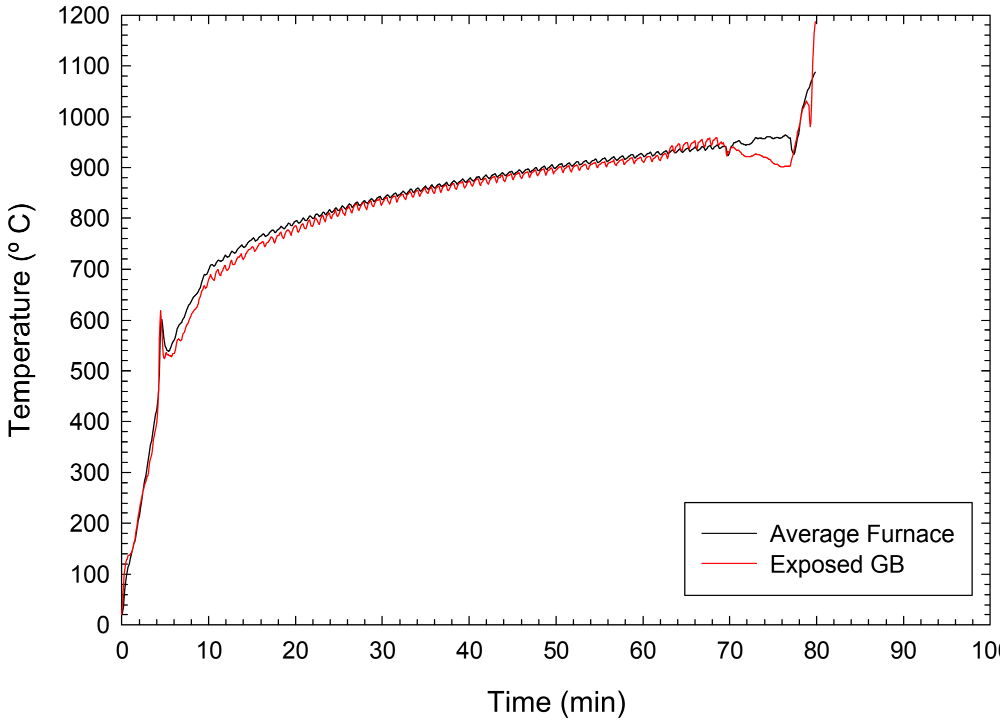


Figure 14. Temperature profiles for Test IS-5 with 2 layers 12.7 mm Type X gypsum board.

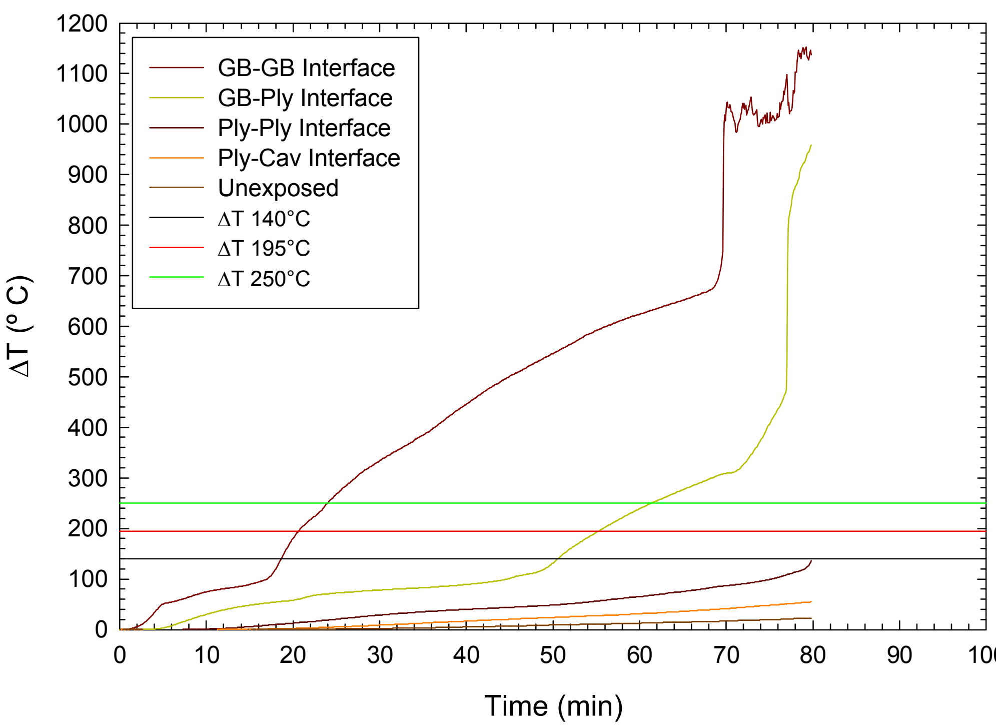


Figure 15. Temperature rise value profiles for Test IS-5 with 2 layers 12.7 mm Type X gypsum board.

4.2 Results – 15.9 mm Thick Type X Gypsum Board

Two tests were conducted using 15.9 mm thick Type X gypsum board as the encapsulation material, using the standard time-temperature curve:

1. Test IS-4. A single layer of gypsum board with two layers of 15.9 mm thick plywood as the substrate.
2. Test IS-9. Two layers of gypsum board with two layers of 15.9 mm thick plywood as the substrate.

The drawings for the test assemblies are shown in Figure 16 and Figure 17, respectively.

4.2.1 Results for Test IS-4

The results for Test IS-4 with a single layer of 15.9 mm thick Type X gypsum board and two layers of 15.9 mm thick plywood as the substrate are shown in Figure 18, Figure 19Figure 20 and Figure 21. The temperature rise profiles measured by the thermocouples at the interface between the two layers of plywood and at the interface between the gypsum board and the plywood are shown in Figure 18 and Figure 19, respectively. The furnace temperature and the temperature measured at the exposed gypsum board surface are shown in Figure 20. The average temperature at each interface and the temperature rise values at the plywood/cavity interface and on the unexposed surface of the gypsum board on the unexposed side of the assembly are shown in Figure 21.

At the interface between the gypsum board and plywood substrate, there was an initial rapid increase of temperature rise values to approximately 60 – 65°C within approximately 6 min (Figure 19). Subsequently, there was a second phase, with a slower rate of increase of temperature rise values during calcination and vaporization of the water in the gypsum board. The average temperature rise value at the interface reached 100°C at approximately 19 min (Figure 20).

After 19 min, there was a third phase for the temperature rise values measured at the interface between the gypsum board and plywood substrate, with a higher rate of increase of temperature rise values. The temperature rise values reached approximately 600°C at approximately 59 min, at which time the gypsum board fell off, resulting in direct exposure of the plywood substrate to the furnace environment.

There was minimal variation in the temperature rise values measured by the nine thermocouples at the interface between the gypsum board and plywood substrate until Phase 3. After 20 min, there was an increasing variation in the measured temperature rise values, with the time difference between thermocouples at that interface to reach a temperature rise value of 270°C of approximately 4 min. This is comparable to the time difference for Test IS-1, which had the same test setup with 12.7 mm thick Type X gypsum board instead of 15.9 mm thick. Test IS-2 with the 12.7 mm thick and a single layer of plywood as the substrate had a time difference of approximately 2 min at a temperature rise value of 270°C.

There was a steady increase of temperature rise values at the interface between the two layers of plywood beginning at approximately 7 min after the start of the test (Figure 18). Initially, there was minimal variation in the temperature rise values measured by the 9 thermocouples at that interface. However, between 27 and 34 min the measured temperature rise values began to show variation. At approximately 37 min, an increasing variation started, with the fastest increases in temperature rise values occurring at TC 3 and TC 8 near the end of the test. TC 3 was located at the center of the northeast quadrant of the test assembly and TC 8 was located on the south side of the assembly at its mid-length.

The average furnace temperature and the temperature measured on the exposed surface of the gypsum board on the exposed side of the assembly (TC 21) are shown in Figure 20. The temperature measured on the exposed surface of the exposed gypsum board lagged the furnace temperature until approximately 30 min. At 30 min, the average temperature at the gypsum board and plywood interface was 348°C. Subsequent to this, the higher temperature measured on the exposed surface of the exposed gypsum board compared to the average furnace temperature would suggest that burning in the furnace of pyrolysis gases from the plywood was being recorded by the TC located at the exposed surface of the gypsum board from that point in time onwards.

The temperature rise values measured on the plywood in the cavity and on the unexposed surface of the gypsum board on the unexposed side of the assembly remained low throughout the test (Figure 22), with maximum temperatures of 93.2 (TC 2) and 35.6 C (TC 1), respectively, by the end of the test.

4.2.2 Results for Test IS-9

The results for Test IS-9 with two layers of 15.9 mm thick Type X gypsum board and two layers of 15.9 mm thick plywood as the substrate are shown in Figure 22, Figure 23, Figure 24, Figure 25 and Figure 26. The temperature rise profiles measured by the thermocouples at the interface between the two layers of plywood, at the interface between the gypsum board and the plywood and at the interface between the two layers of gypsum board are shown in Figure 22, Figure 23 and Figure 24, respectively. The furnace temperature and the temperature measured at the exposed gypsum board surface are shown in Figure 25. The average temperature at each interface and the temperature rise values at the plywood/cavity interface and on the unexposed surface of the gypsum board on the unexposed side of the assembly are shown in Figure 26.

At the interface between the two gypsum board layers (Figure 24), the increase of temperature rise values followed the same general trend as those observed for Test IS-4. There was an initial rapid increase of temperature rise values to approximately 50°C at 5 min. Subsequently, there was a second phase, with a slower rate of increase of temperature rise values with calcination and vaporization of the water in the gypsum board. The average temperature rise value at the interface reached 100°C at approximately 21 min (Figure 26).

After 21 min, there was a third phase for the temperature rise values measured at the interface between the two gypsum board layers, with a higher rate of increase of temperature rise values. The temperature rise values reached approximately 790°C at approximately 90 min, at which time the face layer of gypsum board fell off, resulting in direct exposure of the base layer of gypsum board to the furnace environment.

There was minimal variation in the temperature rise values measured by the nine thermocouples at the interface between the gypsum board layers until the later stage of Phase 2. However, after approximately 16 min, there was an increasing variation in the measured temperature rise values. The time difference between thermocouples at that interface for the temperature rise values to reach 270ºC was approximately 4 min.

At the interface between the gypsum board and plywood substrate (Figure 23), there was a gradual increase of temperature rise values beginning at approximately 5 min. There was not a distinct initial phase with a fast increase of temperature rise value as was found in the tests with a single layer of gypsum board. However, there was a decrease in the rate of increase of temperature rise value during calcination and vaporization of the water in the gypsum board. The average temperature rise value at that interface reached 100°C at approximately 56 min (Figure 26). Subsequently, there was a higher rate of increase of temperature rise value. The temperature rise values reached approximately 600°C at the end of the test at the interface between the gypsum board and plywood substrate.

There was minimal variation in the temperature rise values measured by the nine thermocouples at the interface between the gypsum board and plywood substrate until approximately 60 min. Subsequently, there was an increasing variation in the measured temperature rise values, with the slowest rate of increase of temperature rise value during Phase 3 at TC 13, which was on the center line of the test assembly at the east end. The time difference between thermocouples at that interface to reach a temperature rise value of 270º was approximately 4 min.

There was a steady increase of temperature values at the interface between the two layers of plywood beginning at approximately 12 min after the start of the test (Figure 22). There was a faster rate of increase of temperature rise values after 80 min. There was no obvious reason for this increase of rate as the face layer of gypsum board stayed in place until 94 min.

There was minimal variation in the temperature rise values measured by the 9 thermocouples at the interface between the two layers of plywood until near the end of the test. The difference in time for the temperature rise values measured by the 9 thermocouples to reach 270ºC was approximately 5 min.

The average furnace temperature and the temperature measured on the exposed surface of the gypsum board on the exposed side of the assembly (TC 30) are shown in Figure 25. The temperature measured on the exposed surface of the exposed gypsum board initially lagged the furnace temperature and during the later stages of the test was comparable to the furnace temperature. There was no indication of burning of the plywood during the test.

The increase in temperature rise value ~~increase~~ was minimal on the plywood in the cavity (TC 2: 92°C) and on the unexposed surface of the gypsum board on the unexposed side of the assembly (TC 1: 21°C) by the end of the test. This indicates there was limited heat loss through the back portion of the test assembly.

4.2.3 Discussion and Summary – 15.9 mm Thick Type X Gypsum Board

Two tests were conducted using 15.9 mm thick Type X gypsum board as the encapsulation material: 1 test with a single layer and 1 test with a double layer of gypsum board.

For the face layer of gypsum board, the temperature rise value profiles followed the same trend or phases as the tests with 12.7 mm thick Type X gypsum board:

1. Phase 1. Initial fast increase of temperature rise values to approximately 60°C.
2. Phase 2. Relatively steady increase of temperature rise values during the calcination and subsequent vaporization of water in the gypsum board.
3. Phase 3. Rapid increase of temperature rise values to high values.

There was minimal variation in the temperature rise values measured by the nine thermocouples at the interface behind the gypsum board face layer until the beginning of Phase 3 in both tests. With the 15.9 mm thick gypsum board, the variations in the temperature rise values were typically less than those with the thinner gypsum board.

The fall-off time for the gypsum board face layer was 59 and 90 min in Tests IS-4 and IS-9, respectively. The fall-off time in Test IS-4 was considerably longer than in the two tests with a single layer of the thinner gypsum board (38 and 41 min). As with the 12.7 mm thick gypsum board, the fall-off time for the face layer was considerably longer with the double layer of gypsum board than with a single layer of gypsum board directly attached to the plywood substrate. Also, the base layer fell off shortly after the face layer in Test IS-9, similar to what happened in the tests with a double layer of 12.7 mm thick gypsum board.

The edges of the assembly and thus the edges of the encapsulation material were supported by the sides of the furnace. This support for the encapsulation material, combined with the intermediate size of the assembly, may be one of the reasons why fall-off times for the encapsulation materials in some tests occurred at more extended times than is sometimes seen in standard full-scale fire-resistance tests.

The increase of temperature rise values at the gypsum board/plywood interface in Test IS-9 had three phases similar to the other gypsum board tests. However, the initial two phases in Test IS-9 were similar to those in Test IS-5, with the temperature rise values showing a relatively steady increase until approximately 100°C. There was not a distinct interface between Phase 1 and 2 as was noted in the tests with a single layer of gypsum board.

In both Tests IS-4 and IS-9, the initial temperature rise values at the plywood/plywood interface showed a steady increase. The rate of increase of temperature rise values was faster near the end of the tests.

The times at which the temperature rise values measured at the various interfaces in the test assemblies exceeded the temperature rise criteria are shown in Table 3.

For Test IS-4, the average temperature rise criteria were exceeded first for Criteria 1 and 2 and the single-point criteria were exceeded first for Criteria 3, at the interface between the gypsum board and the plywood. The differences in time between reaching the average and single-point criteria were 0.83, 1.33 and 0.24 min for Criteria 1, 2 and 3, respectively.

At the plywood/plywood interface, the average temperature rise criteria were exceeded before the single-point criteria for all three sets of criteria. The differences in time between reaching the average and single-point criteria were 2.42, 0.50 and 1.17 min for Criteria 1, 2 and 3, respectively.

The extended period before the gypsum board fell off resulted in a longer time (45 – 55 min) for the temperature rise values to reach the three sets of criteria at the plywood/plywood interface in Test IS-4 with the single layer of 15.9 mm thick Type X gypsum board compared with Test IS-1 with a single layer of 12.7 mm thick Type X gypsum board (41 – 42 min).

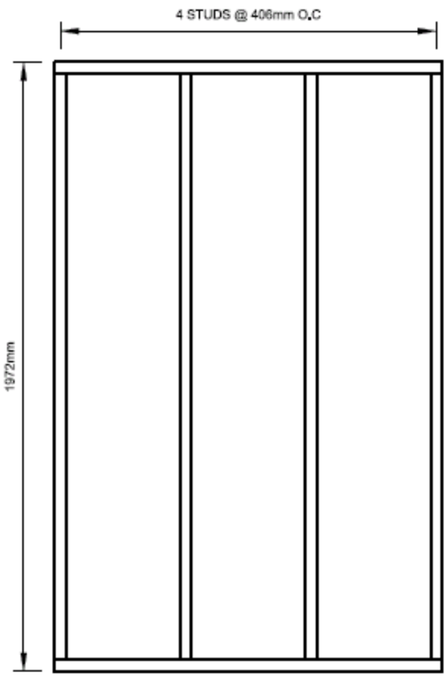
The times at which the temperature rise criteria were exceeded at the interface between the two layers of gypsum board in Test IS-9 were comparable to but longer than the times to exceed the temperature rise criteria at the gypsum board/plywood interface in Test IS-4. The time difference for reaching the average temperature rise criteria was 2.1 – 2.5 min, and was 1.0 – 1.7 min for the single-point criteria.

For Test IS-9, the average temperature rise criteria were exceeded first for Criteria 1 and 2 and the single-point criteria were exceeded first for Criteria 3, at the interface between the gypsum board and the plywood substrate. The differences in time between reaching the average and single-point criteria were 1.41, 3.17 and 0.77 min for Criteria 1, 2 and 3, respectively.

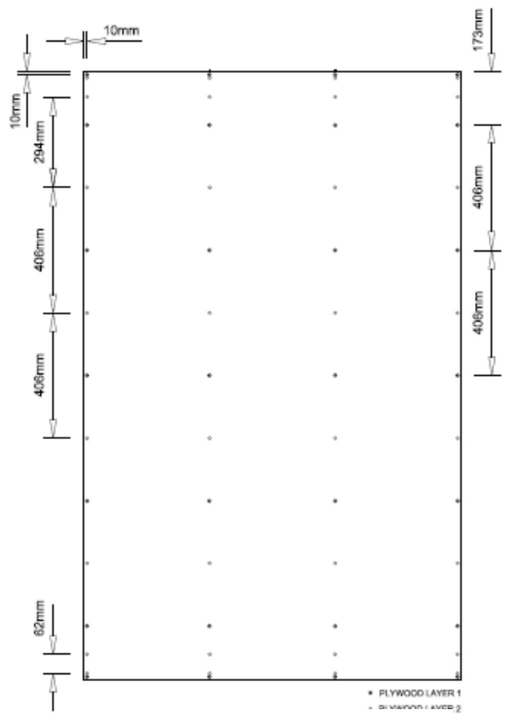
Extended times (between 90 and 105 min) were required for the various temperature rise criteria to be reached at the interface between the two layers of plywood in Test IS-9. However, the base and face layer of gypsum board stayed in place for approximately 90 and 94 min, respectively. This is considerably longer than the fall-off time for the gypsum board in Test IS-4 (59 min).

Table 3. Times at which temperature rise values exceeded the average and single-point temperature rise criteria for tests with 15.9 mm thick Type X gypsum board.

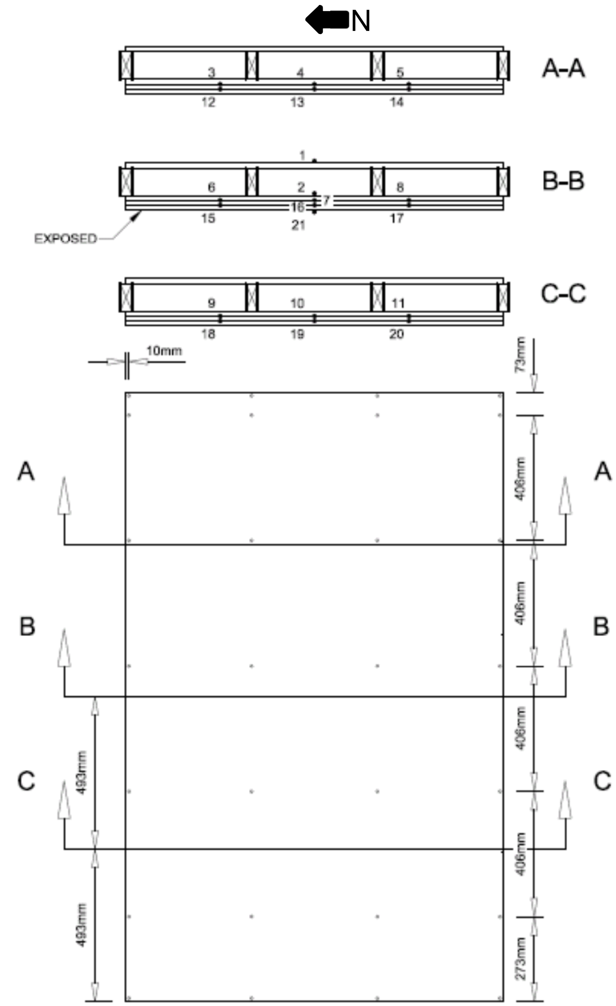
Test	Number of Layers	Interface	Time ΔT Exceeded					
			Average ΔT (ºC)			Single-Point ΔT (ºC)		
			140 (min)	195 (min)	250 (min)	180 (min)	250 (min)	270 (min)
IS-4	1	Gypsum board-Plywood	21.25	23.42	25.75	22.08	24.75	25.50
		Plywood-Plywood	45.33	52.17	54.92	47.75	52.67	53.75
IS-9	2	Gypsum board-Gypsum board	23.75	25.58	27.92	23.75	25.83	26.50
		Gypsum board-Plywood	61.92	65.33	69.58	63.33	68.50	70.35
		Plywood-Plywood	90.33	97.67	104.7	92.50	100.00	100.80



Wood Frame



Plywood Base Layer



Gypsum Board

Figure 16. Drawings for the assemblies used for Test IS-4 and Test IS-10 with one layer of 15.9 mm thick Type X gypsum board.

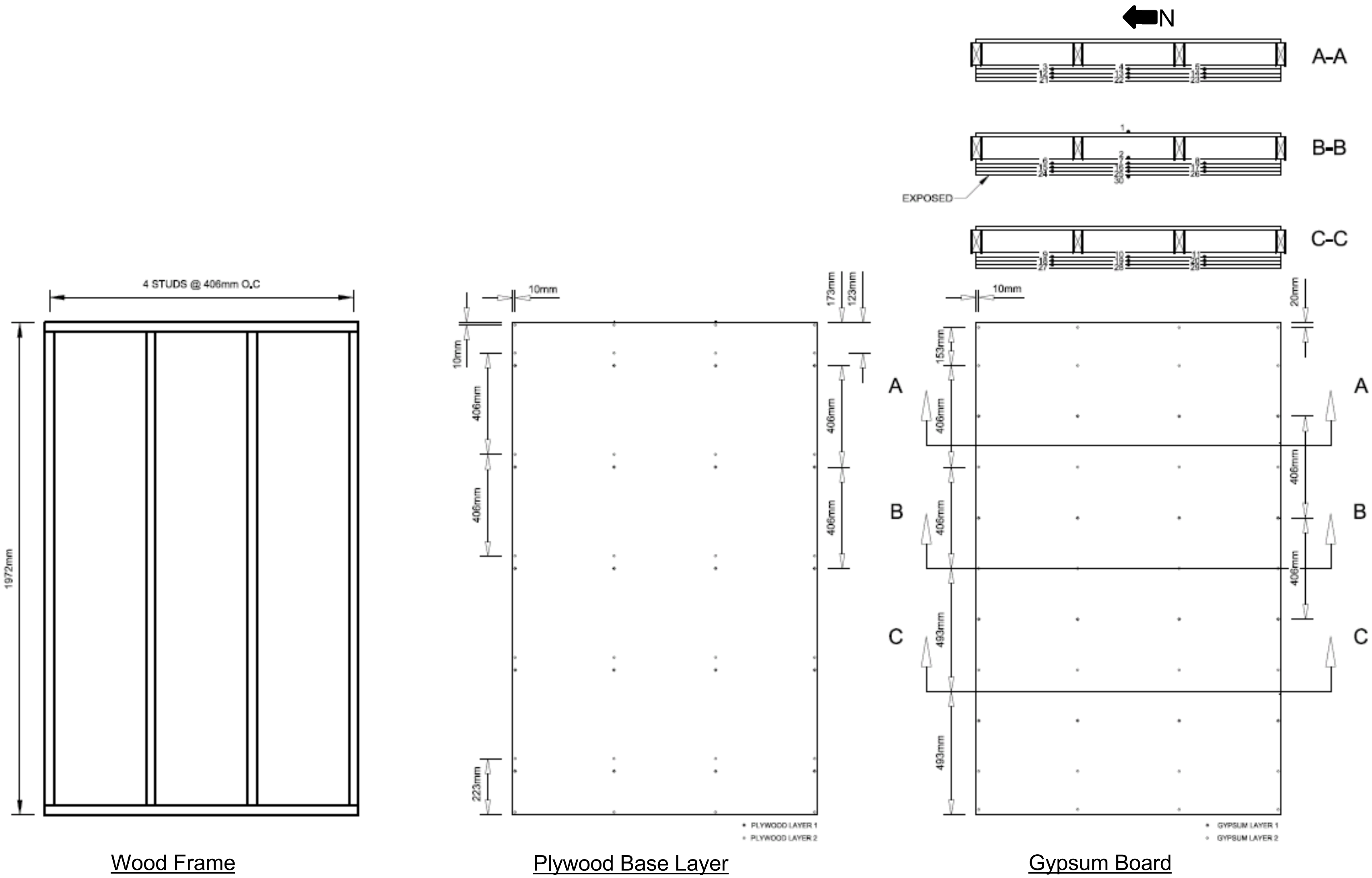


Figure 17. Drawings for the assembly used for Test IS-9 with two layers of 15.9 mm thick Type X gypsum board.

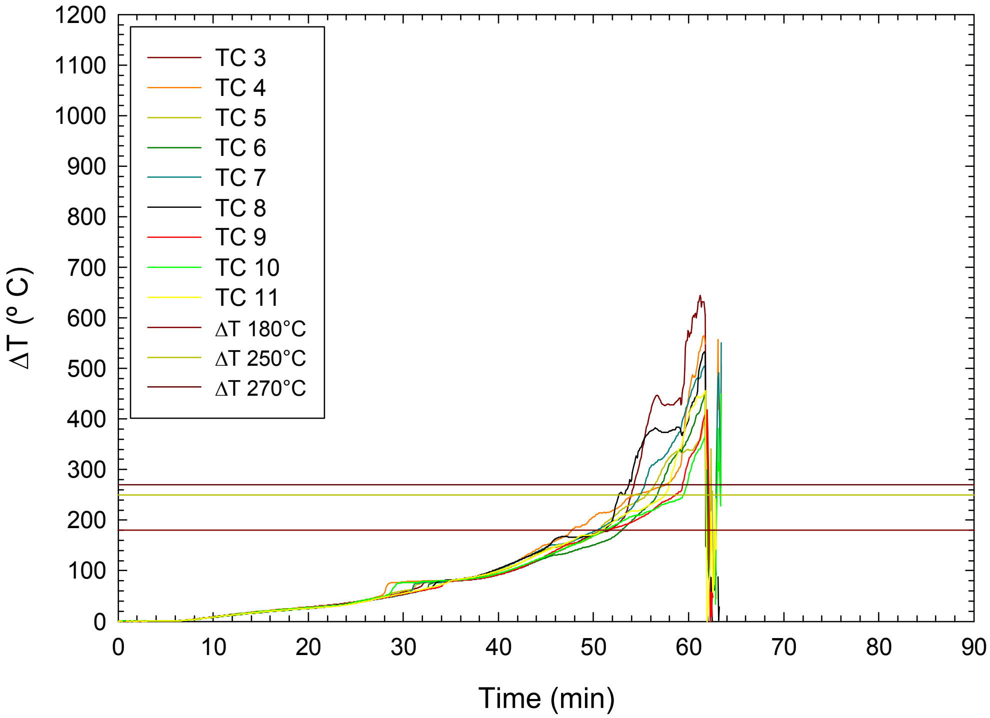


Figure 18. Temperature rise value profiles at Ply-Ply interface for Test IS-4 with 1 layer 15.9 mm Type X gypsum board.

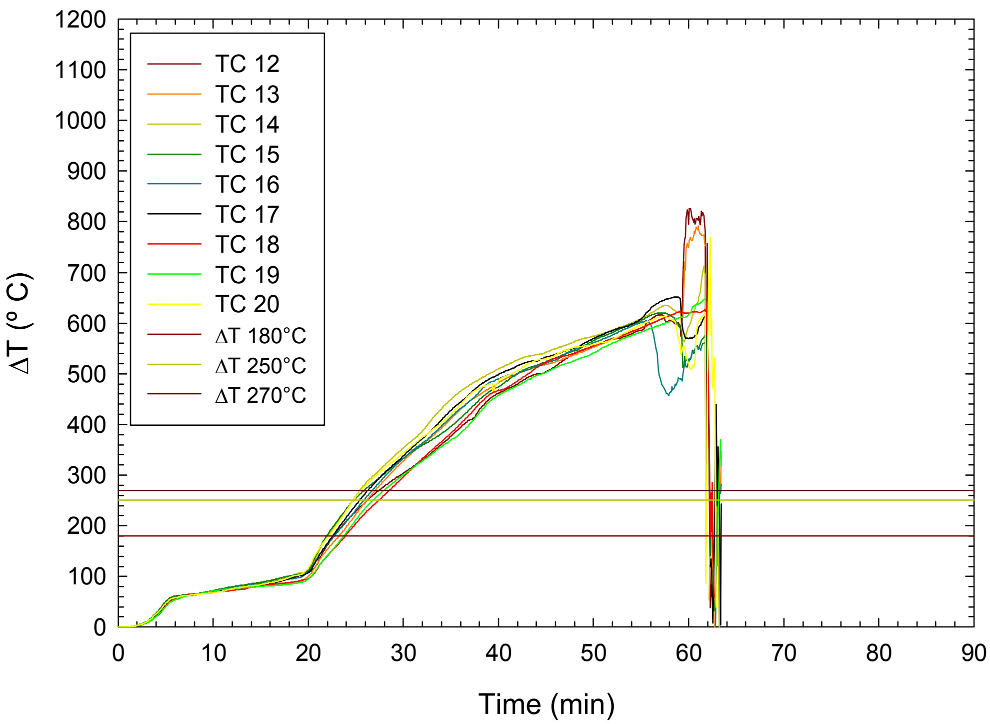


Figure 19. Temperature rise value profiles at GB-Ply interface for Test IS-4 with 1 layer 15.9 mm Type X gypsum board.

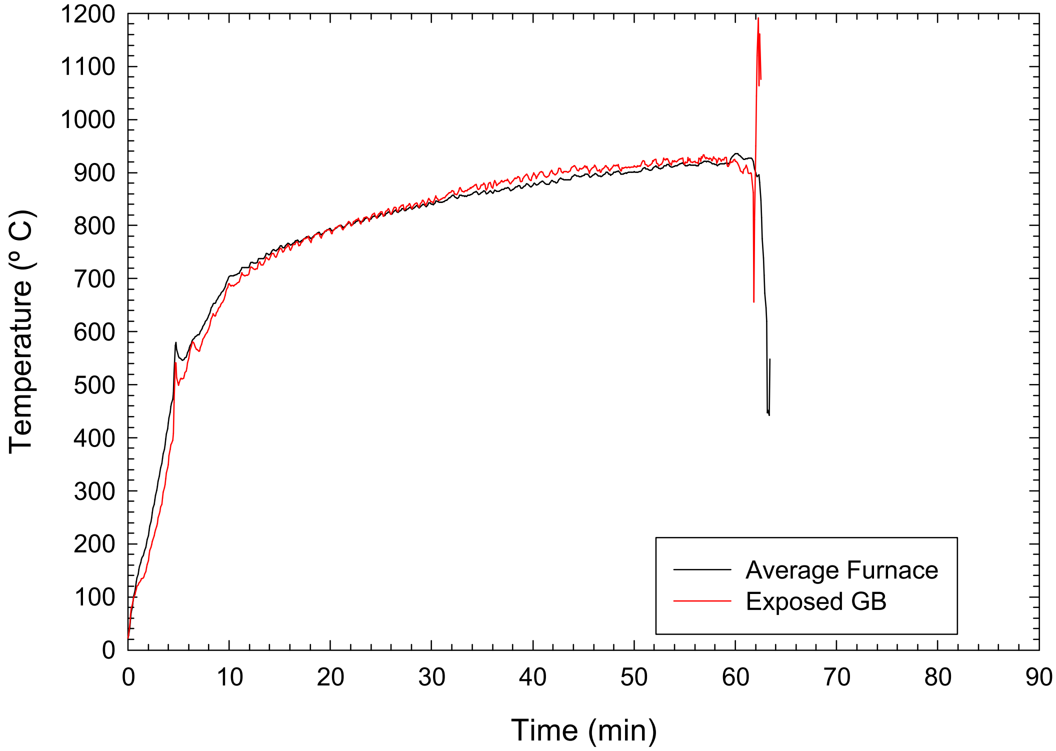


Figure 20. Temperature profiles for Test IS-4 with 1 layer 15.9 mm Type X gypsum board.

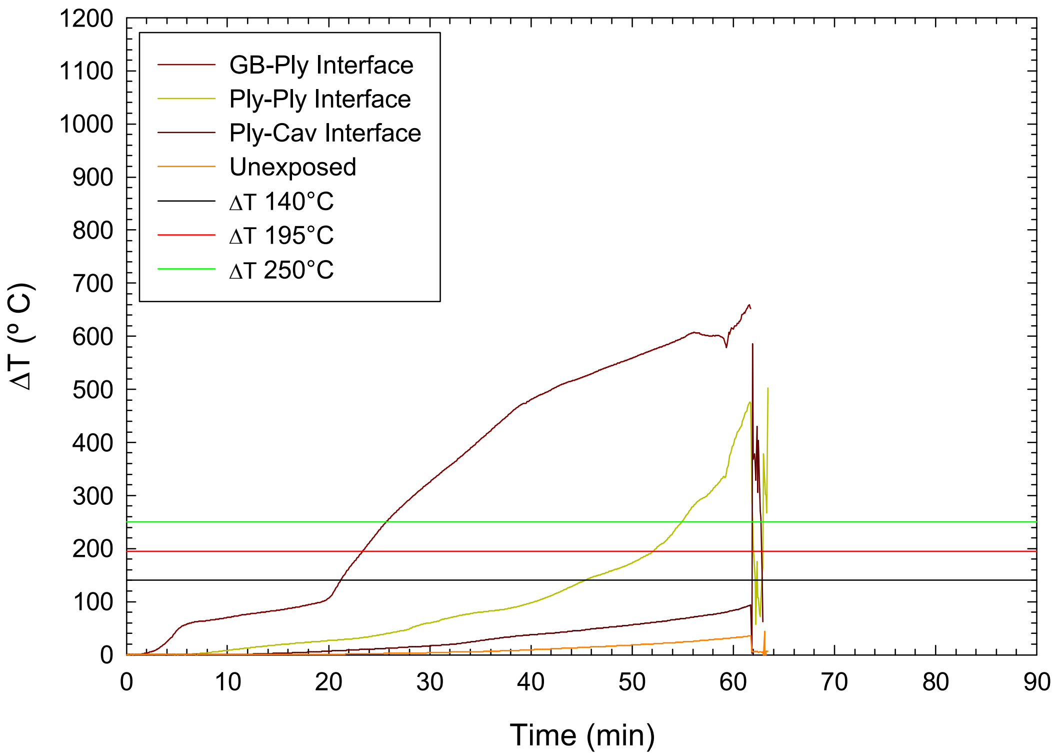


Figure 21. Temperature rise value profiles for Test IS-4 with 1 layer 15.9 mm Type X gypsum board.

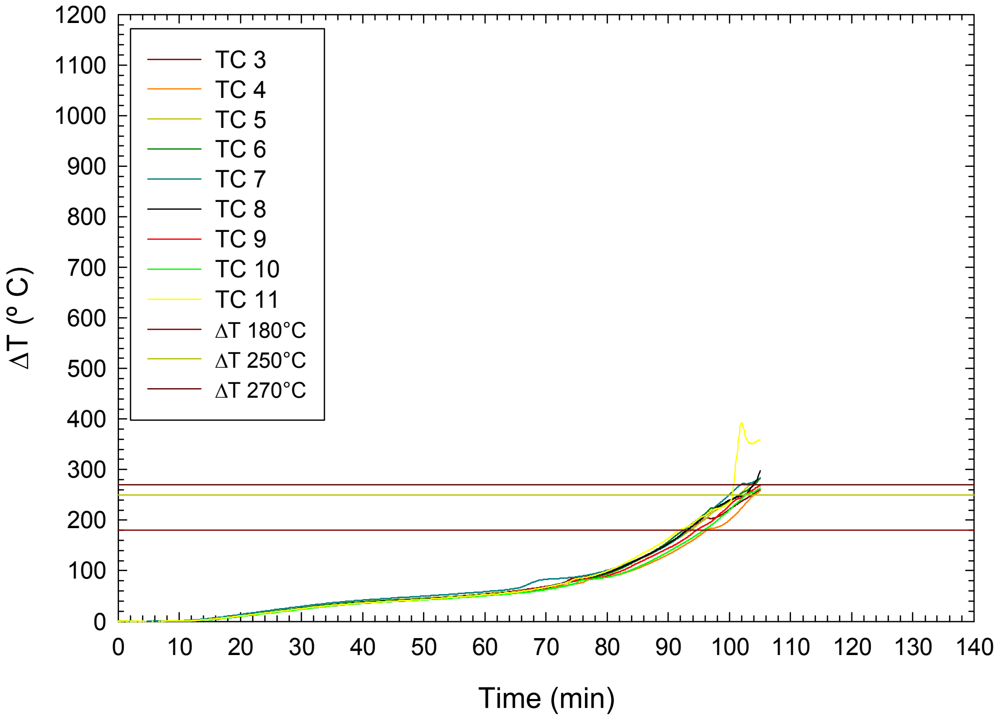


Figure 22. Temperature rise value profiles at Ply-Ply interface for Test IS-9 with 2 layers 15.9 mm Type X gypsum board.

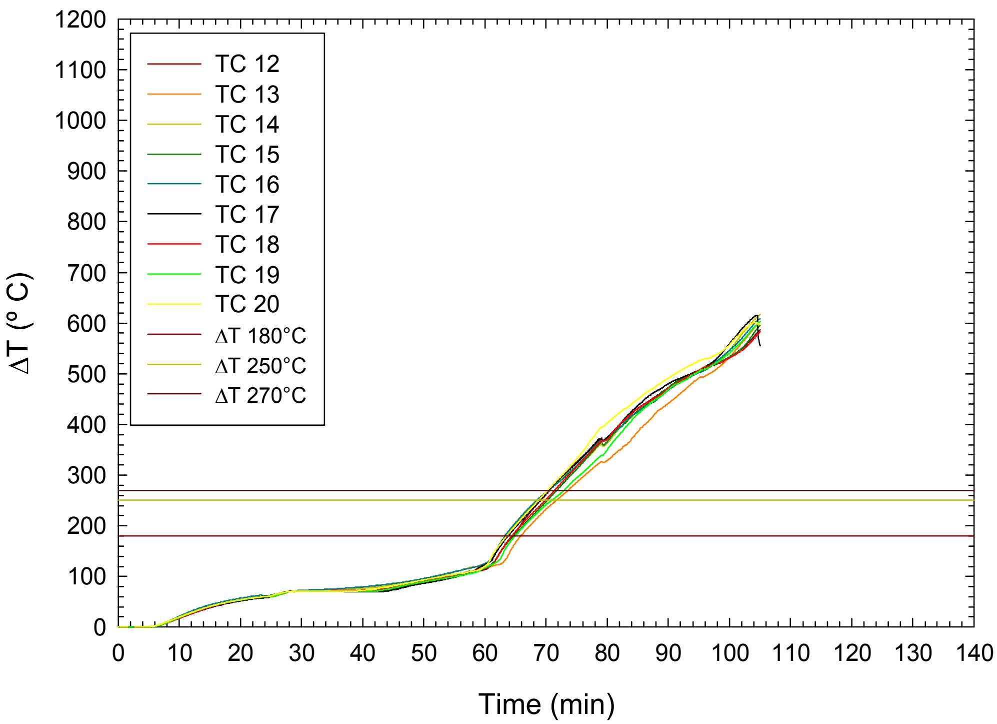


Figure 23. Temperature rise value profiles at GB-Ply interface for Test IS-9 with 2 layers 15.9 mm Type X gypsum board.

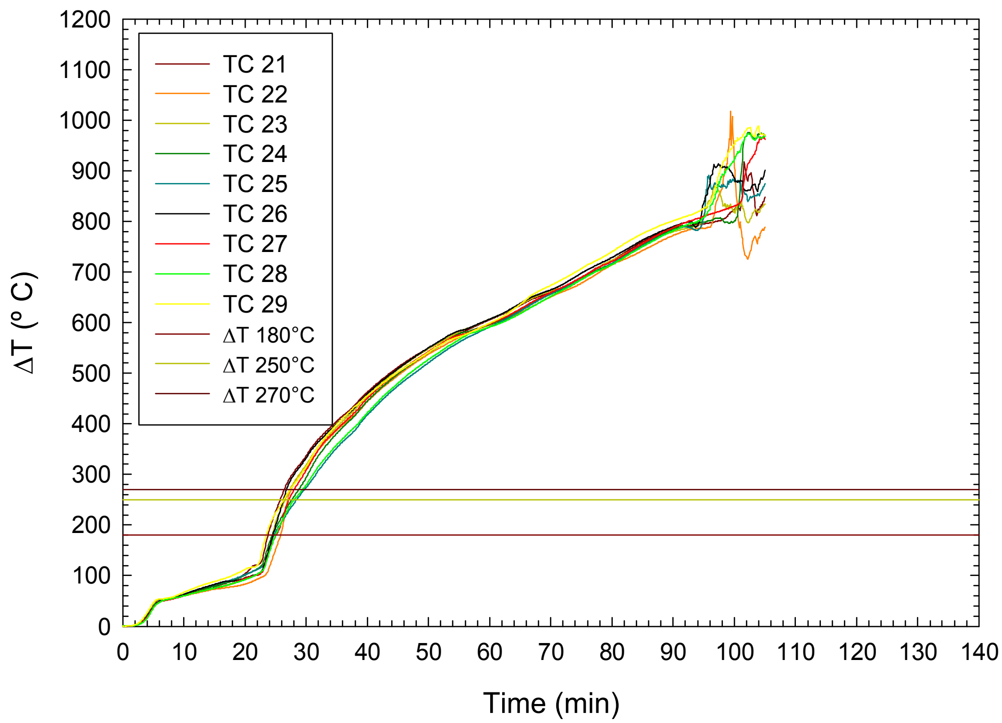


Figure 24. Temperature rise value profiles at GB-GB interface for Test IS-9 with 2 layers 15.9 mm Type X gypsum board.

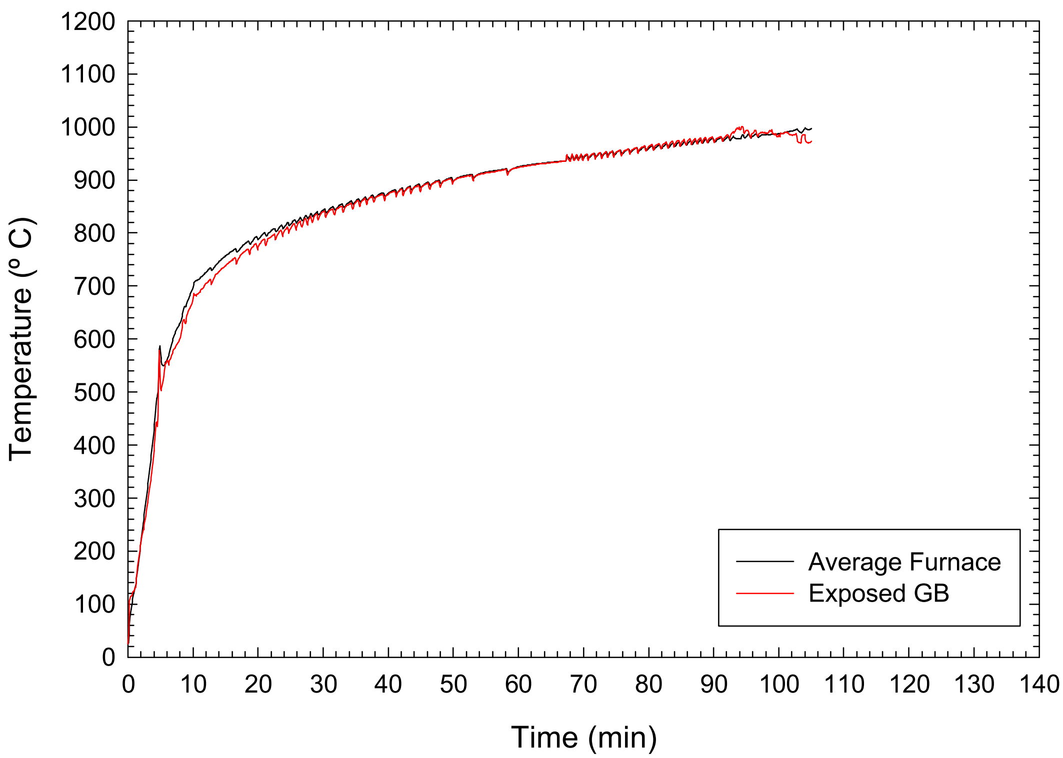


Figure 25. Temperature profiles for Test IS-9 with 2 layers 15.9 mm Type X gypsum board.

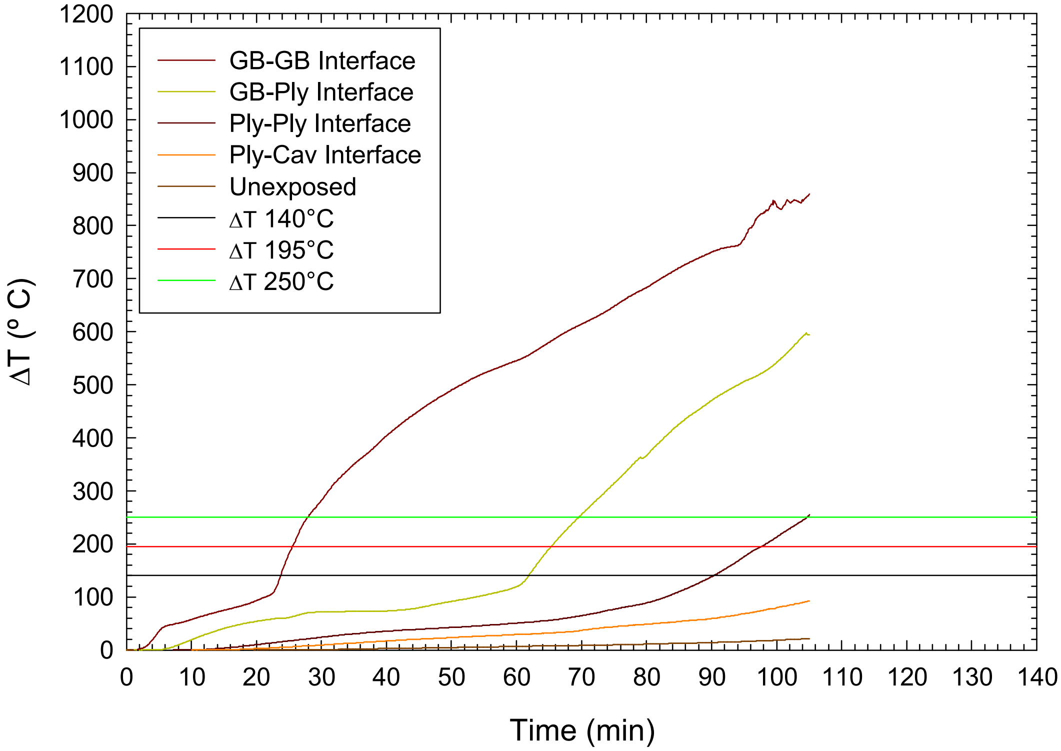


Figure 26. Temperature rise value profiles for Test IS-**9 with 2 layers 15.9 mm Type X gypsum board.**

4.3 Results - 12.7 mm Thick Cement Board

Two tests were conducted using 12.7 mm thick cement board as the encapsulation material, using the standard time-temperature curve:

1. Test IS-3. A single layer of cement board with two layers of 15.9 mm thick plywood as the substrate.
2. Test IS-8. Two layers of cement board with two layers of 15.9 mm thick plywood as the substrate.

The drawings for the test assemblies are shown in Figure 27 and Figure 28, respectively.

4.3.1 Results for Test IS-3

The results for Test IS-3 with a single layer of 12.7 mm thick cement board and two layers of 15.9 mm thick plywood as the substrate are shown in Figure 29, Figure 30 and Figure 31. The temperature rise profiles measured by the thermocouples at the interface between the two layers of plywood and at the interface between the cement board and the plywood are shown in Figure 29 and Figure 30, respectively. The furnace temperature and the temperature measured at the exposed cement board surface are shown in Figure 31. The average temperature at each interface and the temperature rise values at the plywood/cavity interface and on the unexposed surface of the gypsum board on the unexposed side of the assembly are shown in Figure 32.

At the interface between the cement board and plywood substrate, there was an initial rapid increase of temperature rise values to approximately 60 – 65°C within approximately 6 min (Figure 30). Subsequently, there was a short second phase, with a slower rate of increase of temperature rise values during vaporization of the water in the cement board. The average temperature rise value at the interface reached 100°C at approximately 11 min (Figure 32).

After 11 min, there was a third phase, with a higher rate of increase of temperature rise values. The temperature rise values reached approximately 500°C at approximately 28 min, at which time there was a decrease in the rate of increase until the end of the test at 60 min. The cement board stayed in place.

There was minimal variation in the temperature rise values measured by the nine thermocouples at the interface between the cement board and plywood substrate in Phase 1. However, in both Phase 2 and 3, there was a variation in the measured temperature rise values. The time difference between thermocouples at that interface to reach a temperature rise value of 270°C was approximately 4 min, which is comparable to the time differences for the tests with gypsum board.

There was a steady increase of temperature rise value at the interface between the two layers of plywood beginning at approximately 5 min after the start of the test (Figure 29). There was minimal variation in the temperature rise values measured by the 9 thermocouples at the interface between the two layers of plywood until approximately 45 min after the start of the test. After 45 min there was increasing variations in the measured temperature rise values with a rapid increase at TC 12, which was located at the center of the northeast quadrant of the assembly. However, the time difference at a temperature increase rise value of 270°C was only 2.5 min.

The average furnace temperature and the temperature measured on the exposed surface of the cement board on the exposed side of the assembly are shown in Figure 31. The temperature measured on the exposed surface of the exposed cement board lagged the furnace temperature until approximately 21.5 min. At 21.5 min, the average temperature at the cement board and plywood interface was 375°C. Subsequent to this, the higher temperature measured on the exposed surface of the exposed cement board compared to the average furnace temperature would suggest that burning in the furnace of pyrolysis gases from the plywood was being recorded by the TC located at the exposed surface of the cement board from that point in time onwards.

The temperature rise values measured on the plywood in the cavity and on the unexposed surface of the gypsum board on the unexposed side of the assembly remained low throughout the test (Figure 32), with maximum temperatures of 129.6 (TC 2) and 48.9 C (TC 1), respectively, by the end of the test.

4.3.2 Results for Test IS-8

The results for Test IS-8 with two layers of 12.7 mm thick cement board and two layers of 15.9 mm thick plywood as the substrate are shown in Figure 33, Figure 34, Figure 35 Figure 36 and Figure 37. The temperature rise profiles measured by the thermocouples at the interface between the two layers of plywood, at the interface between the cement board and the plywood and at the interface between the two layers of cement board are shown in Figure 33, Figure 34 and Figure 35, respectively. The furnace temperature and the temperature measured at the exposed cement board surface are shown in Figure 36. The average temperature at each interface and the temperature rise values at the plywood/cavity interface and on the unexposed surface of the gypsum board on the unexposed side of the assembly are shown in Figure 37.

At the interface between the two cement board layers (Figure 35), during the initial phase of this test, there was not the fast temperature rise value increase that was observed in the tests with gypsum board and in Test IS-3 with the single layer of cement board. Initially, there was a steady increase of temperature rise values, with the average temperature rise value at the interface (Figure 37) reaching 100°C at approximately 11.5 min. Subsequently, there was a second phase, with a faster increase of temperature rise values (Figure 36). The average temperature rise value reached approximately 600°C at 50 min, prior to the fall off of the face layer of cement board.

There was minimal variation in the temperature rise values measured by the nine thermocouples at the interface between the two cement board layers until approximately 10 min. Subsequently, there was an increasing variation in the measured temperature rise values. The time difference between thermocouples at that interface for the temperature rise values to reach 270ºC was approximately 5 min.

At the interface between the cement board and plywood substrate (Figure 34), there was a gradual increase of temperature rise values beginning at approximately 5 min. There was not as distinct an initial phase, in that there was not the fast increase of temperature rise values that was found in the tests with gypsum board. However, there was a decrease in the rate of increase of temperature rise values during vaporization of the water in the cement board as was seen in other tests. The average temperature rise value at the interface reached 100°C at approximately 30 min (Figure 36). Subsequently, there was a faster rate of increase of temperature rise values. The temperature rise values reached approximately 660°C prior to the base layer of cement board falling off at approximately 65 min.

There was minimal variation in the temperature rise values measured by the nine thermocouples at the interface between the cement board and plywood substrate until approximately 30 min. Subsequently, there was an increasing variation in the measured temperature rise values, with the fastest increase of temperature rise value after 30 min at TC 20, which was located at the center of the southwest quadrant of the assembly. The time difference between thermocouples at that interface to reach a temperature rise value of 270º was approximately 6.5 min. This time difference was primarily due to the rapid increase of temperature rise values measured by TC 20. There was considerably less variation between the temperature rise values measured by the other 8 thermocouples at the interface between the cement board and plywood substrate.

There was a steady increase of temperature rise values at the interface between the two layers of plywood beginning at approximately 12 min after the start of the test (Figure 33). There was an initial rise in the rate of increase of temperature rise values after the face layer of cement fell off at between 50 and 55 min. There was a rapid increase of temperature rise values after approximately 65 min with the fall of the base layer of cement board.

There was minimal variation in the temperature rise values measured by the 9 thermocouples at the interface between the two layers of plywood throughout the test. The difference in time for the temperature rise values measured by the 9 thermocouples to reach 270ºC was approximately 1 min.

The average furnace temperature and the temperature measured on the exposed surface of the cement board on the exposed side of the assembly (TC 30) are shown in Figure 36. The temperature measured on the exposed surface of the exposed cement board lagged the furnace temperature until the face layer of cement board fell off between 50 and 55 min.

The increase in temperature rise values was minimal on the plywood in the cavity (TC 2: 62°C) and on the unexposed surface of the gypsum board on the unexposed side of the assembly (TC 1: 21°C) by the end of the test. This indicates there was limited heat loss through the back portion of the test assembly.

4.3.3 Discussion and Summary – 12.7 mm Thick Cement Board

Two tests were conducted using 12.7 mm thick cement board as the encapsulation material: 1 test with a single layer and 1 test with a double layer of cement board.

For the face layer of cement board, the temperature rise value profile followed the same trend or phases as the tests with gypsum board:

1. Phase 1. Initial fast increase of temperature rise values to approximately 60°C.
2. Phase 2. Relatively steady increase of temperature rise values with the vaporization of water in the cement board.
3. Phase 3. Rapid increase of temperature rise values to high values.

However, Phase 2 was shorter for the tests with cement board than for the tests with gypsum board. This is likely due to two factors: the water in the cement board is not chemically bonded as it is in the gypsum board; and, there is less water to remove from the cement board.

There were larger variations in the temperature rise values measured by the 9 thermocouples located at the interface with the face layer of cement board with either the base layer of cement board or the plywood substrate (for those tests with only one layer of cement board) than at the corresponding interface for the tests with gypsum board. The temperature variations started at the beginning Phase 2. This suggests that the cement board was not as homogeneous as the gypsum board.

The face layer of cement board had not fallen off when Test IS-3 was stopped at 60 min. It fell off at 50 min in Test IS-8. Based on the fall-off times, the results suggest that the cement board was more stable at high temperatures than the 12.7 mm thick gypsum board and would continue to provide some protection from the fire.

The edges of the assembly and thus the edges of the encapsulation material were supported by the sides of the furnace. This support for the encapsulation material, combined with the intermediate size of the assembly, may be one of the reasons why fall-off times for the encapsulation materials in some tests occurred at more extended times than is sometimes seen in standard full-scale fire-resistance tests.

The temperature increase at the cement board/plywood interface in Test IS-8 had three phases similar to the other tests with two layers of encapsulation material, with the temperature rise values showing a relatively steady increase until approximately 100°C. There was not a distinct interface between Phase 1 and 2 as was noted in the tests with a single layer of gypsum board.

In both Tests IS-3 and IS-8, the initial temperature rise values at the plywood/plywood interface showed a steady increase. The rate of increase of temperature rise values was faster near the end of the tests.

The times at which the temperature rise values measured at the various interfaces in the two tests with cement board exceeded the temperature rise criteria are shown in Table 4.

For Test IS-3, the average temperature rise criteria were exceeded first for Criteria 1 and 2 and the single-point criteria were exceeded first for Criteria 3, at the cement board interface with the plywood. The differences in time between reaching the average and single-point criteria were 0.75, 0.25 and 1.08 min for Criteria 1, 2 and 3, respectively.

At the plywood/plywood interface, the average temperature rise criteria were exceeded first for Criteria 1 and 2 and the single-point criteria were exceeded first for Criteria 3. The differences in time between reaching the average and single-point criteria were 2.59, 3.49 and 0.50 min for Criteria 1, 2 and 3, respectively.

For Test IS-8, the average temperature rise criteria were exceeded first for Criteria 1 and 2 and the single-point criteria were exceeded first for Criteria 3, at the interface between the cement board and plywood. The differences in time between reaching the average and single-point criteria were 0.74, 0.50 and 2.75 min for Criteria 1, 2 and 3, respectively.

At the interface between the two layers of cement board in Test IS-8, the average temperature rise criteria were exceeded first for Criteria 1 and the single-point criteria were exceeded first for Criteria 2 and 3. The differences in time between reaching the average and single-point criteria were 0.17, 0.59 and 2.67 min for Criteria 1, 2 and 3, respectively.

The times at which the temperature rise criteria were exceeded at the interface between the two layers of cement board in Test IS-8 were comparable to but slightly longer than the times to exceed the temperature rise criteria at the cement board/plywood interface in Test IS-3. The time difference for reaching the average temperature rise criteria was 0.71 – 1.1 min, and was 0.0 – 0.1 min for the single-point criteria.

Extended times (between 62 and 67 min) were required for the various temperature rise criteria to be reached at the interface between the two layers of plywood in Test IS-8. However, the face layer of cement board stayed in place for more than 50 min and the base layer for approximately 65 min.

Table 4. Times at which temperature rise values exceeded the average and single-point termperature rise criteria for tests with 12.7 mm thick cement board.

Test	Number of Layers	Interface	Time ΔT Exceeded					
			Average ΔT (ºC)			Single-Point ΔT (ºC)		
			140 (min)	195 (min)	250 (min)	180 (min)	250 (min)	270 (min)
IS-3	1	Cement board-Plywood	13.08	15.08	17.08	13.83	15.33	16.00
		Plywood-Plywood	35.33	41.67	46.25	37.92	45.16	45.75
IS-8	2	Cement board-Cement board	13.75	15.92	18.17	13.92	15.33	16.00
		Cement board-Plywood	34.67	40.25	45.25	35.41	40.75	42.50
		Plywood-Plywood	62.58	65.83	66.58	63.58	66.25	66.33

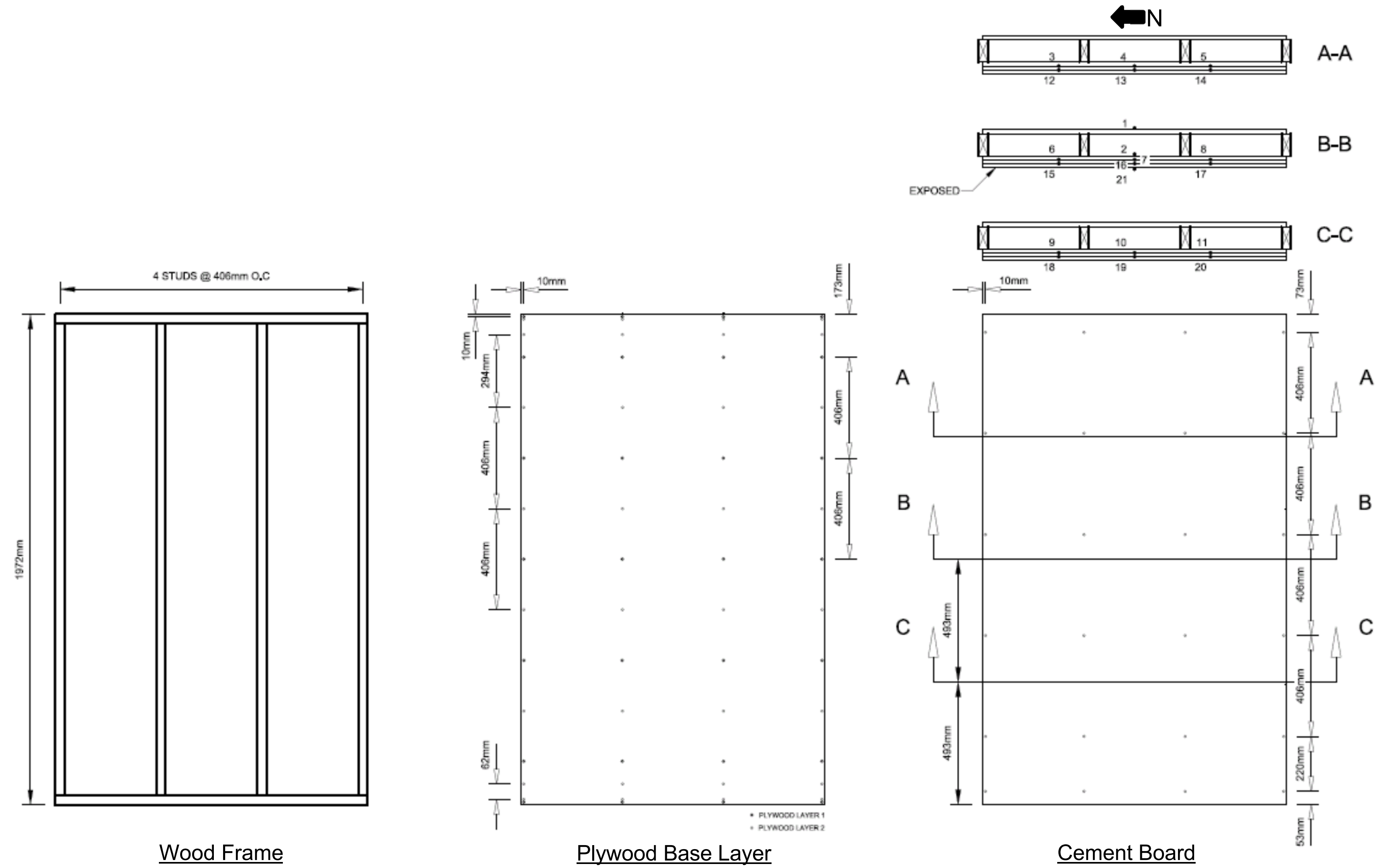
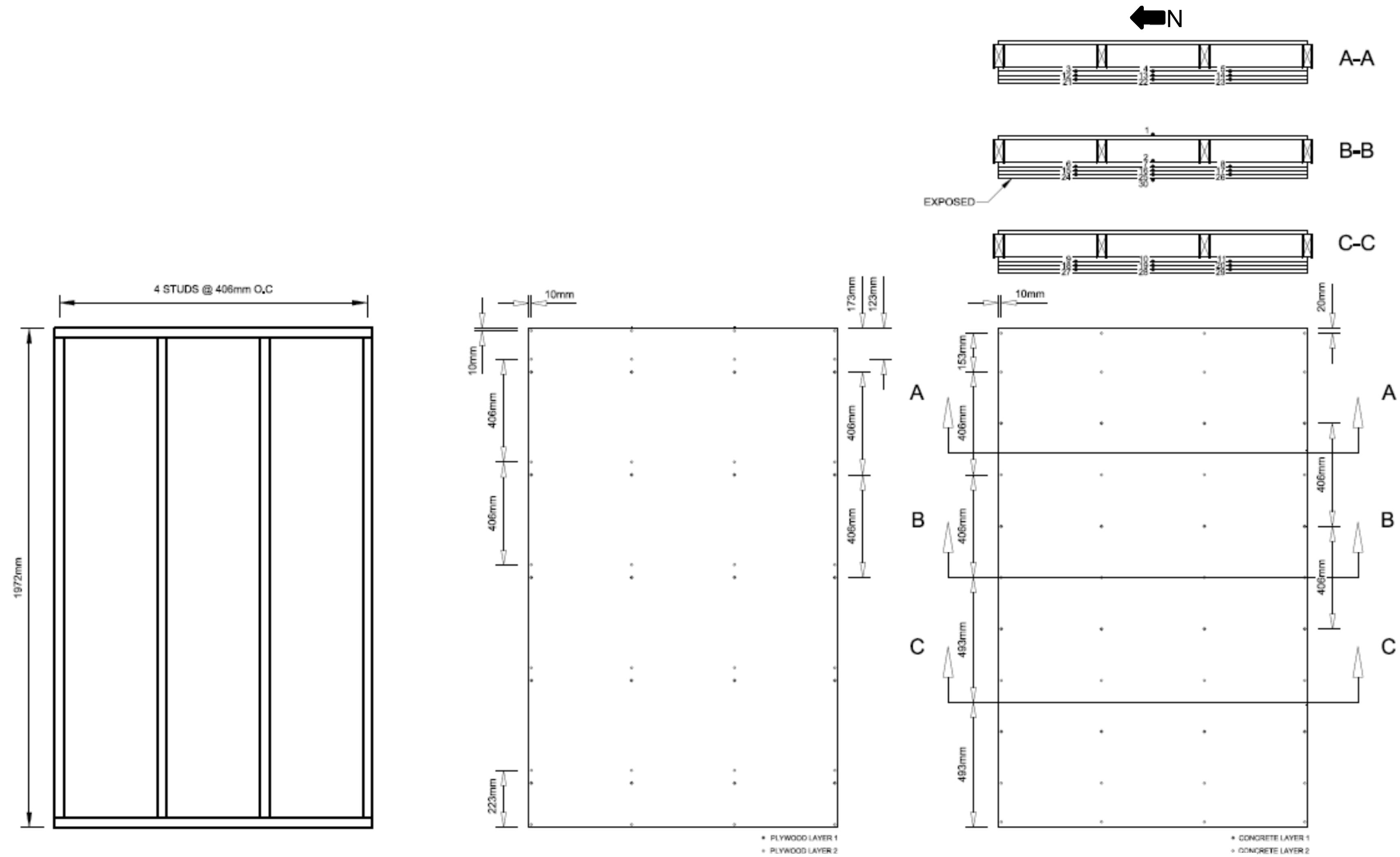


Figure 27. Drawings for the assembly used for Test IS-3 with one layer of 12.7 mm thick cement board.



Wood Frame

Plywood Base Layer

Cement Board

Figure 28. Drawings for the assembly used for Test IS-8 with two layers of 12.7 mm thick cement board.

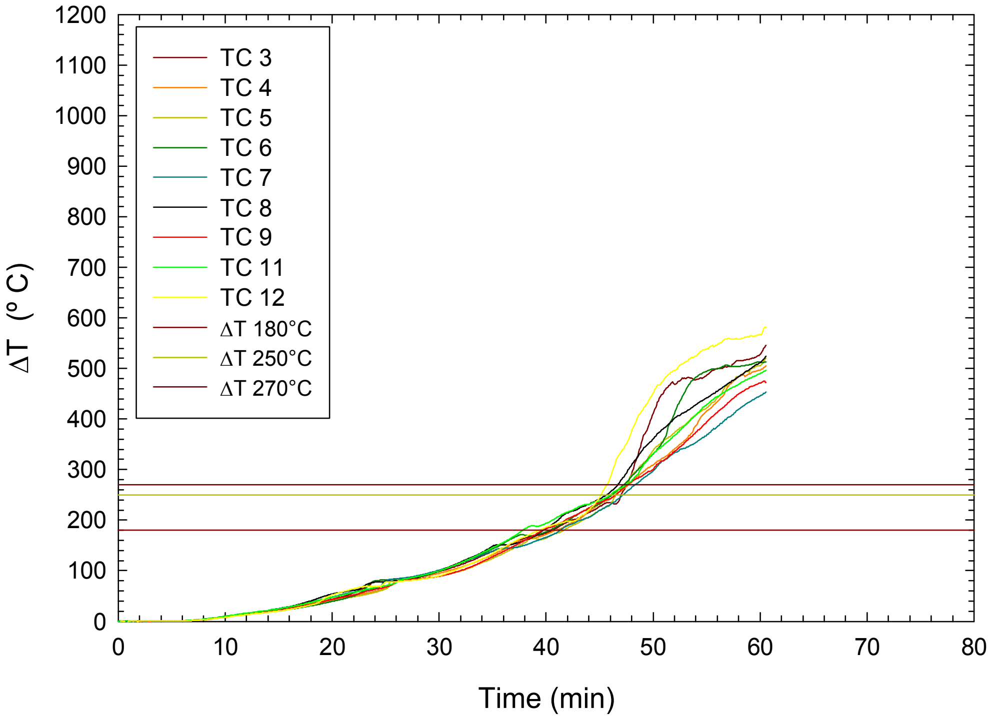


Figure 29. Temperature rise value profiles at Ply-Ply interface for Test IS-3 with 1 layer 12.7 mm cement board.

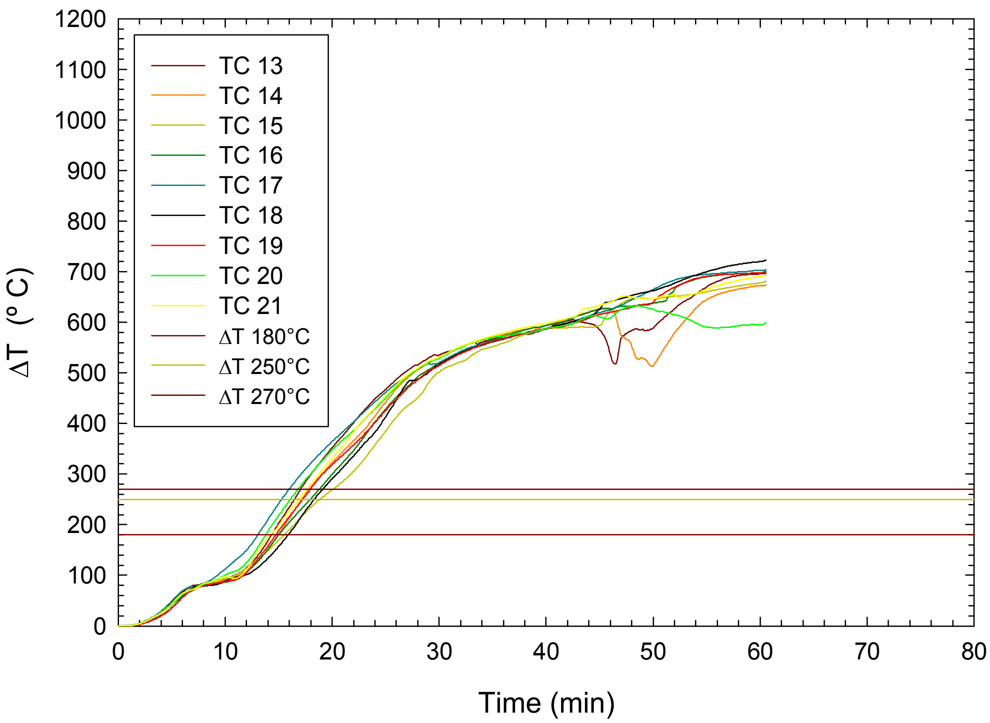


Figure 30. Temperature rise value profiles at CB-Ply interface for Test IS-3 with 1 layer 12.7 mm cement board.

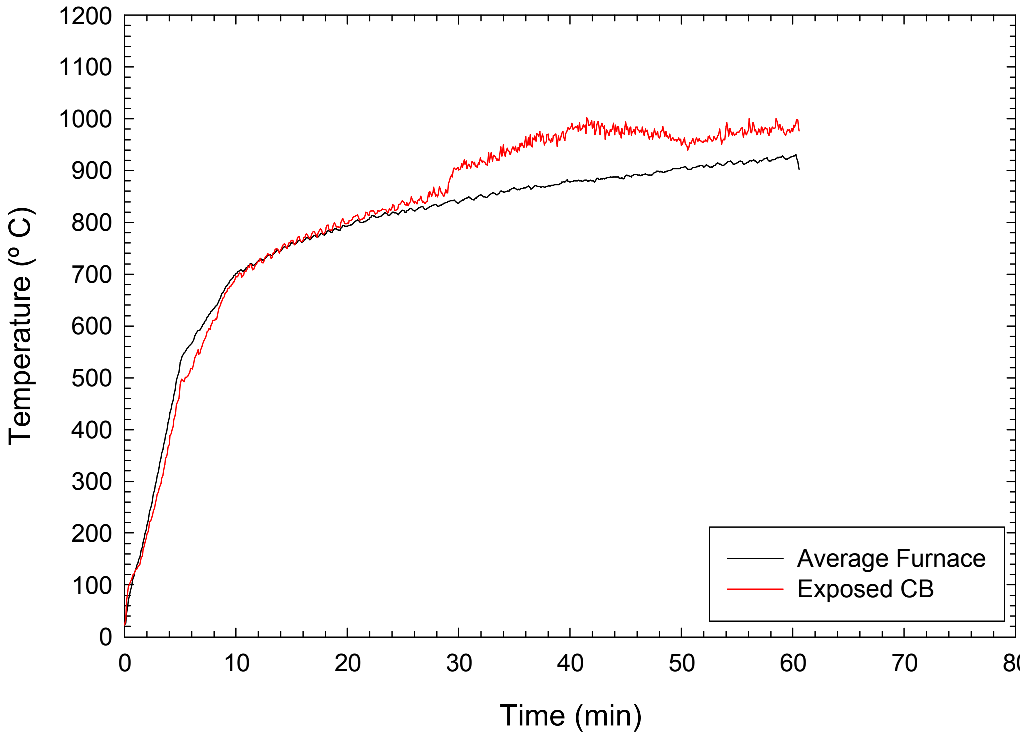


Figure 31. Temperature profiles for Test IS-3 with 1 layer 12.7 mm cement board.

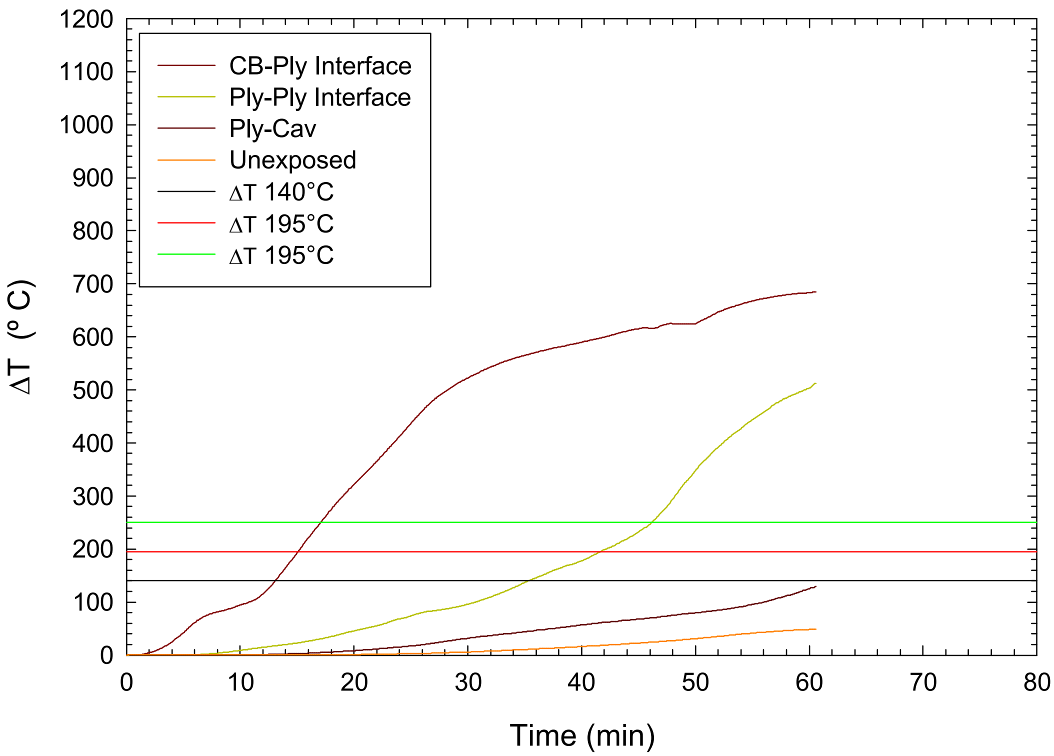


Figure 32. Temperature rise value profiles for Test IS-**3 with 1 layer 12.7 mm cement board.**

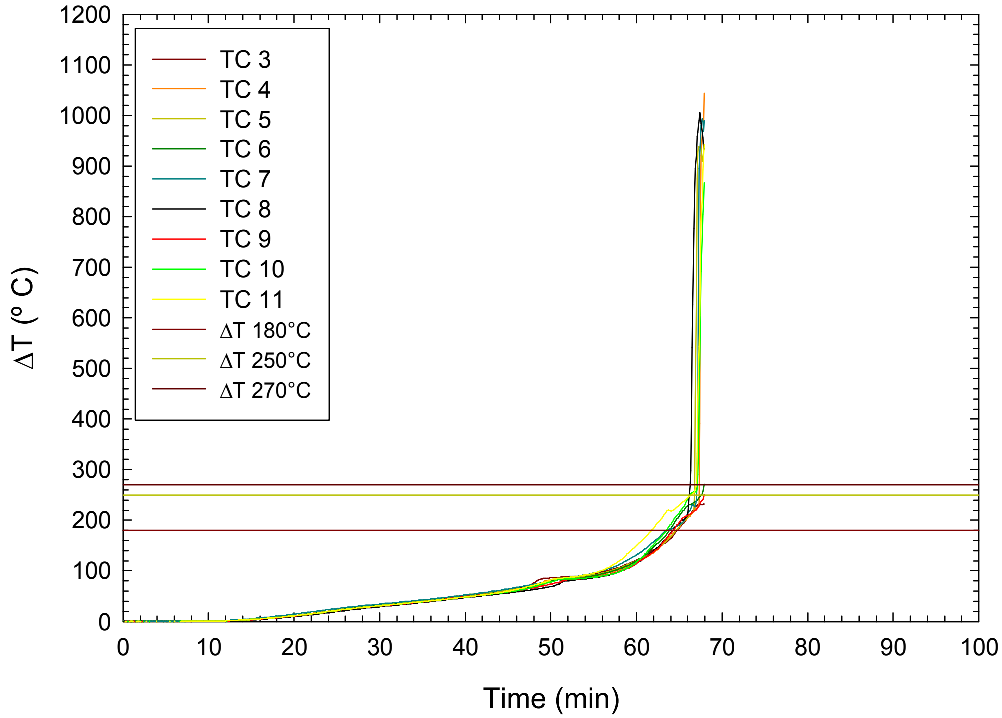


Figure 33. Temperature rise value profiles at Ply-Ply interface for Test IS-8 with 2 layers 12.7 mm cement board.

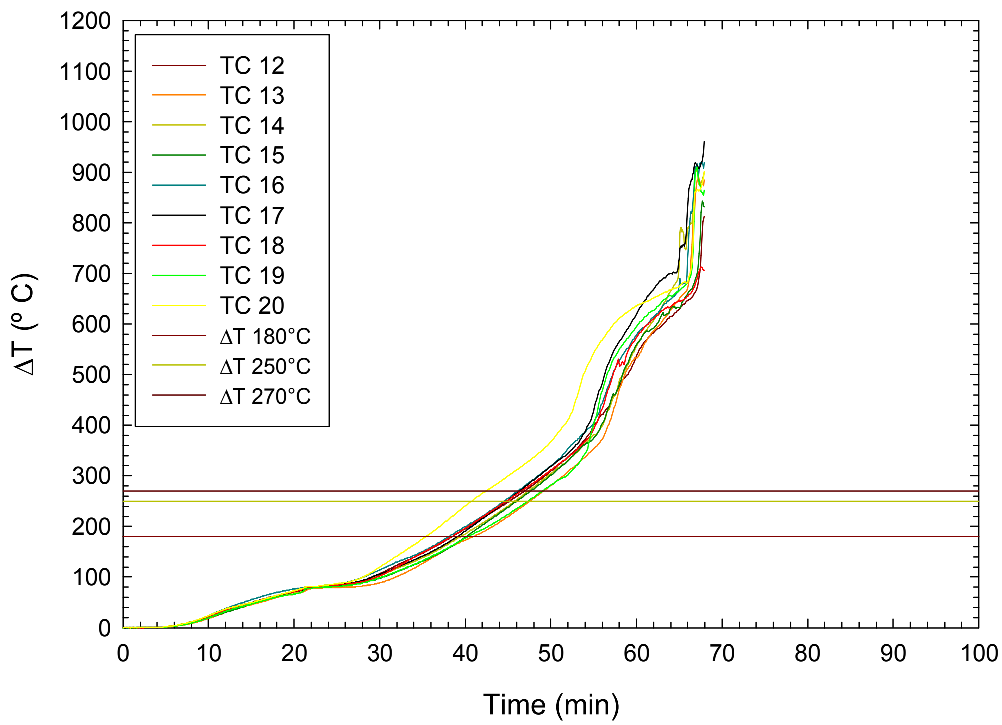


Figure 34. Temperature rise value profiles at CB-Ply interface for Test IS-8 with 2 layers 12.7 mm cement board.

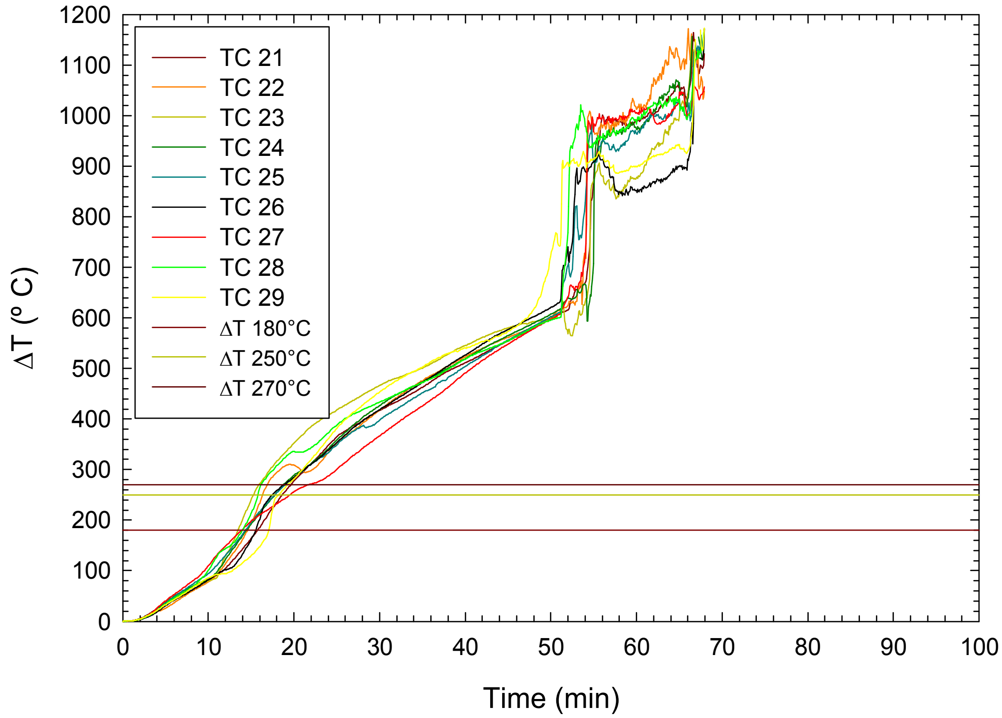


Figure 35. Temperature rise value profiles at CB-CB interface for Test IS-8 with 2 layers 12.7 mm cement board.

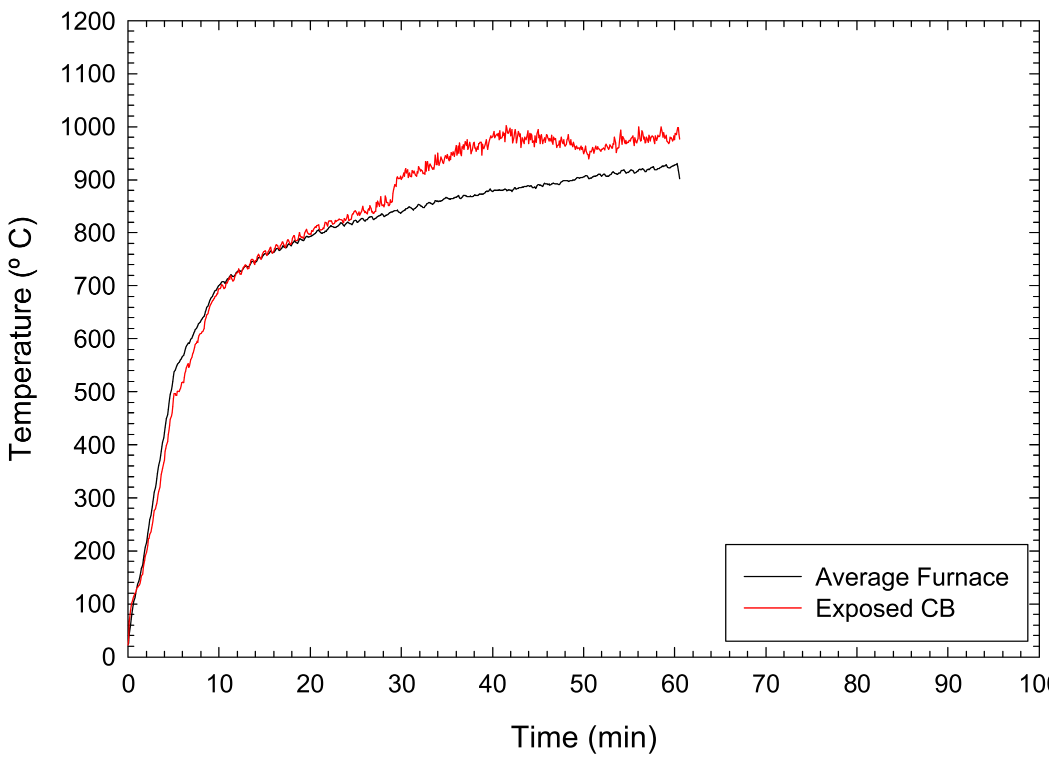


Figure 36. Temperature profiles for Test IS-8 with 2 layers 12.7 mm cement board.

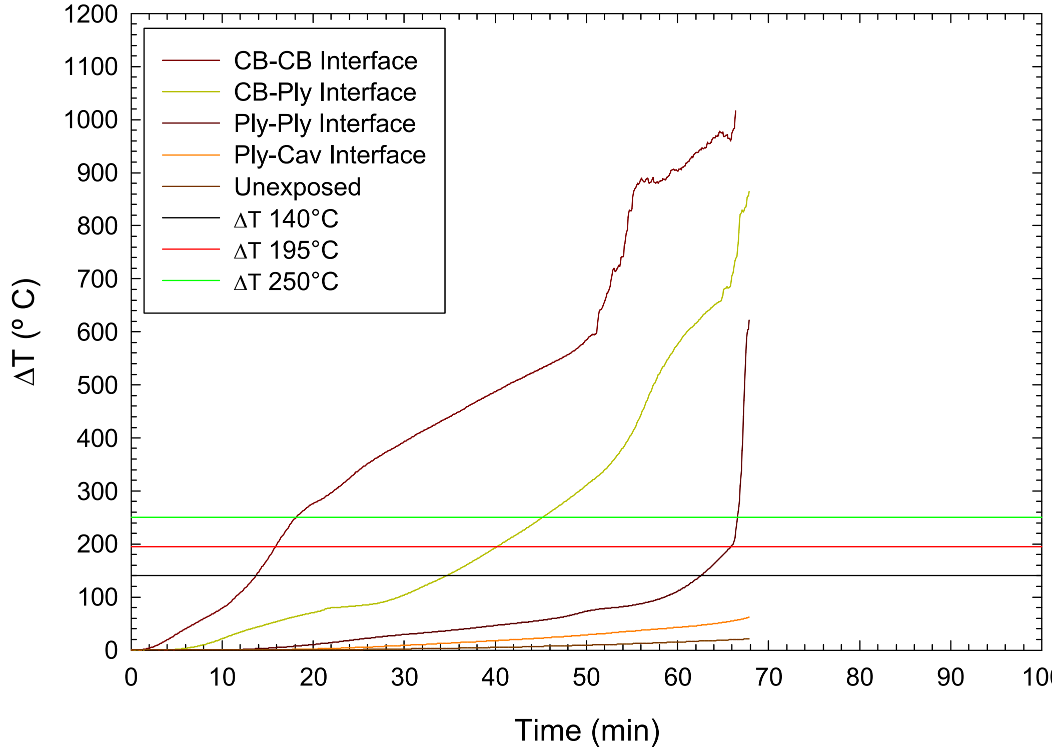


Figure 37. Temperature rise value profiles for Test IS-**8 with 2 layers 12.7 mm cement board.**

4.4 Results - 25 and 39 mm Thick Gypsum-concrete

Two tests were conducted using gypsum-concrete as the encapsulation material, using the standard time-temperature curve:

1. Test IS-6. A single layer of 39 mm thick gypsum-concrete with two layers of 15.9 mm thick plywood as the substrate.
2. Test IS-7. A single layer of 25 mm thick gypsum-concrete with two layers of 15.9 mm thick plywood as the substrate.

The drawings for the test assemblies are shown in Figure 38.

4.4.1 Results for Test IS-6

The results for Test IS-6 with a 39 mm thick layer of gypsum-concrete and two layers of 15.9 mm thick plywood as the substrate are shown in Figure 39, Figure 40 Figure 41 and Figure 42. The temperature rise profiles measured by the thermocouples at the interface between the two layers of plywood and at the interface between the gypsum-concrete and the plywood are shown in Figure 39 and Figure 40, respectively. The furnace temperature is shown in Figure 41. The average temperature at each interface and the temperature rise values at the plywood/cavity interface and on the unexposed surface of the gypsum board on the unexposed side of the assembly are shown in Figure 42.

At the interface between the gypsum-concrete and plywood substrate, there was an initial rapid increase of temperature rise values to approximately 85°C within approximately 17 min (Figure 40). Subsequently, there was a second phase during which the temperature rise values remained relatively steady, with the vaporization of the water in the gypsum-concrete. The average temperature rise value at the interface reached 100°C at approximately 40 min (Figure 41).

After 40 min, there was a third phase for the temperature rise values measured at the interface between the gypsum-concrete and plywood substrate, with a higher rate of increase of temperature rise values. The average temperature rise values reached approximately 460°C at approximately 93 min, at which time there was a rapid increase of temperature rise value measured by TC 16 located at the center of assembly, indicating a section of the gypsum-concrete fell off.

There was minimal variation in the temperature rise values measured by the nine thermocouples at the interface between the gypsum-concrete and plywood substrate in Phase 1. However, in both Phase 2 and 3, there was a variation in the measured temperature rise values, with particularly low temperature rise values measured by TC 18 located at the center of the northwest quadrant of the assembly. There were also large variations in temperature rise values measured by TC 19 and TC 20, with temperature rise values above 300ºC. Both of these thermocouples were located at the west end of the assembly. The time difference between thermocouples at that interface to reach a temperature rise value of 270°C was approximately 12 min

There was a steady increase of temperature rise values at the interface between the two layers of plywood beginning at approximately 12 min after the start of the test (Figure 39). There was minimal variation in the temperature rise values measured by the 9 thermocouples until approximately 85 min after the start of the test. After 85 min, there was increasing variation in the measured temperature rise values, with the fastest rate of increase of temperature rise values at TC 4, which was located on the assembly center line at its east end. The temperature at this location reached temperatures equivalent to the furnace temperature, indicating burn-through of the first layer of plywood at the east end of the assembly at approximately 100 min. TC 6 and TC 8 located at the mid-length of the assembly also indicated a rapid increase of temperature rise values. The slowest rate of increase of temperature rise values after 85 min were for TC 9 and TC 10 located at the west end of the assembly. The time difference between thermocouples at that interface to reach a temperature rise value of 270°C was approximately 6 min.

The average furnace temperature is shown in Figure 41. The temperature was not measured on the exposed surface of the gypsum-concrete, unlike what was done in the intermediate-scale tests for other encapsulation materials. There was concern that the structural stability of the gypsum-concrete could be affected if a thermocouple was attached to its surface.

The temperature rise values measured on the plywood in the cavity and on the unexposed surface of the gypsum board on the unexposed side of the assembly remained low throughout the test (Figure 42), with maximum temperature rise values of 234.1 (TC 2) and 52.7°C (TC 1), respectively, by the end of the test. The temperature rise values on the plywood indicated there was heat loss to the cavity with the extended test duration (106 min). However, the low temperature rise value on the unexposed surface of the gypsum board on the unexposed side of the assembly indicated there was minimal heat loss through the back portion of the test assembly.

4.4.2 Results for Test IS-7

The results for Test IS-7 with a 25 mm thick layer of gypsum-concrete and two layers of 15.9 mm thick plywood as the substrate are shown in Figure 43, Figure 44 Figure 45 and Figure 46. The temperature rise profiles measured by the thermocouples at the interface between the two layers of plywood and at the interface between the gypsum-concrete and the plywood are shown in Figure 43 and Figure 44, respectively. The furnace temperature is shown in Figure 45. The average temperature at each interface and the temperature rise values at the plywood/cavity interface and on the unexposed surface of the gypsum board on the unexposed side of the assembly are shown in Figure 46.

At the interface between the gypsum-concrete and plywood substrate, there was an initial rapid increase of temperature rise values to approximately 80°C within approximately 10 min (Figure 44). Subsequently, there was a second phase during which the temperature rise values remained relatively steady with the vaporization of the water in the gypsum-concrete. The average temperature rise value at the interface reached 100°C at approximately 25 min (Figure 46).

After 25 min, there was a third phase, with a higher rate of increase of temperature rise values. The average temperature rise value reached approximately 325°C at approximately 38 min, at which time there was a rapid increase of temperature rise values measured by the 9 thermocouples at the interface between the gypsum-concrete and plywood substrate, indicating the gypsum-concrete fell off.

There was minimal variation in the temperature rise values measured by the nine thermocouples at the interface between the gypsum-concrete and plywood substrate in Phase 1. However, in both Phase 2 and 3, there was a variation in the measured temperature rise values, with particularly low temperature rise values measured by TC 12 located at the center of the northeast quadrant of the assembly and TC 18 located at the mid-length of the assembly on the south side. A rapid increase of temperature rise values was measured by TC 14 beginning at approximately 20 min. The time difference between thermocouples at that interface to reach a temperature rise value of 270°C was approximately 9 min.

The temperature rise values started to increase at the interface between the two layers of plywood at approximately 8 min after the start of the test (Figure 43). However, unlike the other tests with encapsulation materials, there were variations in the temperature rise values measured by the 9 thermocouples. The 3 thermocouples (TC 9, TC 10 and TC 11) located at the west end of the test assembly indicated an initial rapid increase of temperature rise values at approximately 14 min. The temperature rise values measured by the other 6 thermocouples showed a slow increase similar to that observed in other tests. The reason for this rapid increase of temperature rise values at the west end of the assembly is not known.

After 14 min, the temperature rise values at the plywood/plywood interface remained relatively steady with an average temperature rise value of 30 – 40ºC until approximately 45 min (Figure 45). At this time, there was a rapid increase of the temperature rise values at all locations, indicating burn-through of the first layer of plywood.

The average furnace temperature is shown in Figure 45, along with the temperature rise values measured at various locations in the test assembly. The temperature was not measured on the exposed surface of the gypsum-concrete, unlike what was done in the intermediate-scale tests for other encapsulation materials. There was concern that the structural stability of the gypsum-concrete could be affected if a thermocouple was attached to its surface.

The temperature rise values measured on the plywood in the cavity and on the unexposed surface of the gypsum board on the unexposed side of the assembly remained low throughout the test (Figure 45), with maximum temperature rise values of 44.7 (TC 2) and 13.5ºC (TC 1), respectively, by the end of the test. This indicates there was limited heat loss through the back portion of the test assembly.

4.4.3 Discussion and Summary – 25 and 39 mm Thick Gypsum-concrete

Two tests were conducted using gypsum-concrete as the encapsulation material: 1 test with a 25 mm thick gypsum-concrete layer and 1 test with a 39 mm thick gypsum-concrete layer.

The temperature rise value profiles at the interface with the plywood substrate followed the same trend or phases as the tests with the other encapsulation materials:

1. Phase 1. Initial fast increase of temperature rise values to approximately 60°C. However, this phase was slower with the gypsum-concrete then with the other materials.
2. Phase 2. Relatively steady increase of temperature rise values with the vaporization of water in the gypsum-concrete.
3. Phase 3. Rapid increase of temperature rise values to high values.

There were variations in the temperature rise values measured by the 9 thermocouples located at the interface between the gypsum-concrete and the plywood substrate starting in Phase 2. The variations increased in Phase 3. These variations suggest that the gypsum-concrete was not as homogeneous as the gypsum board.

The gypsum-concrete layer fell off at 38 and 93 min in Tests IS-7 and IS-6, respectively. For the 25 mm thick layer, the fall-off time was equivalent to the fall-off times from the tests of the single layer of 12.7 mm thick Type X gypsum board. However, it was less than the fall-off time for the single layer of cement board. Overall the results indicate the gypsum-concrete was less stable in this hanging test configuration than the manufactured panels at high temperatures. However, it is typically only used to cover floors and, as such, the lack of stability in the hanging configuration is unlikely to have an effect on the protection provided to the structural elements in the floor covering configuration.

In both Tests IS-6 and IS-7, the initial temperature rise values at the plywood/plywood interface showed a steady increase. The rate of increase of temperature rise values was faster near the end of the tests. In both tests, the fire had charred through the face layer of plywood at the end of the test. The temperature rise value measurements indicated there was a variation in the times at which this occurred with the thicker gypsum-concrete layer (Test IS- 6). However, there was minimal variation with location at the plywood/plywood interface in Test IS-7 with the 25 mm thick gypsum-concrete.

The times at which the temperature rise values measured at the various interfaces exceeded the temperature rise criteria are shown in Table 5.

For Test IS-6, the average temperature rise criteria were exceeded first for Criteria 1 and 2 and the single-point criteria were exceeded first for Criteria 3, at the interface between the gypsum-concrete and the plywood. The differences in time between reaching the average and single-point criteria were 2.25, 2.25 and 0.57 min for Criteria 1, 2 and 3, respectively.

At the plywood/plywood interface, the average temperature rise criteria were exceeded first for Criteria 1. The average and the single-point criteria were at comparable times for Criteria 2 and Criteria 3. The differences in time between reaching the average and single-point criteria were 1.42, 0.0 and 0.01 min for Criteria 1, 2 and 3, respectively.

A section of the gypsum-concrete fell off at approximately 93 min in Test IS-6. However, most of the encapsulation material remained in place until the test was terminated at 106 min and the assembly was lifted off the furnace.

For Test IS-7, the single-point temperature rise criteria were exceeded first for the sets of criteria at the gypsum-concrete interface with the plywood. The differences in time between reaching the average and single-point criteria were 2.92, 3.58 and 6.09 min for Criteria 1, 2 and 3, respectively. The dominance of the single-point criteria in Test IS-7 is due to the very fast temperature increase at TC 14 relative to the other 8 thermocouples at that interface.

At the plywood/plywood interface, the average and the single-point temperature rise criteria were at comparable times for the three sets of criteria. The differences in time between reaching the average and single-point criteria were 0.16, 0.0 and 0.0 min for Criteria 1, 2 and 3, respectively. This is consistent with the fall-off of the gypsum-concrete at 38 min and the subsequent burn-through of the exposed layer of plywood in approximately 7 min.

Table 5. Times at which temperature rise values exceeded the average and single-point temperature rise criteria for tests with 25 and 39 mm thick gypsum-concrete.

Test	Number of Layers	Interface	Time ΔT Exceeded					
			Average ΔT (ºC)			Single-Point ΔT (ºC)		
			140 (min)	195 (min)	250 (min)	180 (min)	250 (min)	270 (min)
IS-6	1	Gypsum-concrete-Plywood	43.92	49.58	55.67	46.17	51.83	55.08
		Plywood-Plywood	95.50	98.33	98.92	96.92	98.33	98.33
IS-7	1	Gypsum-concrete-Plywood	27.75	31.25	34.92	24.83	27.67	28.83
		Plywood-Plywood	45.83	45.92	46.00	45.67	45.92	46.00

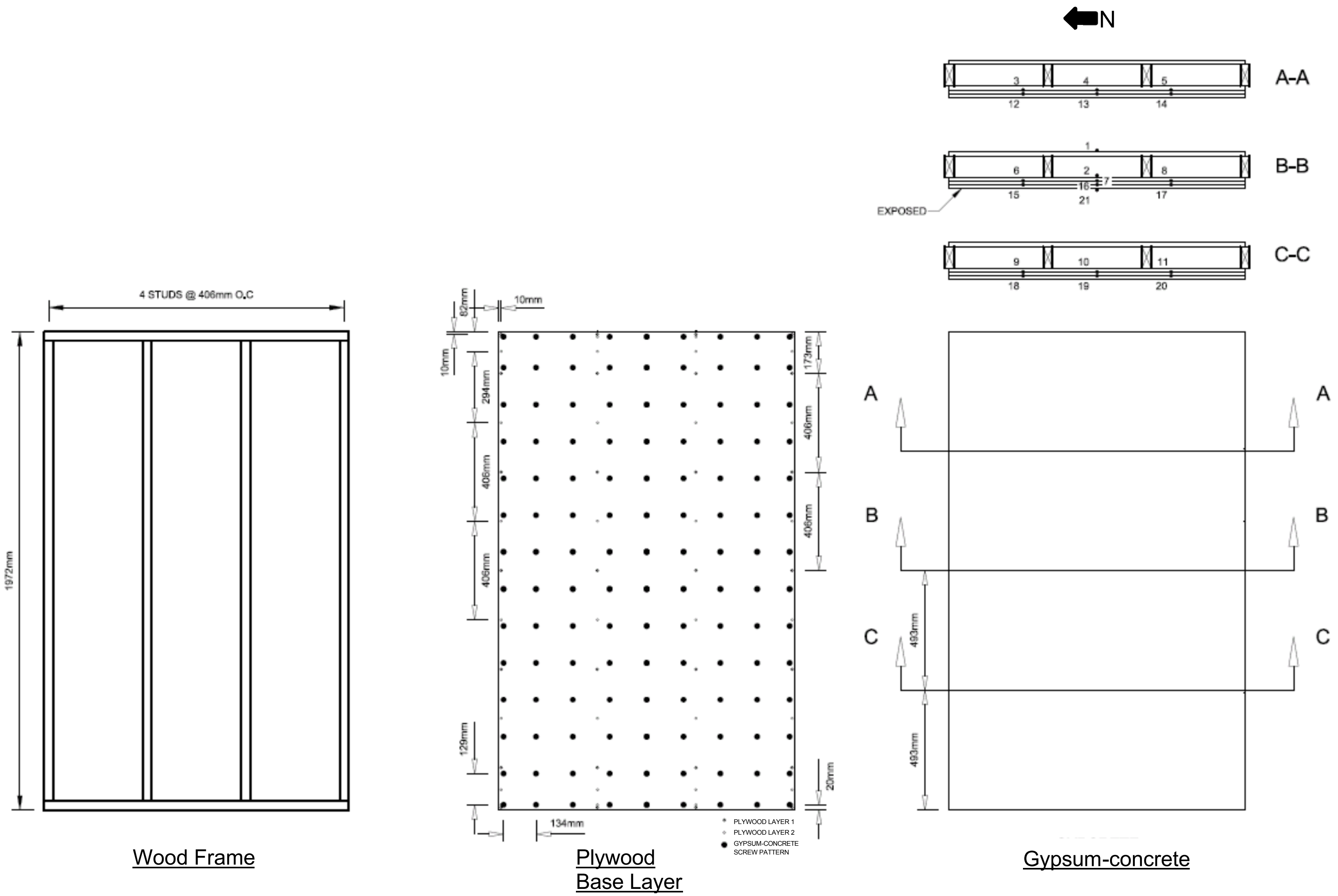


Figure 38. Drawings for the assemblies used for Tests IS-6 and IS-7 with gypsum-concrete.

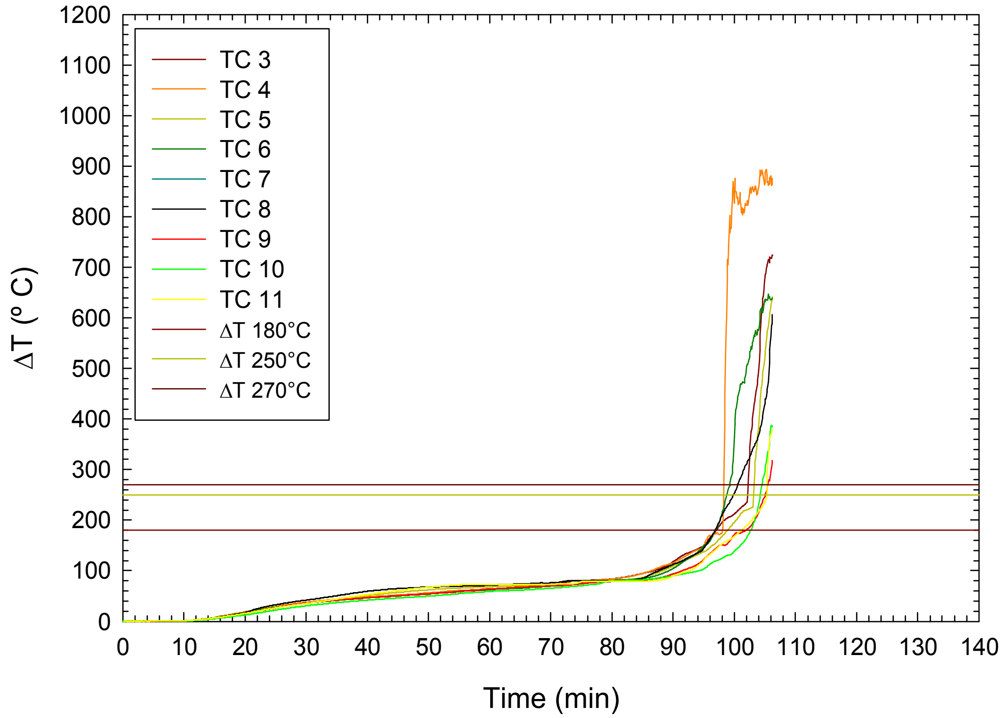


Figure 39. Temperature rise value profiles at Ply-Ply interface for Test IS-6 with 39 mm gypsum- concrete.

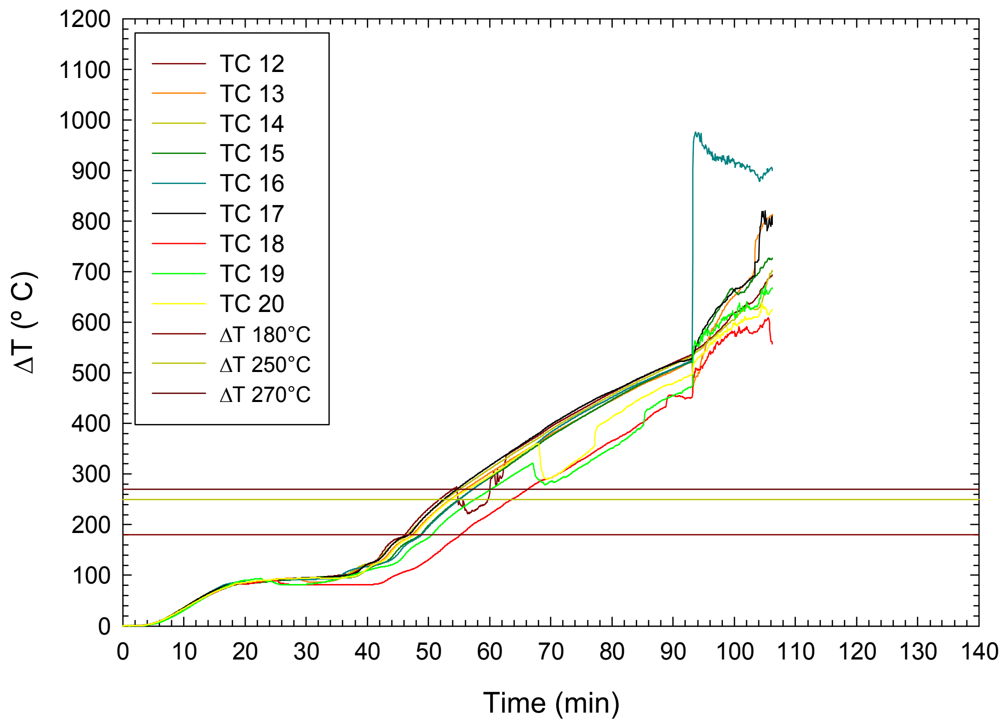


Figure 40. Temperature rise value profiles at GC-Ply interface for Test IS-6 with 39 mm gypsum- concrete.

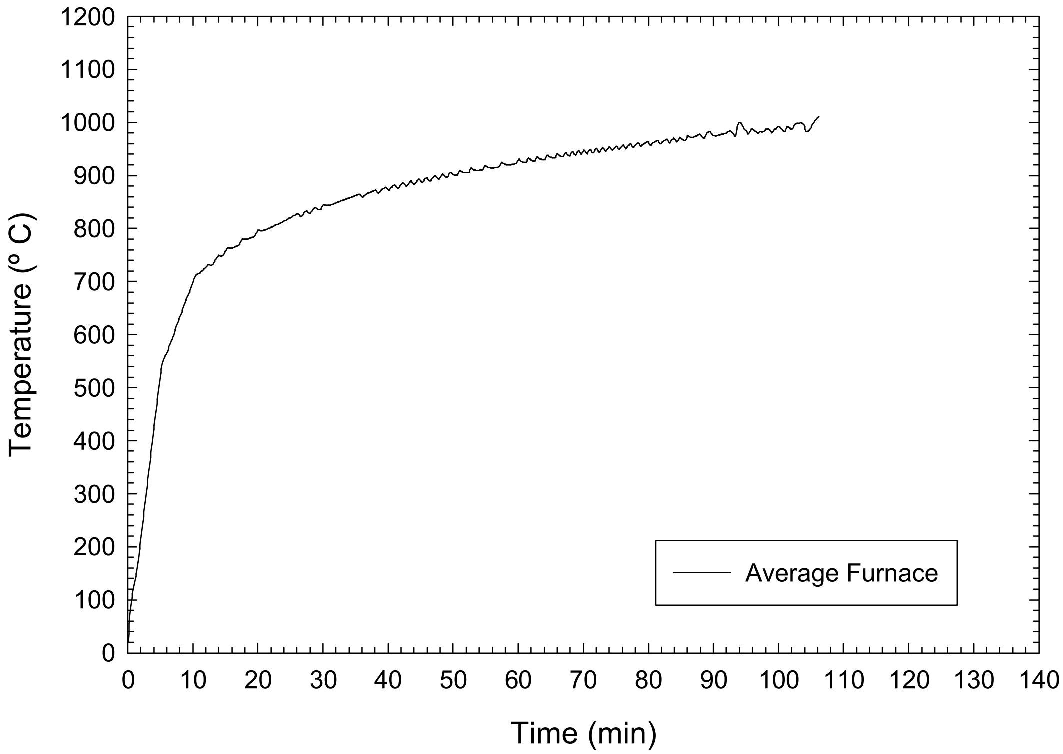


Figure 41. Temperature profiles for Test IS-6 with 39 mm gypsum- concrete.

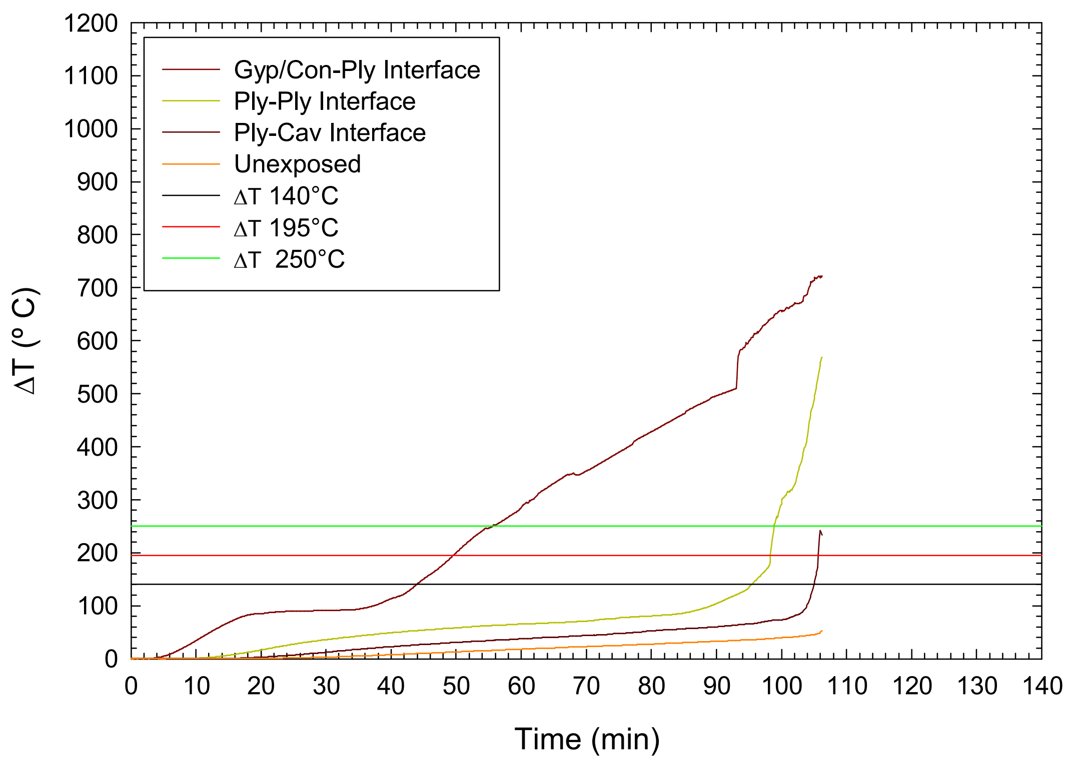


Figure 42. Temperature rise value profiles for Test IS-6 with 39 mm gypsum- concrete.

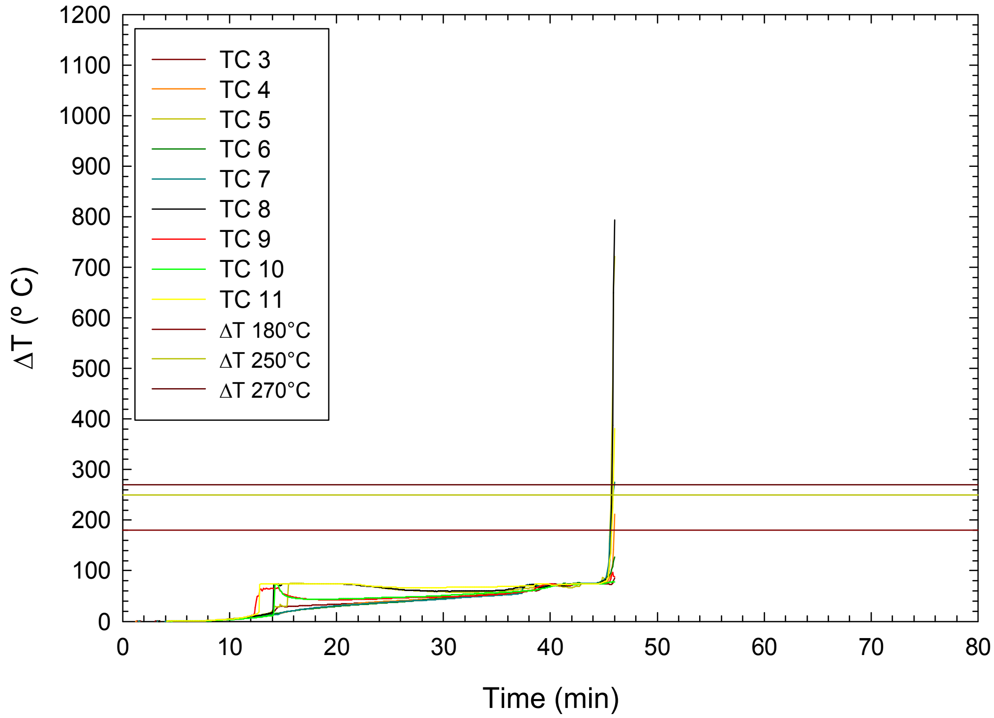


Figure 43. Temperature rise value profiles at Ply-Ply interface for Test IS-7 with 25 mm gypsum- concrete.

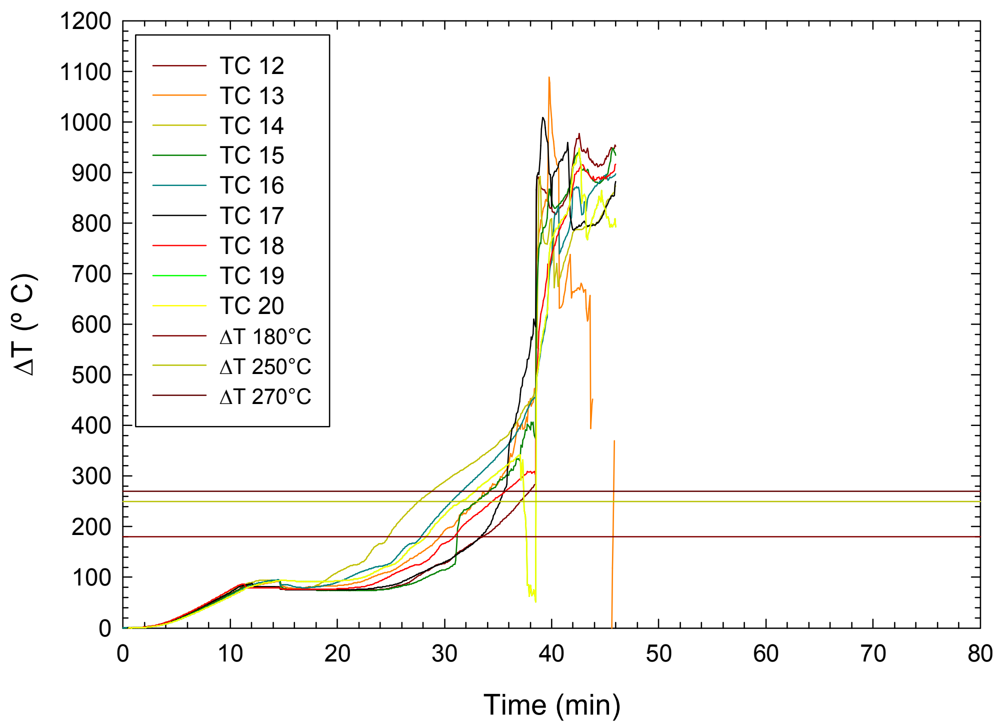


Figure 44. Temperature rise value profiles at GC-Ply interface for Test IS-7 with 25 mm gypsum- concrete.

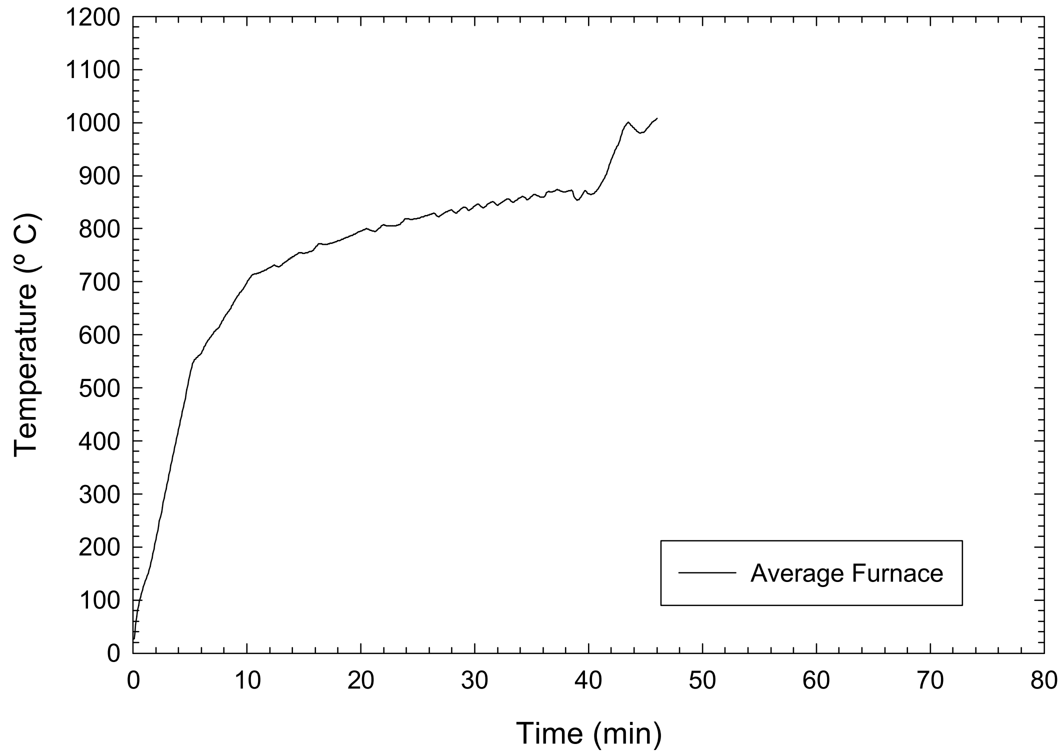


Figure 45. Temperature profiles for Test IS-7 with 25 mm gypsum- concrete.

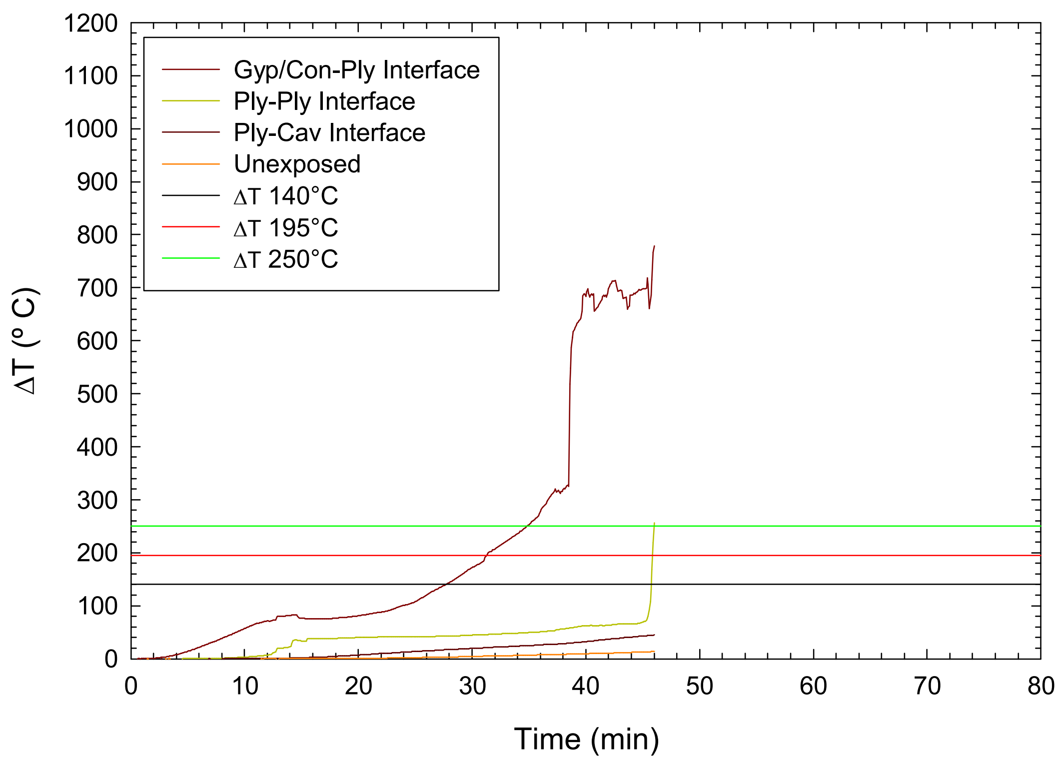


Figure 46. Temperature rise value profiles for Test IS-7 with 25 mm gypsum- concrete.

5 RESULTS OF INTERMEDIATE-SCALE FURNACE TESTS USING A NON-STANDARD TIME-TEMPERATURE CURVE

5.1 Non-standard Time-Temperature Exposure

As part of a project to characterize fires in multi-suite residential dwellings [6], five full-scale tests were conducted with a test arrangement and fuel load simulating a primary bedroom. Four tests (PRF-01, PRF-03, PRF-04 and PRF-08) had the same size ventilation opening. Test PRF-02 had a smaller opening. In Test PRF-08, the bedroom was connected to a living room, which included a second ventilation opening.

Thermocouple trees were located at the center of the four quadrants of each test room, with thermocouples 0.4, 1.4 and 2.4 m above the floor; the thermocouples at the 2.4 m height were located 50 mm below the ceiling. Figure 47 shows the average temperature for the four thermocouples at the 2.4 m (upper layer) height for each of the four tests with the same size ventilation opening in the primary bedroom.

Three tests (PRF-01, PRF-04 and PRF-08) had carpet covering the OSB subfloor while Test PRF-03 had hardwood flooring. The initial temperature profiles (< 15 min) for the three tests with carpeting were similar to each other and were higher than that measured in the initial stages for the single scenario with a hardwood floor. This difference in the initial temperature profile is likely due to the contribution of the carpeting and OSB to the fire.

The average temperature for Test PRF-08 was higher than the other two tests with carpeting between 15 min and the beginning of the decay phase at approximately 30 min. This may be due to additional combustible gases contributed from the living room contents.

After 900 s, the temperature profile for Test PRF-03 was higher than that for PRF-01 and PRF-04. The higher temperatures at that time were likely due to the extended contribution to the fire of the hardwood flooring and OSB subfloor combination.

The standard time-temperature curve [5] prescribed for standard fire-resistance tests is also shown in Figure 47. The average temperatures measured in the bedroom scenarios are higher than the standard time-temperature curve until 38 – 42 min. As such, tests using temperature profiles based on the room fire tests will impose a more severe exposure to a test assembly during the initial part of a test.

Since the apartment-scale tests for the mid-rise project had the floors covered with hardwood, the average temperature profile measured in Test PRF-03 was used as the basis for the non-standard fire tests conducted with the intermediate furnace.

Bare-bead thermocouples were used for the thermocouple trees in the project to characterize fires in multi-suite residential dwellings. These thermocouples have a faster response than the shielded thermocouples used in standard fire-resistance tests [5]. However, the upper layer temperature in the simulated bedroom was also measured using a shielded thermocouple similar to that used in fire-resistance tests. The average temperature profile and the temperature measured using the shielded thermocouple is shown in Figure 48. (After approximately 4.2 min, the temperatures measured using the shielded thermocouples were typically comparable to but slightly higher (approximately, 50°C) than the average temperature based on the bare-bead thermocouples. However, the temperatures measured using the shielded thermocouple were more erratic in subsequent stages of Test PRF-03 and are not shown in Figure 48 as a result.

However, the initial temperature profile was consistent with those measured in the other bedroom tests.)

It may be difficult for a standard furnace using shielded thermocouples to follow the initial temperature profile based on the average upper layer temperature measured using the bare-bead thermocouples. Also, attempts to have the furnace follow the average upper layer temperature profile using its slow-response shielded thermocouples would result in an over exposure to the test assembly during the initial stages of a test. Therefore, the temperature measured using the shielded thermocouple in the bedroom scenario was used for the initial time-temperature profile up to 4.2 min. After 4.2 min, the average upper layer temperature (as measured by the bare-bead thermocouples) was used. This combination formed the basis for the non-standard fire curve that was used for the two non-standard encapsulation material assembly tests.

Two preliminary calibration tests were conducted using the intermediate-scale furnace to develop the control points for the furnace for the non-standard fire curve. The average furnace temperature in the second test is shown in Figure 49, along with the combined non-standard fire temperature profile. Also shown in Figure 49 is the relative error for the test. The average furnace temperature is typically within 1% of the non-standard fire curve. The largest relative errors (up to approximately 3%) were in the initial stages of the temperature profile (5-15 min) and during the initial decay phase (30-35 min) and were the result of fluctuations in the non-standard fire profile from the data produced in the project to characterize fires in multi-suite residential dwellings.

The temperature in the intermediate-scale furnace is measured using sheathed thermocouples with a faster response than those used in large standard furnaces. As a result, it was necessary to run the furnace with only the pilot flame until 4.2 min in order to follow the initial temperature profile based on the standard sheathed thermocouple. After 4.2 min, additional heat was required and the main burners were ignited.

Two encapsulation material assembly tests were conducted using the non-standard fire time-temperature curve. The test assemblies duplicated setups used for tests with the standard time-temperature curve:

1. Test IS-10. This test was with a single layer of 15.9 mm thick Type X gypsum board and duplicated the setup used in Test 4. .
2. Test IS-11. This test was with a double layer of 12.7 mm thick Type X gypsum board and duplicated the setup used in Test 5. .

The drawings for the test assembly in Test 10 are shown in Figure 16. The drawings for the test assembly in Test 11 are shown in Figure 3.

5.2 Results_- Test IS-10 with a Single Layer 15.9 mm Thick Type X Gypsum Board

The results for Test IS-10 with a single layer of 15.9 mm thick Type X gypsum board and two layers of 15.9 mm thick plywood as the substrate, using the non-standard time-temperature curve, are shown in Figure 50, Figure 51, Figure 52 and Figure 53. The temperature rise profiles measured by the thermocouples at the interface between the two layers of plywood and at the interface between the gypsum board and the plywood are shown in Figure 50 and Figure 51, respectively. The furnace temperature and the temperature measured at the exposed gypsum board surface are shown in Figure 52. The average temperature at each interface and the temperature rise values at the plywood/cavity interface and on the unexposed surface of the gypsum board on the unexposed side of the assembly are shown in Figure 53.

At the interface between the gypsum board and plywood substrate, there was an initial rapid increase of temperature rise values to approximately 60°C within between 4 and 6 min (Figure 51). Subsequently, there was a second phase, with minimum increase of temperature rise values during calcination and vaporization of the water in the gypsum board. The average temperature rise value at the interface reached 100°C at approximately 16 min (Figure 52).

After 16 min, there was a third phase, with a higher rate of increase of temperature rise values. This was approximately 3 min earlier than Phase 3 was reached in Test IS-4 with the standard time-temperature exposure. The temperature rise values reached approximately 600°C at approximately 28.5 min, at which time the gypsum board fell off, resulting in direct exposure of the plywood substrate to the furnace environment. Similar temperature rise values and gypsum fall-off occurred at 59 min in Test IS-4.

There was minimal variation in the temperature rise values measured by the nine thermocouples located at the interface between the gypsum board and the plywood substrate until the temperature rise values reached approximately 400°C at approximately 24 min (Figure 51). After 24 min, there was a variation in the measured temperature rise values until the gypsum board fell off at 28.5 min.

Overall, the non-standard fire temperature profile resulted in faster rates of increase of temperature rise values at the interface between the gypsum board and the plywood substrate. This was particularly notable in Phase 3, with a more-rapid increase of temperature rise values and the fall-off of the gypsum board approximately 50% earlier than in Test IS-4.

There was a steady increase of temperature rise values at the interface between the two layers of plywood beginning at approximately 11 min after the start of the test (Figure 50). The maximum temperature rise value was approximately 75°C at the time the test was terminated shortly after the gypsum board fell off. The direct exposure of the plywood resulted in extensive flames issuing from the exhaust and the test was stopped to minimize damage to the facility. As such, there was a minimal period of time with the plywood directly exposed to the furnace.

There was minimal variation in the temperature rise values measured by the 9 thermocouples at the interface between the two layers of plywood.

The average furnace temperature and the temperature measured on the exposed surface of the gypsum board on the exposed side of the assembly (TC 21) are shown in Figure 52, The temperature measured on the exposed surface of the exposed gypsum board lagged the furnace temperature until approximately 24 min. At 24 min, the average temperature at the gypsum board and plywood interface was 415.2°C. As such, the higher temperature measured on the gypsum board relative to the average furnace temperature would suggest burning of pyrolysis gases from the plywood in the furnace.

The temperature rise values measured on the plywood in the cavity and on the unexposed surface of the gypsum board on the unexposed side of the assembly remained low throughout the test (Figure 53), with maximum temperatures of 44.1 (TC 2) and 27.5°C (TC 1), respectively, by the end of the test.

The times at which the temperature rise values measured at the interface between the gypsum board and plywood exceeded the temperature rise criteria are shown in Table 6

At the gypsum board interface with the plywood, the average temperature rise criteria were exceeded first for the three sets of criteria. The differences in time between reaching the average and single-point criteria were 0.32, 1.00 and 0.09 min for Criteria 1, 2 and 3, respectively.

The non-standard fire exposure resulted in faster rates of increase of temperature rise values at the interface between gypsum board and the plywood substrate. As a result, the three sets of temperature rise criteria were exceeded earlier than in the test using the standard time-temperature curve. The differences in time (based on the temperature criteria in a set that occurred earlier) were 4.0 min, 4.67 min and 5.17 min for Criteria 1, Criteria 2 and Criteria 3, respectively.

As noted previously, the test was stopped shortly after the gypsum board fell off to minimize damage to the facility. There was insufficient time for any of the temperature rise criteria to be exceeded at the plywood/plywood interface.

5.3 Results - Test IS-11 with a Double Layer 12.7 mm Thick Type X Gypsum Board

The results for Test IS-11 with two layers of 12.7 mm Type X gypsum board and two layers of 15.9 mm thick plywood as the substrate, using the non-standard time-temperature curve, are shown in Figure 54, Figure 55, Figure 56, Figure 57, Figure 57 and Figure 58. The temperature rise profiles measured by the thermocouples at the interface between the two layers of plywood, at the interface between the gypsum board and the plywood and at the interface between the two layers of gypsum board are shown in Figure 54, Figure 55 and Figure 56, respectively. The furnace temperature and the temperature measured at the exposed gypsum board surface are shown in Figure 57. The average temperature at each interface and the temperature rise values at the plywood/cavity interface and on the unexposed surface of the gypsum board on the unexposed side of the assembly are shown in Figure 58.

At the gypsum board/gypsum board interface (Figure 56), the temperature rise values followed the same general trend as those measured in Test IS-5. There was an initial rapid increase of temperature rise values to approximately 50°C at 6 min. Subsequently, there was a second phase, with a slower rate of increase of temperature rise values with calcination and vaporization of the water in the gypsum board. The average temperature rise value at the interface reached 100°C at approximately 13.5 min (Figure 58).

After 13.5 min, there was a third phase, with a higher rate of increase of temperature rise values. The temperature rise values at the gypsum board/gypsum board interface reached approximately 590°C at approximately 27 min, at which time the gypsum board fell off, resulting in direct exposure of the base layer of gypsum board to the furnace environment.

There was minimal variation in the temperature rise values measured by the nine thermocouples at the gypsum board/gypsum board interface until Phase 3. However, after approximately 14 min, there was an increasing variation in the measured temperature rise values. The fastest rate of increase of temperature rise values during Phase 3 was measured by TC 21 located at the east end of the test assembly.

At the interface between the gypsum board and plywood substrate (Figure 55), there was a gradual increase of temperature rise values beginning at approximately 6 min. Subsequently, there was a steady increase of temperature rise values until approximately 16 min, followed by a period with minimal temperature increase until approximately 30 min. The average temperature rise value at the interface reached 100°C at approximately 32 min (Figure 58). After 32 min, there was a faster rate of increase of temperature rise values, with the temperature rise values reaching 450°C at approximately 42 min.

As the temperatures in the furnace decreased, simulating the decay phase in the non-standard fire, there was also a reduction in the rate of increase of temperature rise values at the gypsum board/plywood interface. The maximum temperature rise value was approximately 600°C at 62 min. The temperature rise values were slowly decreasing at the gypsum board/plywood interface until the gypsum board fell off at 67 min.

There was minimal variation in the temperature rise values measured by the nine thermocouples at the gypsum board/plywood interface until after 32 min. Subsequently, there was an increasing variation in the measured temperature rise values. The fastest rate of increase of temperature rise values after 32 min was measured by TC 12 located at the east end of the test assembly.

There was a steady increase of temperature rise values at the interface between the two layers of plywood beginning at approximately 13 min after the start of the test (Figure 54). There was minimal variation in the temperature rise values measured by the 9 thermocouples at that interface until 39 min. Between 39 and 58 min, there were small variations in the temperature rise values. At 58 min, TC 11 measured a rapid increase of temperature rise values, indicating the first layer of plywood was charred through in this area. After 58 min, there was increasing differences in the temperature rise values measured by the 9 thermocouples until 67 min. By 66.5 min, the temperature rise values at all thermocouple locations at that interface were approaching or exceeding 270°C, indicating the face layer of plywood was completely charred at most locations. When the base layer of gypsum fell off at 67 min, the rapid increase of temperature rise values at the plywood/plywood interface suggests that the face layer of plywood (in significantly-charred form) also fell off.

The average furnace temperature and the temperature measured on the exposed surface of the gypsum board on the exposed side of the assembly are shown in Figure 57. The temperature measured on the exposed surface of the exposed gypsum board initially lagged the furnace temperature until approximately 18 min.

The increase in temperature rise values was minimal on the plywood in the cavity (TC 2: 62°C) and on the unexposed surface of the gypsum board on the unexposed side of the assembly (TC 1: 21°C) by the end of the test. This indicates there was limited heat loss through the back portion of the test assembly.

The times at which the temperature rise values measured at the plywood/plywood interface, at the interface between the gypsum board and plywood, and at the interface between the two layers of gypsum board exceeded the temperature rise criteria are shown in Table 7.

At the interface between the gypsum board and plywood, the average temperature rise criteria were exceeded first for Criteria 1 and 2 and the single-point criteria were exceeded first for Criteria 3. The differences in time between reaching the average and single-point criteria were

0.16, 0.25 and 1.25 min for Criteria 1, 2 and 3, respectively. The increasing difference between the average and single-point times is consistent with the temperature rise value profiles shown Figure 55, which show a faster rate of increase of the temperature rise values measured by TC 12 than at the other 8 locations at that interface.

The non-standard fire exposure resulted in faster rates of increase of temperature rise values at the interface between gypsum board and the plywood substrate. As a result, the three sets of temperature rise criteria were exceeded earlier than in Test IS-5 using the standard time-temperature curve. The differences in time were 17.25 min, 20.75 min and 23.58 min for Criteria 1, Criteria 2 and Criteria 3, respectively.

A part of the time difference is likely due to the large difference in fall-off time for the face layer of gypsum board in the two tests. In Test IS-5, the gypsum board face layer fell off at 68 min and in Test IS-11, it fell off at 27 min.

At the interface between the two gypsum board layers, the average temperature rise criteria were exceeded first for Criteria 1 and the single-point criteria were exceeded first for Criteria 2 and 3. The differences in time between reaching the average and single-point criteria were 0.16, 0.09 and 1.25 min for Criteria 1, 2 and 3, respectively. The increasing difference between the average and single-point times is consistent with the temperature increase profiles shown Figure 56, which show a faster rate of increase of the temperature rise values measured by TC 21 than at the other 8 locations at that interface.

The non-standard fire exposure resulted in faster rates of increase of temperature rise values at the interface between the two layers of gypsum board than in Test IS- 5. As a result, the three sets of temperature criteria were exceeded earlier than in that test using the standard time-temperature curve. The differences in time were 3.3 min, 4.5 min and 5.6 min for Criteria 1, Criteria 2 and Criteria 3, respectively.

At the plywood/plywood interface, the average temperature rise criteria were exceeded first for Criteria 1 and the single-point criteria were exceeded first for Criteria 2 and 3. The differences in time between reaching the average and single-point criteria were 1.50, 0.17 and 3.25 min for Criteria 1, 2 and 3, respectively. The increasing difference between the average and single-point times is consistent with the temperature increase profiles shown in Figure 56, which show a faster rate of increase of the temperature rise values measured by TC 11 than at the other 8 locations at that interface.

Table 6. Times at which temperature rise values exceeded the average and single-point temperature rise criteria for tests with a single layer of 15.9 mm thick Type X gypsum board.

Test	Number of Layers	Interface	Time ΔT Exceeded					
			Average ΔT (ºC)			Single-Point ΔT (ºC)		
			140 (min)	195 (min)	250 (min)	180 (min)	250 (min)	270 (min)
IS-4	1	Gypsum board-Plywood	21.25	23.42	25.75	22.08	24.75	25.50
		Plywood-Plywood	45.33	52.17	54.92	47.75	52.67	53.75
IS-10	1	Gypsum board-Plywood	17.25	18.75	20.33	17.58	19.75	20.42
		Plywood-Plywood	NA	NA	NA	NA	NA	NA

Table 7. Times at which temperature rise values exceeded the average and single-point temperature rise criteria for tests with two layers of 12.7 mm thick Type X gypsum board.

Test	Number of Layers	Interface	Time ΔT Exceeded					
			Average ΔT (ºC)			Single-Point ΔT (ºC)		
			140 (min)	195 (min)	250 (min)	180 (min)	250 (min)	270 (min)
IS-5	2	Gypsum board-Gypsum board	18.67	20.67	24.00	19.50	21.83	21.92
		Gypsum board-Plywood	50.67	55.33	61.50	51.00	57.08	58.75
		Plywood-Plywood	80.0*	NA	NA	NA	NA	NA
IS-11	2	Gypsum board-Gypsum board	15.33	16.17	17.58	15.17	16.08	16.33
		Gypsum board-Plywood	33.42	34.58	35.67	33.58	34.83	35.17
		Plywood-Plywood	54.17	58.17	61.33	55.67	58.00	58.08

*Test terminated at 80 min with temperature increase at 136ºC. It was estimated that only 3-5 mm of the first layer of plywood was not charred (see Subsection Results for Test IS-5).

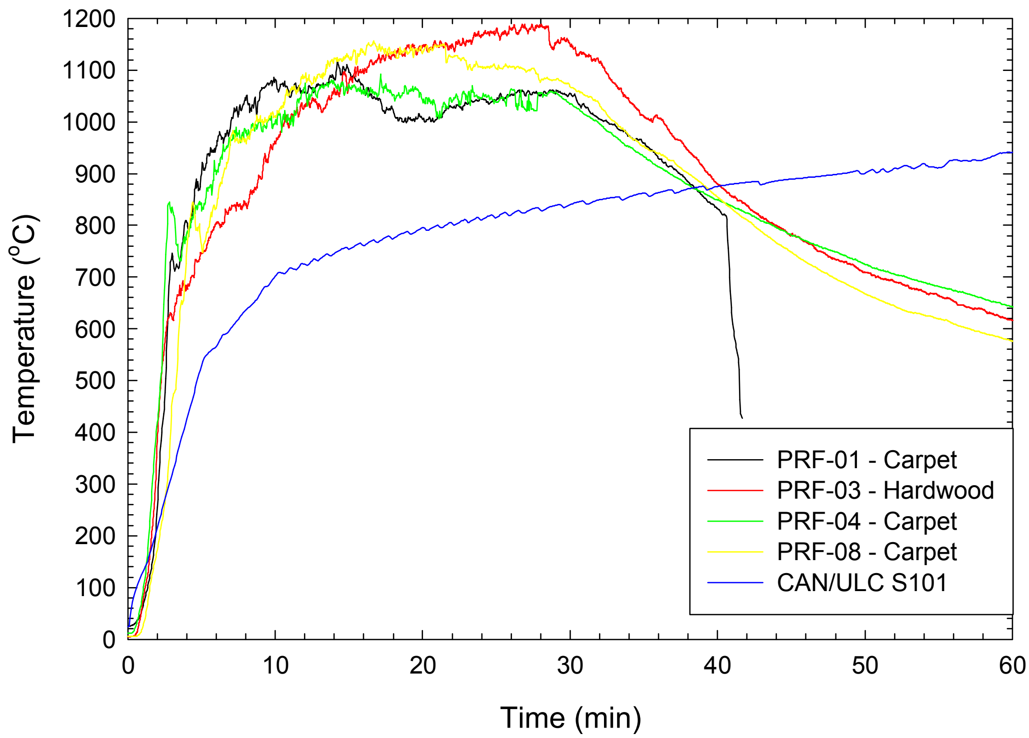


Figure 47. Average upper layer temperature profiles (bare-bead thermocouples) for primary bedroom tests.

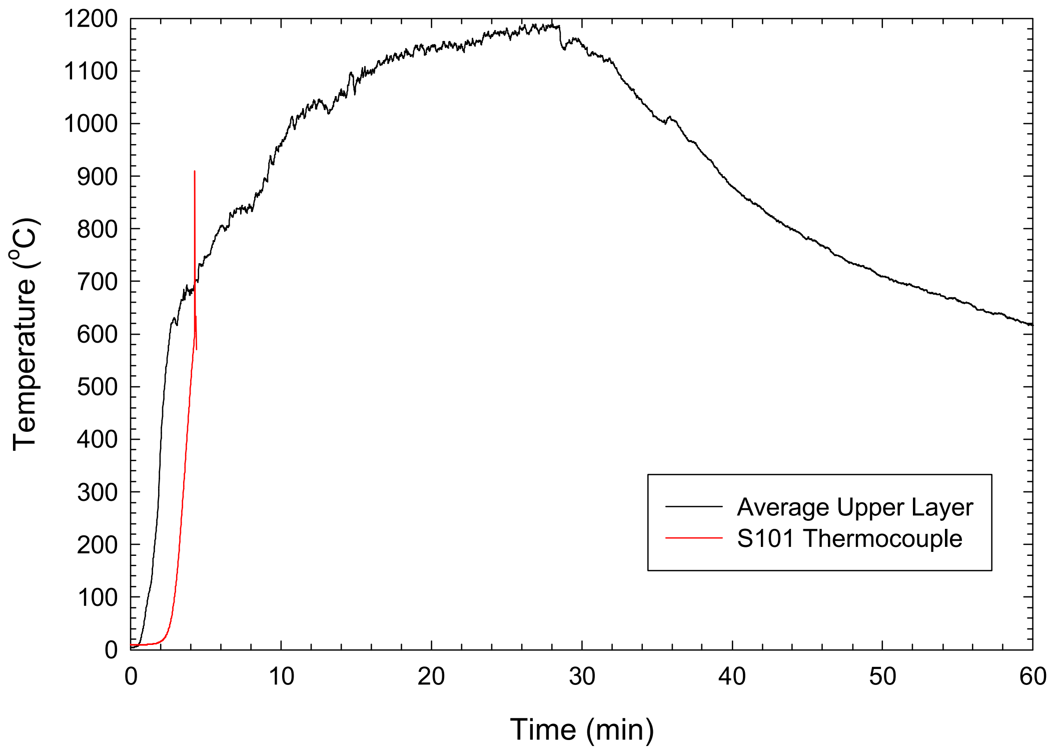


Figure 48. Temperatures measured in Test PRF-03 (Average Upper Layer: bare-bead thermocouples; S101 Thermocouple: shielded thermocouple).

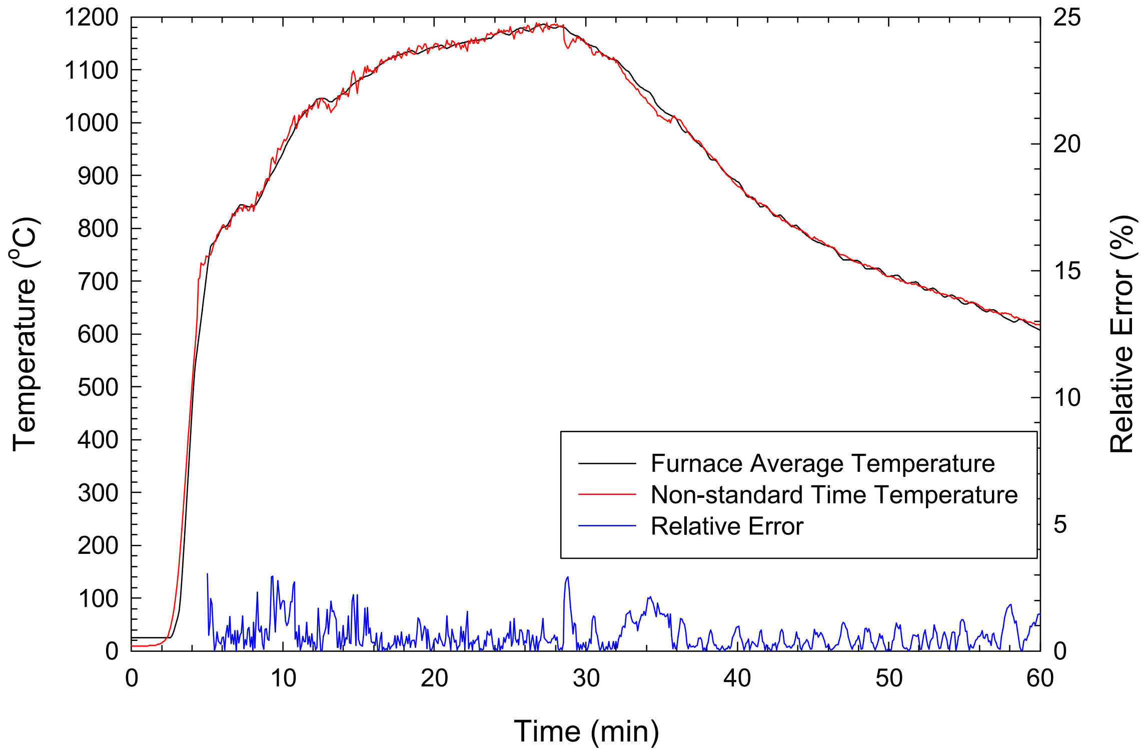


Figure 49. Comparison of average furnace temperature with non-standard curve.

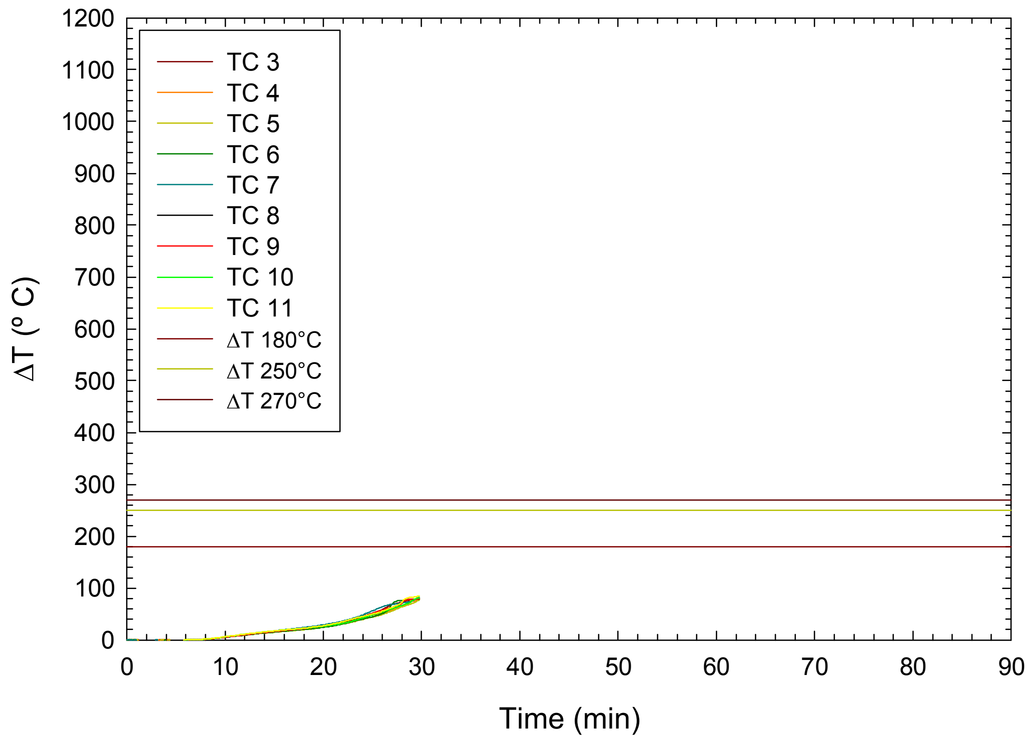


Figure 50. Temperature rise value profiles at Ply-Ply interface for Test IS-10 with 1 layer 15.9 mm Type X gypsum board.

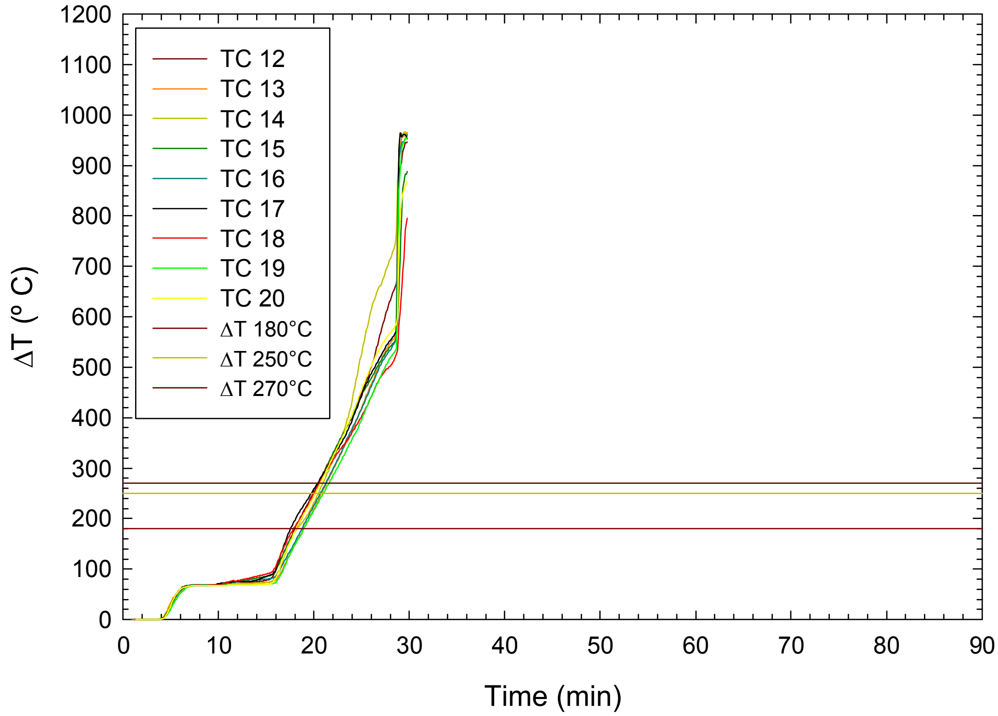


Figure 51. Temperature rise value profiles at GB-Ply interface for Test IS-10 with 1 layer 15.9 mm Type X gypsum board.

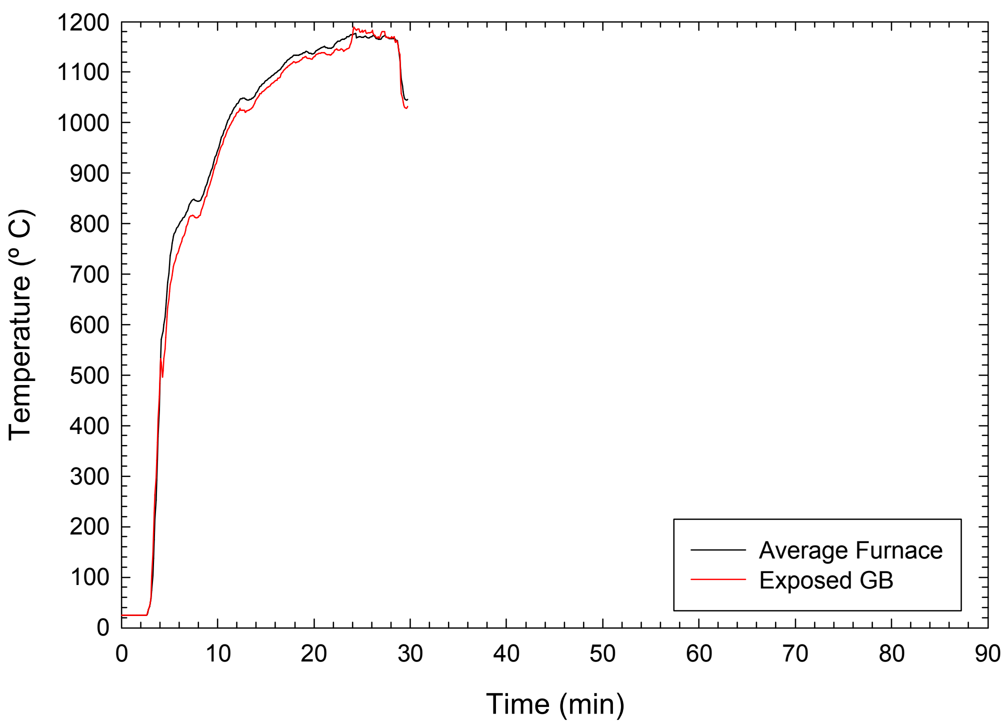


Figure 52. Temperature profiles for Test IS-10 with 1 layer 15.9 mm Type X gypsum board.

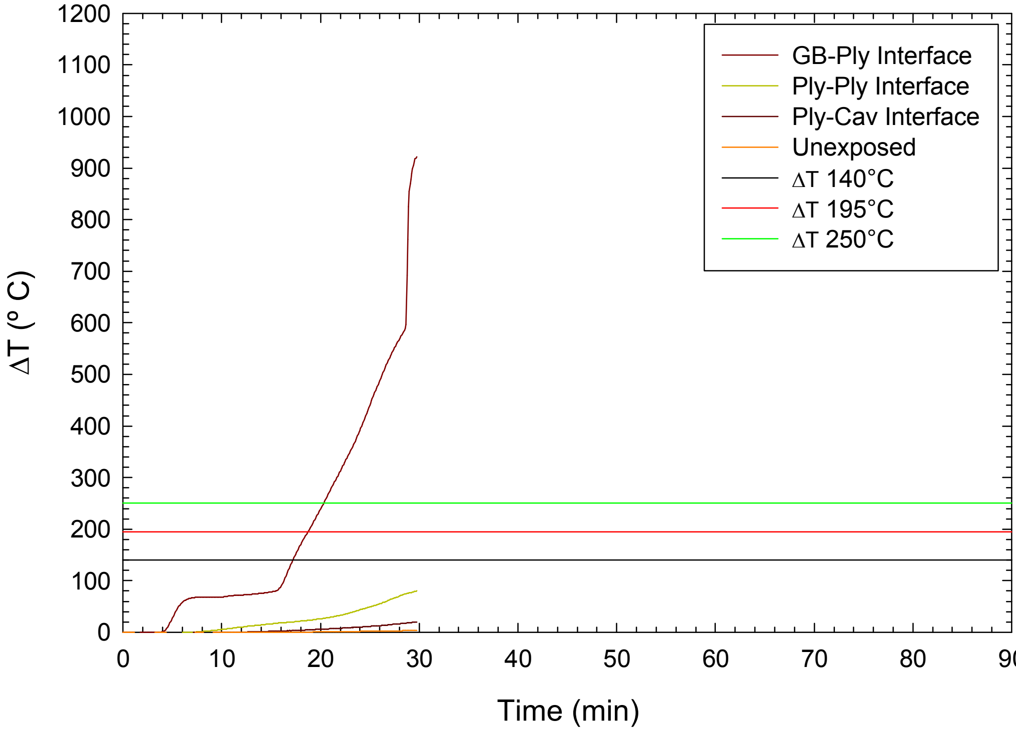


Figure 53. Temperature rise value profiles for Test IS-10 with 1 layer 15.9 mm Type X gypsum board.

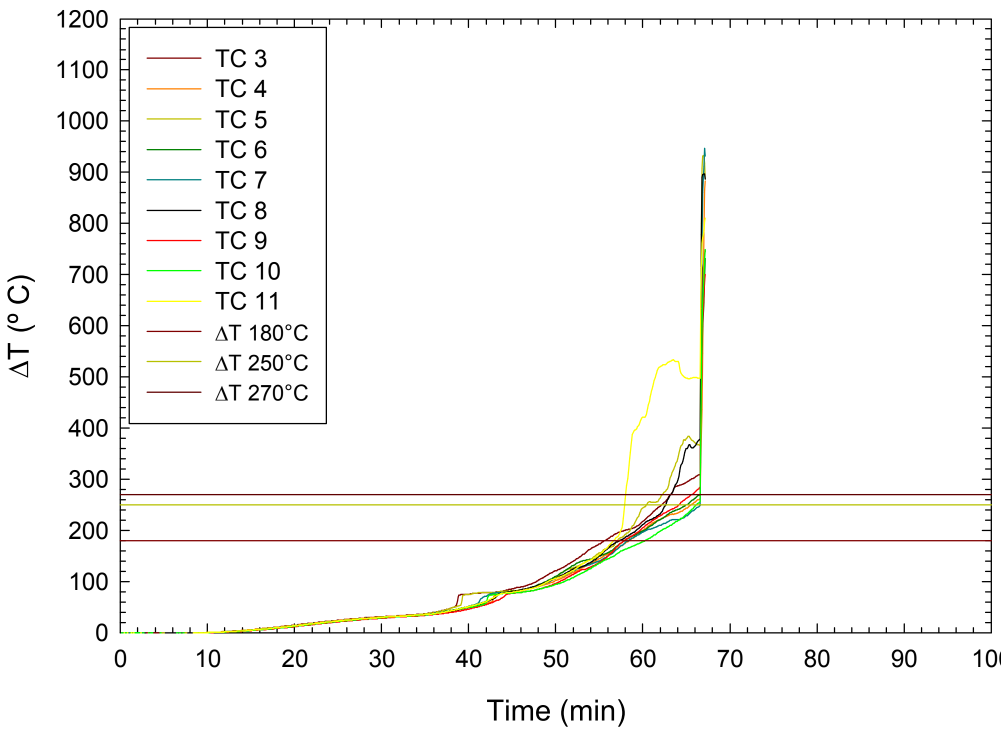


Figure 54. Temperature rise value profiles at Ply-Ply interface for Test 11 with 2 layers 12.7 mm Type X gypsum board.

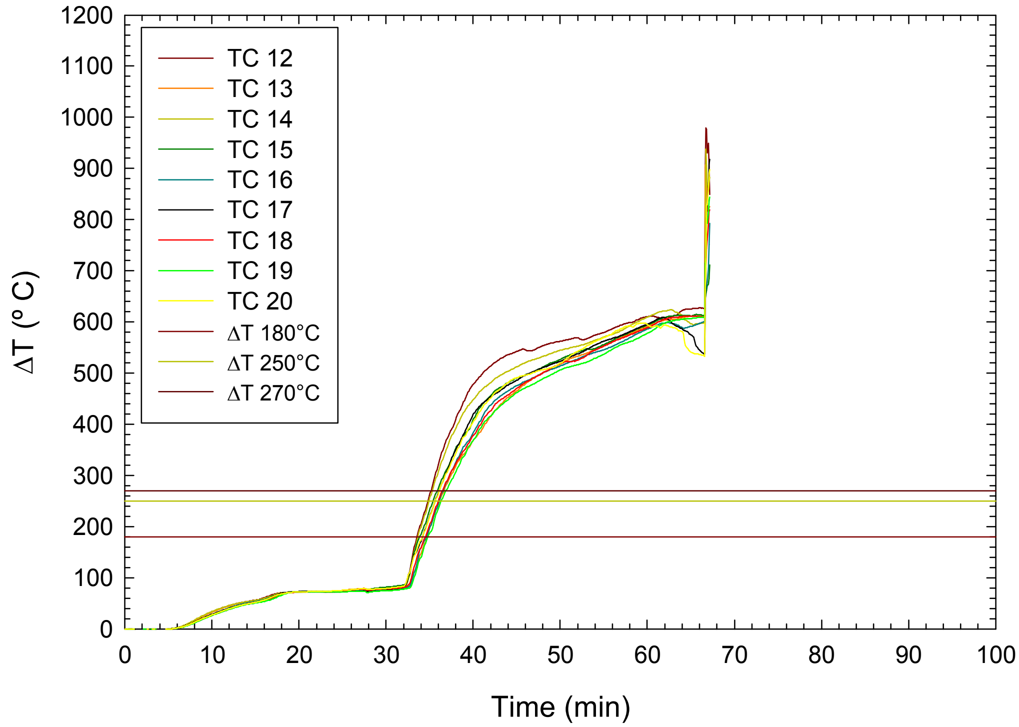


Figure 55. Temperature rise value profiles at GB-Ply interface for Test IS-11 with 2 layers 12.7 mm Type X gypsum board.

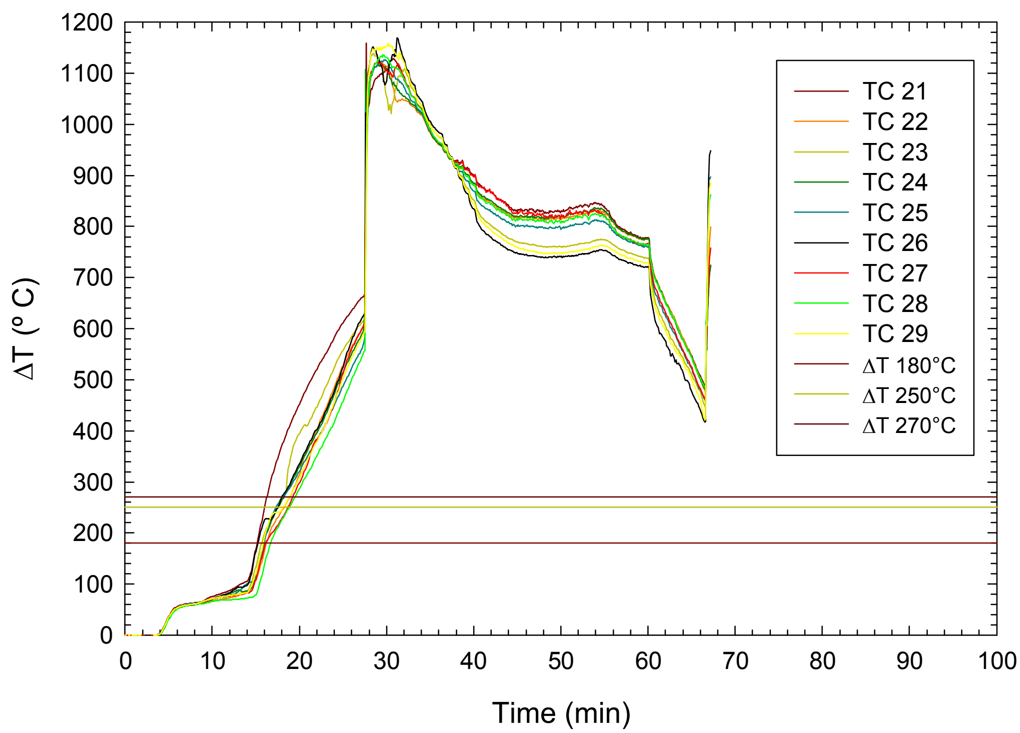


Figure 56. Temperature rise value profiles at GB-GB interface for Test IS-11 with 2 layers 12.7 mm Type X gypsum board.

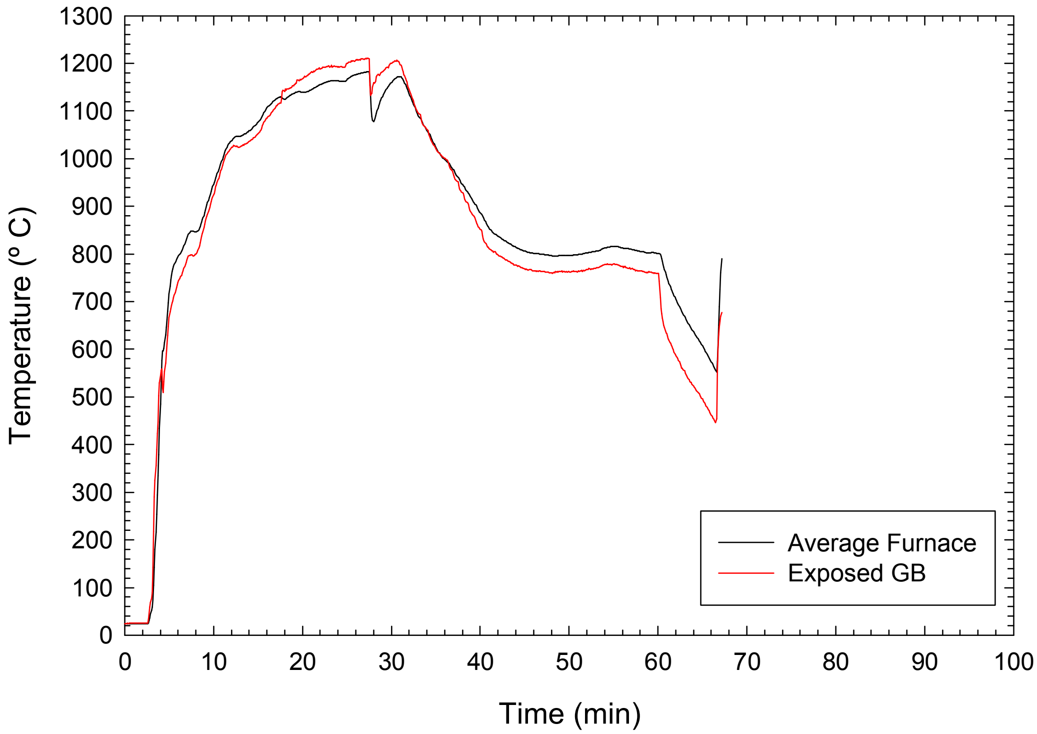


Figure 57. Temperature profiles for Test IS-11 with 2 layers 12.7 mm Type X gypsum board.

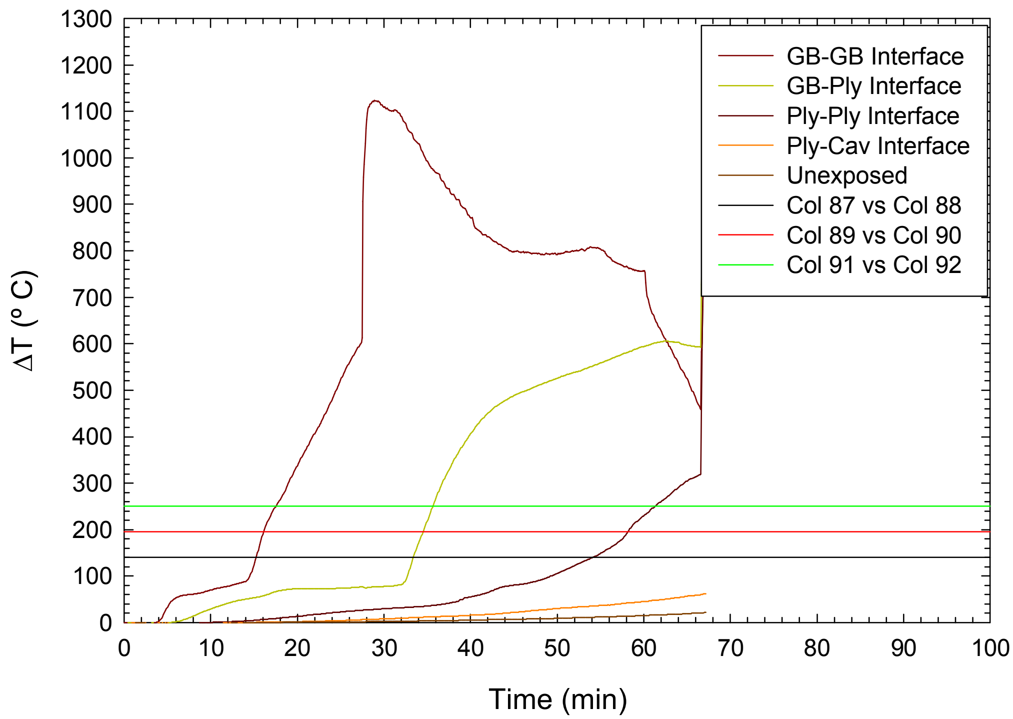


Figure 58. Temperature rise value profiles for Test IS-11 with 2 layers 12.7 mm Type X gypsum board.

6 DISCUSSION AND SUMMARY

This report documents the results of intermediate-scale furnace tests conducted to investigate the performance of three noncombustible encapsulation materials for combustible structural elements. The materials were: Type X gypsum board (12.7 mm and 15.9 mm thick), cement board (12.7 mm thick) and gypsum-concrete (25 mm thick and 39 mm thick).

A total of 11 tests were conducted, with 9 tests conducted using the standard time-temperature curve used for standard fire-resistance tests [5]. Two additional tests were conducted using a non-standard fire exposure based on the results of test PRF-03 conducted as part of a series of tests to characterize fires in multi-suite dwelling units [6]. The results of each test are discussed in this report.

Two initial tests were conducted using 12.7 mm Type X gypsum board, to investigate the effect of the thickness of the plywood substrate to which the encapsulation material was attached on the temperature increase at the interface between the encapsulation material and the substrate. It was determined that the rate of increase of temperature rise values was faster for the assembly with a thicker substrate (2 layers of 15.9 mm thick plywood) than with the single layer of plywood. As a result, two layers of plywood were used for all subsequent tests.

A primary objective of this study was to investigate the use of intermediate-scale testing to determine the relative performance of the three encapsulation materials for use in protecting structural elements. However, in order to evaluate performance of the encapsulation material, a criterion is required. In this project, three existing sets of criteria used in standard testing were investigated:

1. Criteria 1. The average temperature rise over the whole exposed surface of the protected building element is limited to 140ºC, and the maximum temperature rise at any point on that surface does not exceed 180ºC. These temperature criteria are used in CAN/ULC-S101 [5] and CAN/ULC-S124 [3].
2. Criteria 2. The average temperature rise over the whole exposed surface of the protected building element is limited to 195ºC, and the maximum temperature rise at any point on that surface does not exceed 250ºC. These temperature criteria are used in CAN/ULC-S124 [3]
3. Criteria 3. The average temperature rise over the whole exposed surface of the protected building element is limited to 250ºC, and the maximum temperature rise at any point on that surface does not exceed 270ºC. These criteria, used in standard tests used in Europe to evaluate the performance of encapsulation materials, are based on the temperature at which wood-based products will begin to char (approximately 300°C) [7].

The times at which the three sets of criteria were exceeded in each test are provided in Table 8. As would be expected, Criteria 1 is the most conservative and Criteria 3 is the least conservative of the three sets of criteria.

For those materials for which both one and two layers were tested, the temperature rise values measured at the interface between the two layers of encapsulation materials were also used to determine the times at which the three sets of criteria were exceeded. The times determined based on the tests with 2 layers of the encapsulation material were comparable to but consistently higher than those with the material directly attached to the plywood substrate. In principle, a single test with two layers of the material could be used to estimate the performance of both one and two layers of the encapsulation material. However, if the times determined for the face layer are close to a regulatory requirement, a test with a single layer should be conducted.

For Criteria 1 and 2, the average temperature rise requirement was typically exceeded first, whereas for Criteria 3 the single-point temperature rise requirement was more likely to the first to be exceeded. Factors contributing to this trend are:

1. The small temperature difference (20°C) between the average and single-point temperature rise requirements used for Criteria 3 compared with 40°C and 55°C for Criteria 1 and 2, respectively.
2. The increased variation in the temperature rise values measured by the 9 thermocouples located at the interface between the encapsulation material and the substrate with increasing temperature. There are likely two factors contributing to the temperature variations:
    a. Temperature variations within the furnace. The temperatures measured by the furnace thermocouples are comparable but there is a tendency for slightly higher temperatures at the east end of the furnace. There were cases, particularly with the 15.9 mm thick gypsum board assembly tests, in which the rates of increase of temperature rise values were typically faster at the east end of the furnace. However, the difference in time between thermocouples at the interface between the encapsulation material and the substrate for the temperature rise value to reach 270°C was small (<4 min).
    b. Inhomogeneous test specimens. There were large temperature variations measured at the interface between the encapsulation material and the plywood substrate for tests with cement board and gypsum-concrete. These variations started at relatively low temperature rise values and resulted in large variations in the time at which the temperature rise values reached 270°C. The location at which the most rapid increase of temperature rise values occurred varied from test to test, indicating the variations were a result of inhomogeneous test specimens.

The primary objective of using encapsulation materials to protect combustible structural elements is to delay the time at which the structural element ignites and contributes to the fire. The results of the tests with the intermediate-scale furnace, as well as cone calorimeter tests [9] indicate that the combustible element will not ignite or contribute significant heat to a fire until average temperatures of 325 – 380°C or higher are attained at the interface between the encapsulation material and the combustible substrate. These temperatures are consistent with the ignition temperatures for wood-based materials [8]. As such, it is suggested that Criteria 3 provides a technically-based and conservative set of criteria for assessing the performance of encapsulation materials.

The relative performance of the encapsulation materials based on Criteria 3 is shown in Figure 59. The single layer encapsulation materials provide protection times of 16 min (cement board) to 28 min (25 mm thick gypsum-concrete). The thicker encapsulation materials, 2 layers of the board materials and 39 mm thick gypsum-concrete, provide protection times of 42 min (2 layers of cement board) to 69 min (2 layers of 15.9 mm thick Type X gypsum board).

The fall-off times for the face and base layers of the encapsulation materials are provided in Table 8. The fall-off times for the face layer are quite long in some cases. For tests with 2 layers of gypsum board, the increased time to fall-off was 30 min for the 12.7 mm thick Type X gypsum board and 31 min for the 15.9 mm thick Type X gypsum board. As noted previously, the edges of the encapsulation material was supported by the test furnace. This may account for some increase in the time for which the encapsulation material remains in place. However, it would not account for the large differences in the stability of the face layer when attached to a second layer of the encapsulation material rather than directly to the plywood substrate, since in both instances the edges of the encapsulation material were supported by the test furnace.

The extended time for fall-off of the face layer in the tests with two layers of the encapsulation material does affect the rate of increase of the temperature rise values at the interface with the plywood substrate. As such, the times at which the criteria are reached for the assemblies with 2 layers of encapsulation material may be longer than would be measured in full-scale tests and should be used with caution.

Two tests (Tests IS-10 and IS-11) were conducted using a non-standard fire exposure derived from the average upper layer temperature measured in a full-scale fire test from a separate research project to characterize fires in multi-suite residential dwellings. The times at which the temperature rise criteria were exceeded, as well as the fall-off times for the encapsulation materials, are provided in Table 8. For a single layer of encapsulation material, the time to reach Criteria 3 was reduced by 5.25 min (24%) for 12.7 mm Type X gypsum board (comparing results from non-standard fire exposure versus standard fire-resistance time-temperature curve), and by 5.17 min (20%) for 15.9 mm thick Type X gypsum board.

For the two layers of 12.7 mm thick Type X gypsum board, the time at which Criteria 3 was reached at the gypsum board/plywood interface was reduced by 23.58 min (40%). The large reduction in time with the two layers of material may be due in part to the earlier fall off of the face layer of gypsum board (27 min in the test with the non-standard fire exposure versus 68 min with the standard time-temperature curve).

Table 8. Summary of results for tests on encapsulation materials with intermediate-scale furnace.

Encapsulation Material	Thickness (mm)	Number of Layers	Test Number	Layer Position	Time at which Criteria Reached (Average Temperature Rise or Single-point Temperature Rise) (min)			Fall-off Time (min)
					Criteria 1	Criteria 2	Criteria 3	
Type X Gypsum Board	12.7	1	IS-1	face	17.92	19.83	21.58	38
	12.7	1	IS-2*	face	18.58	21.67	24.08	41
	12.7	2	IS-5	face	18.67	20.67	21.92	68
				base	50.67	55.33	58.75	71
	12.7	2	IS-11**	face	15.17	16.08	16.33	27
				base	33.42	34.58	35.17	67
Type X Gypsum Board	15.9	1	IS-4	face	21.25	23.42	25.50	59
	15.9	2	IS-9	face	23.75	25.58	26.50	90
				base	61.92	65.33	69.58	94
	15.9	1	IS-10**	face	17.25	18.75	20.33	29
Cement Board	12.7	1	IS-3	face	13.08	15.08	16.00	60‡
	12.7	2	IS-8	face	13.75	15.33	16.00	50
				base	34.67	40.25	42.50	65
Gypsum-concrete	25	1	IS-7	face	24.83	27.67	28.83	38
	39	1	IS-6	face	43.92	49.58	55.08	93

* Test assembly with a single layer 15.9 mm thick plywood substrate.
** Non-standard fire exposure.
‡ Cement board had not fallen off when test stopped at 60 min.

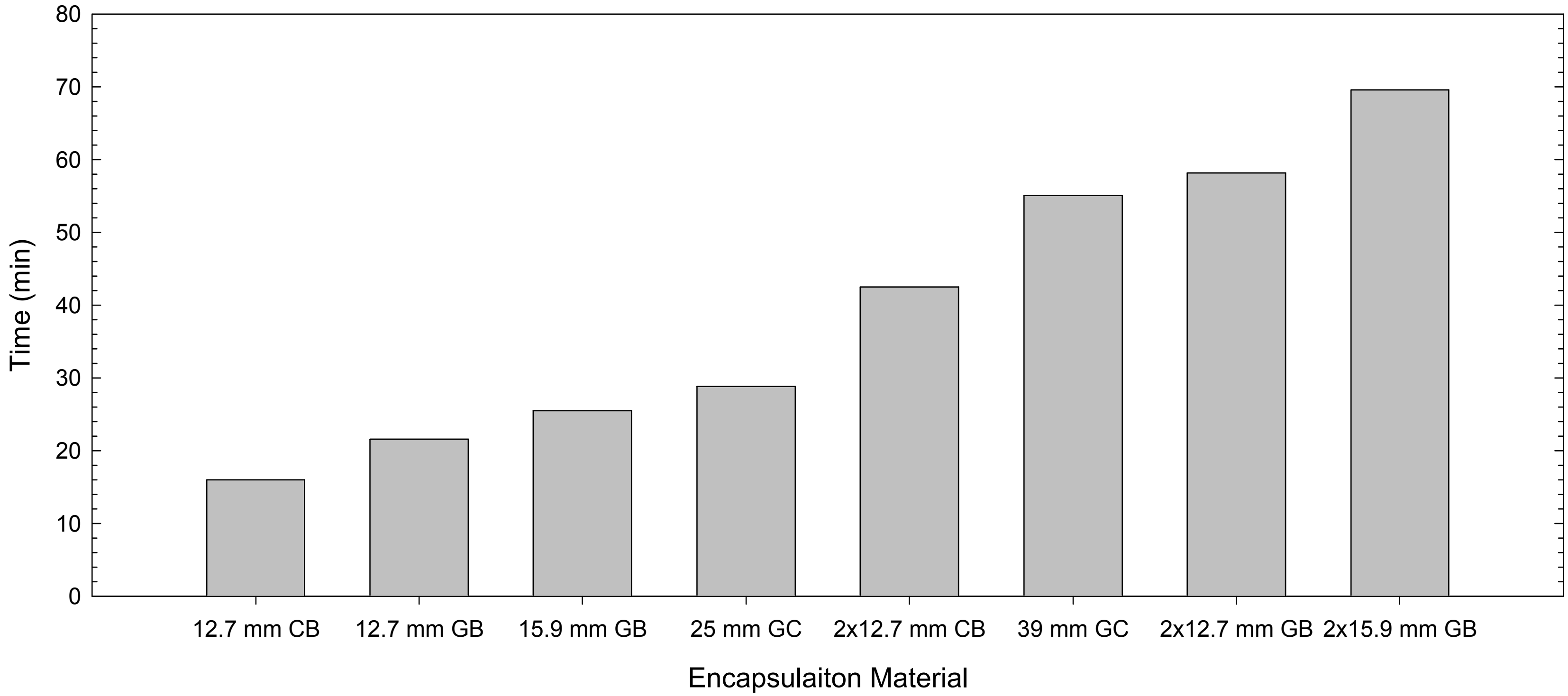


Figure 59. Performance of encapsulation materials based on Criteria 3 at the interface with the plywood substrate.

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