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DEVELOPMENT OF A FIRE PERFORMANCE ASSESSMENT METHODOLOGY FOR QUALIFYING CROSS-LAMINATED TIMBER ADHESIVES

FINAL REPORT
Consisting of 78 Pages

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EXECUTIVE SUMMARY

The objectives of this project were to develop a full-scale room fire test method for assessing the performance of cross-laminated timber (CLT) adhesives, and to evaluate three CLT ceiling panels manufactured with different types of adhesives for the American Wood Council (AWC), located in Leesburg, Virginia. Testing was performed on September 14, 19, and 22, 2017, at Southwest Research Institute's (SwRI's) Fire Technology Department, located in San Antonio, Texas.

SwRI constructed a test room within one of its large open buildings. The building is approximately 40 × 60 ft by 36 ft high, and is connected to a pollution abatement system for safe and effective removal of combustion products. The interior dimensions of the test room were approximately 9 × 19 ft by 8 ft high, with a ventilation opening in the front narrow wall, which was nominally 36 in. wide by 75 in. high. The room was built directly on the test facility floor, which was protected with gypsum board inside the room. The walls of the test room were lined with several layers each of type X gypsum board and ceramic fiber blanket. The 8 × 16 ft CLT panel was simply supported along the narrow ends, but allowed to deflect freely between the two sidewalls. Before the start of each test, concrete blocks were placed on the CLT ceiling panel to impose a distributed structural load of 20 psf (0.96 kN/m^2). A 2 × 6 ft by 1 ft high propane gas diffusion burner was located in the back section of the room, and provided the target fire exposure. The walls and ceiling in the back section of the room were protected with an additional layer of ceramic fiber blanket. Instrumentation included thermocouples, directional flame thermometers (DFTs), and a propane gas flow sensor. Temperatures were monitored within the CLT layers at the center of the panel, at five locations 4 in. below the ceiling (hot gas layer (HGL) thermocouples), in the front right corner of the test room (room thermocouple tree), and at the ventilation opening (door thermocouple tree). Heat fluxes were measured with four DFTs located about 1 ft below the ceiling on the sidewalls (two on each side).

Tests were performed on three 8 × 16 ft CLT panels, each consisted of five 1 3/8 in. (35 mm) layers of softwood lumber (total thickness of 6 7/8 in. or 175 mm), with average density of 31 pcf and average moisture content of 10.8%. The panels were manufactured with different adhesives:

- CLT #1: Manufactured with E1 grade SPF lumber and a polyurethane adhesive (identical to the CLT used in the FPRF tests conducted at NIST). Test duration: 192 min.
- CLT #2: Manufactured with V1 grade Douglas fir lumber and a melamine formaldehyde resin. Test duration: 210 min.
- CLT #3: Manufactured with V1 grade Douglas fir lumber and an improved polyurethane adhesive. Test duration: 240 min.

The failure temperature of the polyurethane adhesive used in the fabrication of CLT #1 is in the range of 200 to 220 °C, which is consistent with the delaminations that were observed at the first glue-line around 60 min, and at the second glue-line around 180 min. The latter resulted in re-ignition and significant combustion of wood on the ceiling, which caused a noticeable increase in the HGL temperatures and DFT heat fluxes, and a secondary flashover at the end of the test.

During the first hour, temperatures and heat fluxes in the compartment for the tests of CLT #2 and CLT #3 were comparable to those recorded in the test of CLT #1. However, no delamination was observed during the cooling phase (≥ 58 min) in the tests of CLT #2 and CLT #3. Consequently, temperatures and heat fluxes recorded in these tests were much lower than for CLT #1. The improved fire performance of CLT #2 and CLT #3 is attributed to the higher failure temperature for the adhesives used in the fabrication of these panels.

1 INTRODUCTION

The objectives of this project were to develop a full-scale room fire test method for assessing the performance of cross-laminated timber (CLT) adhesives, and to evaluate three CLT ceiling panels manufactured with different types of adhesives for the American Wood Council (AWC), located in Leesburg, Virginia. Testing was performed on September 14, 19, and 22, 2017, at Southwest Research Institute's (SwRI's) Fire Technology Department, located in San Antonio, Texas.

This report describes the results of the testing for the three CLT panels. The results presented in this report apply only to the materials tested, in the manner tested, and not to any similar materials or material combinations. Development of the test method, including computer modeling performed to establish the heat release rate (HRR) profile of the burner and calibration tests conducted to validate the test method, is discussed in a supplement to this report.

2 TEST APPARATUS

2.1 Test Room

SwRI constructed a test room within one of its large open buildings. The building is approximately 40 × 60 ft by 36 ft high, and is connected to a pollution abatement system for safe and effective removal of combustion products. The building has a false ceiling at 30 ft with a gap of approximately 18 in. around the perimeter. The interior dimensions of the test room were approximately 9 × 19 ft by 8 ft high. The dimensions of the ventilation opening in the front narrow wall was nominally 36 in. wide by 75 in. high. The test room was built directly on the concrete floor of the building, which was protected with two layers of 5/8 in. type X gypsum board. The front wall of the test room faced the back wall of the building, and was located at approximately 20 ft from the back wall. Combustion products were extracted from the plenum above the false ceiling at the back of the building, nearest the test room ventilation opening. A 6 ft wide strip of the false ceiling was removed near the exhaust duct to facilitate collection of combustion products generated in the fire.

Figure A-1 in Appendix A shows a picture of the finished test room taken from the ventilation opening in the front wall. Two steel I-beams (12 × 41 lbs/ft) welded together (see Figure A-2) were located at approximately 15 ft from the front wall to subdivide the test room into two sections. The ceiling of the front section was left open and allowed for the exposure of a 16 ft long by 8 ft wide CLT ceiling panel. The CLT panel was simply supported by the front wall at one end (bearing length ≈ 6 in.), and by the steel I-beam at the other end (bearing length ≈ 5 1/4 in.). The sides of the panel were not supported, and the CLT was allowed to deflect freely between the two sidewalls. A gas burner to create the desired fire exposure was located in the back section of the room, as shown in Figure A-1. Construction details for the test room walls, floor and ceiling are as follows:

- *Front Wall*—The front wall of the test room consisted of 8 ft tall, 6 in. deep, 16 gauge steel studs, 12 in. on center, with 16 gauge track top and bottom. The interior surface of the frame was covered with three layers of 5/8 in. type X gypsum board (National Gypsum Fire-Shield®), 20-gauge galvanized sheet steel, and three layers of 1 in. thick ceramic fiber blanket (Morgan Thermal Ceramics 6 pcf Cerablanket®). The exterior surface was covered with two layers of 5/8 in. type X gypsum board, 20-gauge galvanized sheet steel (top half only), and one layer of 1 in. thick ceramic fiber blanket (additional layers of blanket were used at the soffit and above the ventilation opening).
- *Sidewalls*—The sidewalls of the test room consisted of three layers of 4 ft wide by 10 ft tall 5/8 in. type X gypsum board attached to steel racks. The interior surface of the gypsum board was covered with three layers of 1 in. thick ceramic fiber blanket. An additional layer of blanket was attached to the sidewalls in the back section of the test room. In the front section of the test room, the web of a 6 in. steel stud covered with 16-gauge track was attached to the sidewalls at 8 ft above the floor. The bottom of the covered studs was protected with three layers of 5/8 in. type X gypsum board. Two layers were used to protect the vertical and top surfaces. The studs and track mounted along the sidewalls were used to reduce the width of the opening in the front section of the test room from 9 ft to 8 ft 4 in. and prevent damage from falling debris to instrumentation attached to or located close to the sidewalls.
- *Back Wall*—The back wall of the test room consisted of 8 ft tall, 3 5/8 in. deep, 18-gauge steel studs, 12 in. on center, with 18-gauge track top and bottom. The interior surface of the frame was covered with four layers of 5/8 in. type X gypsum board and three layers of 1 in. thick ceramic fiber blanket. The exterior surface was not finished. An opening at the bottom of the back wall allowed the 2 in. propane pipe nipple from the burner to pass-through to connect to the supply hose outside the test room. The opening was sealed with ceramic fiber blanket.
- *I-beams*—The space between the exposed surfaces of the flanges and web were filled with several layers of 5/8 in. type X gypsum board, and the beams were then wrapped with four layers of 1 in. thick ceramic fiber blanket.
- *Back Section Ceiling*—The ceiling above the burner consisted of a spare 4.5 × 8 ft CLT panel, protected with four layers of 5/8 in. type X gypsum board and four layers of 1 in. thick ceramic fiber blanket. The front edge of the CLT panel was supported by one of the two I-beams. At the back edge, the CLT panel was attached to a 3 1/2 × 3 1/2 × ¼ in. angle iron welded to the racks supporting the sidewalls.

Fastener details are as follows:

- First layer of gypsum board: 1 7/8 in. #6 type S bugle head drywall screws.
- Second layer of gypsum board: 2 1/2 in. #6 type S bugle head drywall screws.
- Third and fourth layer of gypsum board: 3 in. #8 type S bugle head drywall screws.
- First and second layer of ceramic fiber blanket: 4 1/2 in. coarse thread screws with 1 in. washers.
- Third and fourth layer of ceramic fiber blanket: 12-gauge galvanized steel wire bent into horseshoe shape.

Screw spacing was approximately 12 in. Wires were used where needed. All joints were staggered with at least 1 ft separation.

2.2 Gas Burner

A gas burner was constructed to create the exposing fire. The burner consisted of a 6 × 2 ft by 1 ft tall steel box with open top. The burner was supplied with propane through a 2 in. pipe. The gas flow was evenly distributed to eight downward-facing release points as shown in Figure 1. The burner was filled with coarse gravel to ensure relatively uniform propane flow at the top surface (see Figure A-3). Between each test, debris was cleared from the burner and the top layer of gravel replaced.

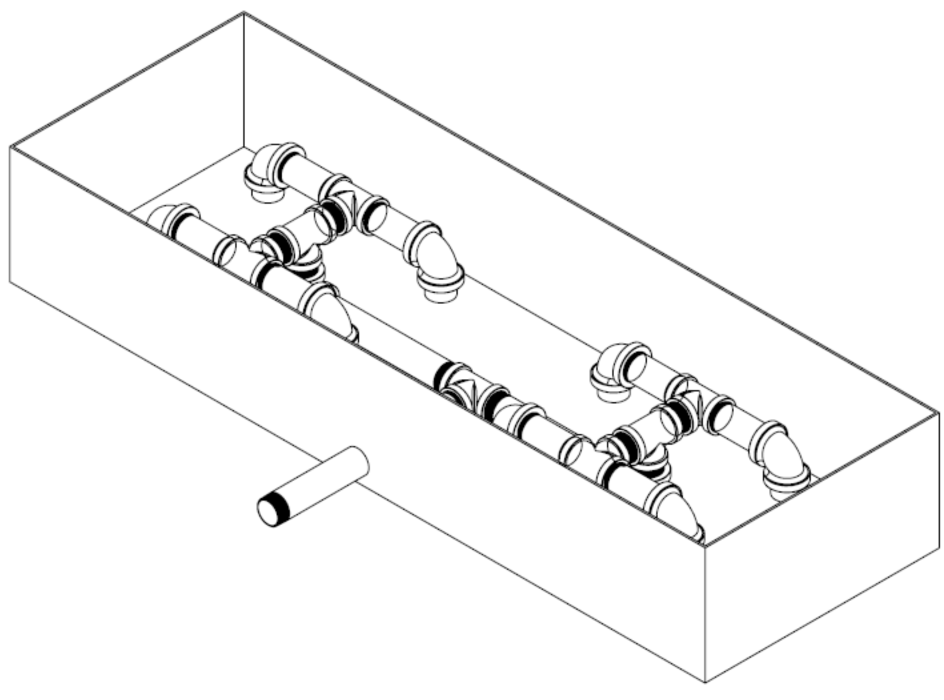

Figure 1. Schematic of Burner Illustrating Distribution of Propane Flow.

2.3 Instrumentation

2.3.1 Room Interior Thermocouples

Three sets of thermocouples (TCs) were used to measure gas temperatures inside the compartment:

- *Hot Gas Layer (HGL) Thermocouples*—Five Duro-Sense 1/8 in. diameter, Inconel sheathed, exposed junction, type K TCs were located 4 in. below the ceiling of the CLT (see Figure A-4; note that this is a picture from one of the calibration tests, in which the same TCs were used to measure the HGL temperature). One TC was located at the center of the CLT ceiling, and the other TCs were located at the four quadrants (as measured from the entire CLT dimension, not just the exposed area).
- *Door Thermocouple Tree*—Six Duro-Sense 1/8 in. diameter, Inconel sheathed, exposed junction, type K TCs were located in the open doorway (see Figure A-5). The TCs were used to measure the inflowing and outflowing gas temperatures at 0.5, 1.5, 2.5, 3.5, 4.5, and 5.5 ft above the test room floor. Some door tree TCs did not survive the test of CLT #2. For the test of CLT #3, all door thermocouples were replaced with Duro-Sense 1/8 in. diameter, Inconel sheathed, grounded junction (instead of exposed junction), type K TCs.
- *Room Thermocouple Tree*—Eight self-renewing, fast-response, type K TCs from Nanmac Corporation were used to measure the temperature profile inside the room. The thermocouple junctions were located at 12 in. from the front wall and 4 in. from the right sidewall. The TCs were used to measure the room gas temperatures at 0.5, 1.5, 2.5, 3.5, 4.5, 5.5, 6.5, and 7.5 ft above the test room floor (see Figure A-6).

2.3.2 Thermocouples Embedded in CLT

Seven Duro-Sense 1/16 in. diameter, Inconel sheathed, grounded junction, type K TCs were embedded at different depths from the top (unexposed side) surface of the CLT (see Figure A-7). The thermocouples were located at the following distance from the top surface:

- 164 mm deep (1/3 of the first layer from the exposed surface).
- 152 mm deep (2/3 of the first layer from the exposed surface).
- 140 mm deep (glue-line between first and second layer).
- 129 mm deep (1/3 of the second layer from the exposed surface).
- 117 mm deep (2/3 of the second layer from the exposed surface).
- 105 mm deep (glue-line between second and third layer).
- 70 mm deep (glue-line between third and fourth layer).

2.3.3 Directional Flame Thermometers

Directional flame thermometers (DFTs) were used to measure heat fluxes to four locations, two on the right wall and two on the left wall. The DFTs were placed about 1 ft below the ceiling, aligned with the HGL TCs at the quadrants. Each DFT consisted of ceramic fiber insulation sandwiched in between two Inconel plates (see Figure A-8). Inconel-sheathed TCs are attached to the interior of the plates. Since the thermal properties of the plates and the insulation are known, the incident heat flux can be calculated based on the measured plate temperatures. The process is described in ASTM E3057. In this report, it is assumed the gas temperature at a DFT is equal to the HGL temperature measured at the nearest quadrant, and the convection coefficient is equal to 10 $W/m^2 \cdot K$. In addition to the incident heat flux, the radiant heat flux emitted by the exposed plate is also reported to facilitate comparison with plate thermometer measurements. The emitted heat flux was calculated from:

$$\dot{q}_e'' \approx \varepsilon \sigma T_s^4$$

$\dot{q}_e''$	=	Emitted heat flux (kW/m^2);
ε	=	Surface emissivity of the Inconel plate (≈ 0.85);
σ	=	Boltzmann constant ($5.67 \cdot 10^{-11}$ $kW/m^2 \cdot K^4$); and
T_s	=	Plate temperature (K)

2.3.4 Heat Release Rate Measurements

A gas sampling probe and flow sensor was installed in the exhaust duct of the building, in an attempt to measure HRR based on oxygen consumption calorimetry. Unfortunately, at HRR in excess of approximately 1 MW, part of the plume hit the false ceiling and drifted toward the front of the building. As a result, the oxygen consumption calorimetry measurements are not reliable. Other methods for estimating the HRR are discussed in the supplement.

2.3.5 Video and Photographic Documentation

Two video cameras were used to obtain footage of the fire compartment from two angles. The primary video camera was used to obtain general video footage of the fire for the entire duration of the test. The second video camera was directed at the ceiling to monitor delamination, but was only used during the cooling phase when the burner HRR was reduced back to 250 kW (see Section 3 below). Photographic documentation was obtained prior to, during, and following each test.

3 BURNER HEAT RELEASE RATE PROFILE

The propane was supplied from two tanks via a vaporizer, a regulator, and a 2 in. diameter pipe with several shut-off valves and a control valve. The propane flow rate was manually controlled, and measured with a Coriolis mass flow sensor (Micro Motion, Inc., Boulder, CO, Model CMF050M315NQFUEZZ).

The burner HRR profile was established from computer modeling and verified with several calibration tests. The objective was to duplicate the thermal exposure (heat flux) measured to the center of the ceiling in FPRF Test #1-1. The resulting step profile (referred to as profile 15) is shown in Table 1 and Figure 2. The development of the profile is discussed in the supplement to this report.

Table 1. Burner HRR Profile.

Start (min)	End (min)	HRR (kW)
0	13	250
13	38	1075
38	58	1377
58	88	834
88	End of Test	250

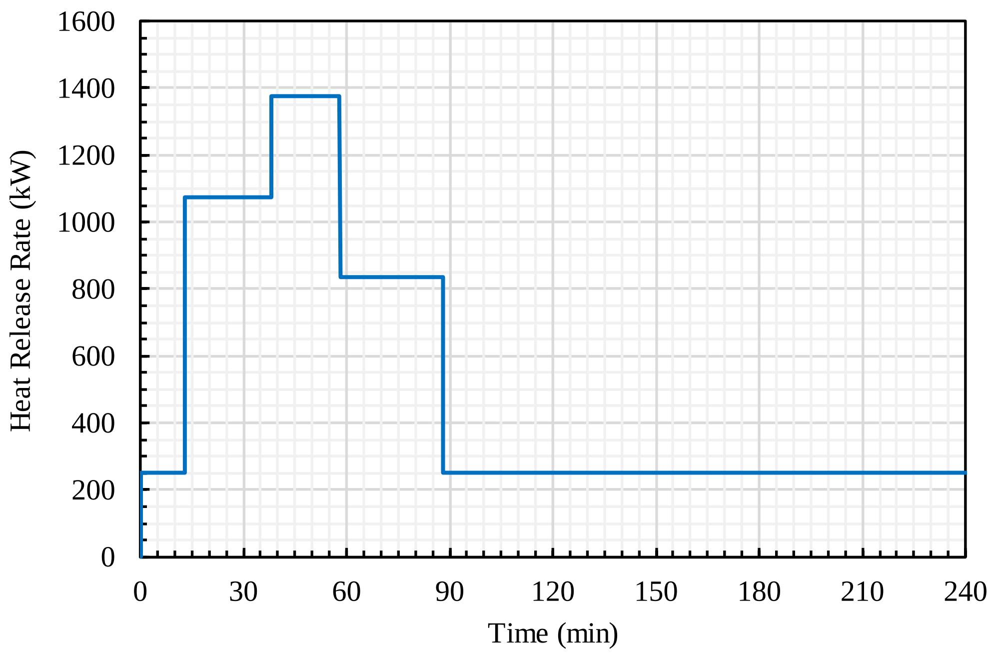

Figure 2. Burner Heat Release Rate Profile.

4 CLT PANELS TESTED

Tests were performed on three 8 × 16 ft CLT panels. The CLT consisted of five 1 3/8 in. (35 mm) layers of softwood lumber (total thickness of 6 7/8 in. or 175 mm). The panels were manufactured with different adhesives:

- CLT #1: Manufactured with E1 grade SPF lumber and a polyurethane adhesive. This panel was identical to the CLT used in the FPRF tests conducted at NIST.
- CLT #2: Manufactured with V1 grade Douglas fir lumber and a melamine formaldehyde resin.
- CLT #3: Manufactured with V1 grade Douglas fir lumber and an improved polyurethane adhesive.

The nominal densities and moisture content measurements for the three CLT specimens are given in Table 2. The moisture content was measured shortly before the start of each test with a Delmhorst RDM³ moisture meter.

Table 2. Nominal Densities and Moisture Contents.

Physical Quantity	CLT #1	CLT #2	CLT #3
Nominal Density (pcf)	31.5	33.0	28.5
Front Left Moisture Content (%)	10.8	10.4	10.7
Front Right Moisture Content (%)	10.7	10.6	10.6
Ceiling Center Moisture Content (%)	11.3	10.7	10.4
Back Left Moisture Content (%)	11.5	11.2	10.6
Back Right Moisture Content (%)	11.2	11.3	10.7
Average Moisture Content (%)	11.1	10.8	10.6

5 TEST RESULTS

Before the start of each test, concrete blocks were placed on the CLT ceiling panel to impose a distributed structural load of 20 psf (0.96 kN/m^2) as shown in Figure A-9.

5.1 Test Results for CLT #1

The first room test was conducted Thursday, September 14, 2017. The data acquisition system was started at approximately 1:33 PM, and the burner flow was initiated at approximately

1:36 PM. Temperature and relative humidity in the laboratory at the start of the test were 85 °F (24 °C) and 96%, respectively. The test was terminated at approximately 4:48 PM.

Photographs and graphical test results for CLT #1 are provided in Appendix B and C, respectively. Figure B-4 and Figure B-5 indicate that the paper on gypsum board covering the floor ignited close to the burner at 14 min 5 s, and that flames spread to the front of the room in the subsequent 35 s. Since the failure temperature of the polyurethane adhesive used in the fabrication of CLT #1 is in the range of 200 to 220 °C, Figure C-9 indicates that delamination in the center of the ceiling is expected to occur at the first glue-line between 55 and 60 min, and around 180 min at the second glue-line. Delamination is expected to occur somewhat earlier in the back of the room and later in the front of the room. This is consistent with the visual observations (see Figure B-8 through Figure B-10 for delamination at the first glue-line; and Figure B-14, Figure B-15, and Figure B- 17 through Figure B-19 for delamination at the second glue-line). Delamination at the second glue-line causes a noticeable increase in the HGL temperatures (see Figure C-3) and heat fluxes (see Figure C-5 through Figure C-8), and a secondary flashover at the end of the test.

5.2 Test Results for CLT #2

The second room test was conducted Tuesday, September 19, 2015. The data acquisition system was started at approximately 9:34 AM, and the burner flow was initiated at approximately 9:46 AM. Temperature and relative humidity in the laboratory at the start of the test were 80 °F (26 °C) and 86%, respectively. The test was terminated at approximately 1:18 PM.

Photographs and graphical test results for CLT #2 are provided in Appendix D and E, respectively. Delamination was not observed in the cooling phase.

5.3 Test Results for CLT #3

The third room test was conducted Friday, September 22, 2017. The data acquisition system was started at approximately 8:52 AM, and the burner flow was initiated at approximately 9:09 AM. Temperature and relative humidity in the laboratory at the start of the test were 77 °F (25 °C) and 73%, respectively. The test was terminated at approximately 1:11 PM.

Photographs and graphical test results for CLT #3 are provided in Appendix F and G, respectively. Delamination was not observed in the cooling phase.

5.4 Summary of Temperature, Heat Flux, and Char Depth Data

5.4.1 HGL TC Temperatures and DFT Heat Fluxes

Table 3 summarizes HGL TC temperatures and Table 4 summarizes DFT heat fluxes at specific times during the three tests, which coincide with HRR changes in the burner step-profile. Temperatures and heat fluxes are comparable for the three tests during the first hour. However significantly higher (peak) temperatures and heat fluxes were recorded in the CLT #1 test during the cooling phase (≥ 58 min) due to delaminations resulting in re-ignition and combustion of wood on the ceiling and the floor. No delamination was observed during the cooling phase in the tests of CLT #2 and CLT #3. This explains why temperatures and heat fluxes recorded during the cooling phase in these two tests were comparable and much lower than for CLT #1.

Table 3. Summary of HGL TC Temperature Data.

Test Time	Value	HGL TC Temperatures (°C)		
		CLT #1	CLT #2	CLT #3
13 min	Average	265	253	259
	Maximum	282	267	276
	Minimum	256	240	249
38 min	Average	975	961	971
	Maximum	996	994	1014
	Minimum	953	921	929
58 min	Average	1114	1082	1104
	Maximum	1174	1141	1172
	Minimum	1053	1013	1034
88 min	Average	1036	903	906
	Maximum	1066	912	918
	Minimum	1002	887	893
≥ 120 min	Average	801	382	395
	Maximum	829	395	414
	Minimum	778	369	379

Table 4. Summary of DFT Heat Flux Data.

Test Time	DFT Measurement Location	Incident Heat Flux (kW/m2)		
		CLT #1	CLT #2	CLT #3
38 min	Front left	106	102	110
	Front right	110	103	104
	Back left	131	123	129
	Back right	137	128	134
58 min	Front left	171	152	171
	Front right	178	159	175
	Back left	221	197	222
	Back right	237	208	230
88 min	Front left	144	90	90
	Front right	143	86	87
	Back left	166	99	100
	Back right	166	99	103
≥ 120 min	Front left	57	10	11
	Front right	60	9	11
	Back left	57	12	13
	Back right	65	11	13

5.4.2 Char Depth Measurements

Post-test samples were cut from areas in the CLT close to the HGL TC locations. Photographs of the samples provide a qualitative indication of the char depth and can be found in Appendix B for CLT #1 (see Figure B- 25 and Figure B- 26), Appendix D for CLT #2 (see Figures D-20 and Figure D-21), and Appendix F for CLT #3 (see Figures F-20 and Figure F-21). The absence of a thick char layer in these pictures should not be interpreted as evidence of delamination since, in several cases, significant amounts of char fell off during extinguishing, post-test removal of the CLT panel from the test room, and cutting of the samples.

Char depths based on average residual wood thickness measurements on four sides of the samples are provided in Table 5. Since the heat fluxes and temperatures were lower in the front of the room compared to the center and the back, the char depths generally increase from front to back

Table 5. Test Duration and Measured Char Depths.

Physical Quantity	CLT #1	CLT #2	CLT #3
Test Duration (min)	192	210	240
Front Left Char Depth (mm)	70.0	51.8	48.5
Front Right Char Depth (mm)	70.0	51.8	48.5
Ceiling Center Char Depth (mm)	83.3	57.5	49.7
Back Left Char Depth (mm)	88.0	56.8	70.0
Back Right Char Depth (mm)	88.5	70.0	70.0

APPENDIX A

GENERAL PHOTOGRAPHS

(CONSISTING OF 5 PAGES)

Figure A-1. View into Finished Test Room Through Open Door in Front Wall.

Figure A-2. Double Beam Separating Burner Section from Specimen Exposure Area.

Figure A-3. Gas Burner.

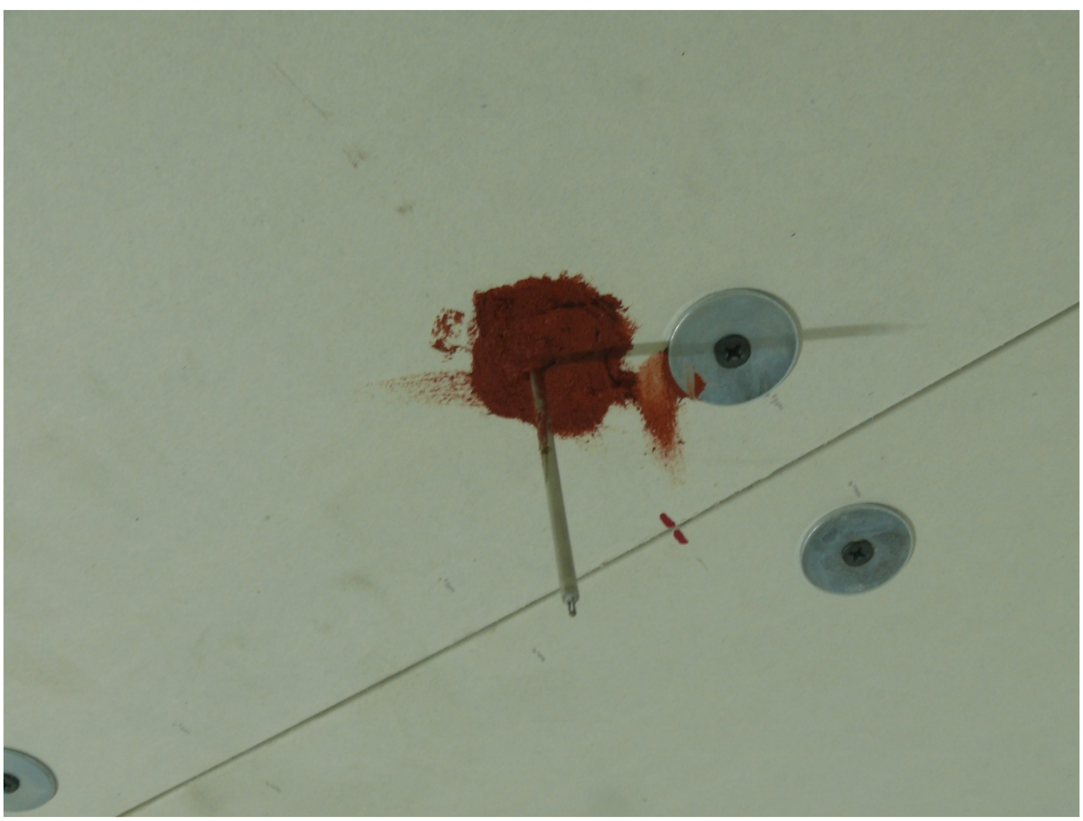

Figure A-4. Hot Gas Layer Thermocouple.

Figure A-5. Door Thermocouple Tree

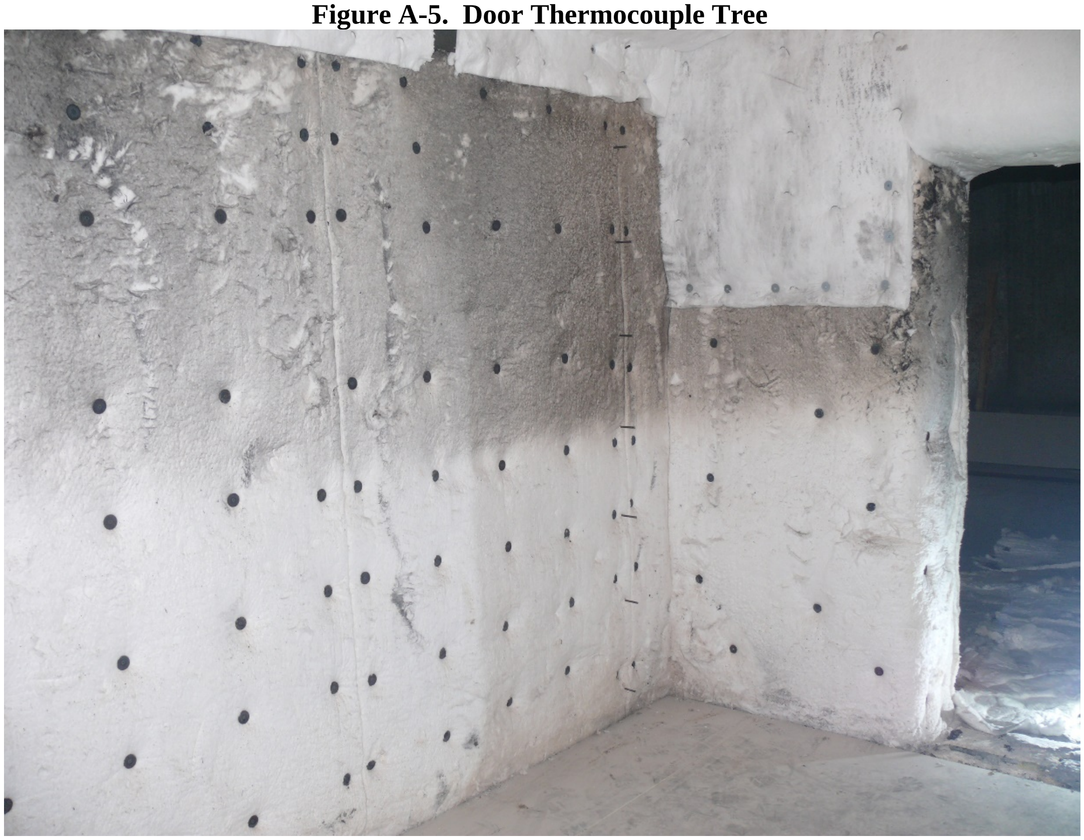

Figure A-6. Room Thermocouple Tree.

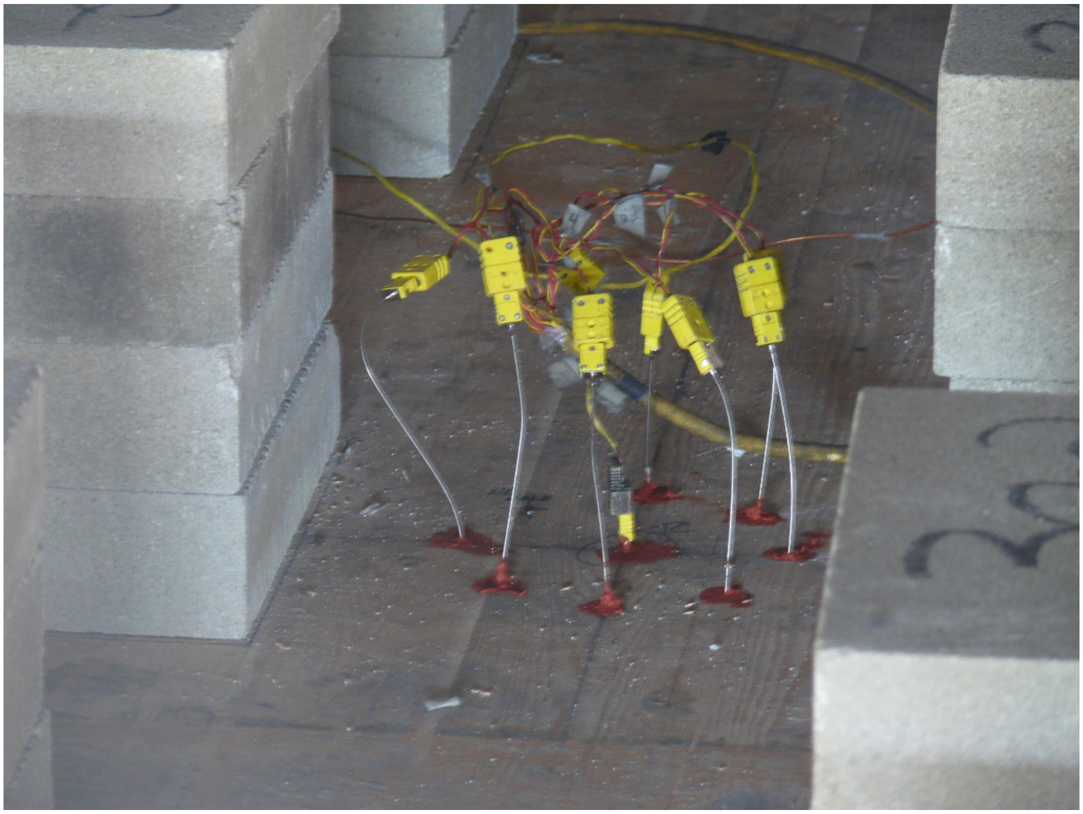

Figure A-7. Embedded Thermocouples.

Figure A-8. Directional Flame Thermometers (DFTs).

Figure A-9. **Applied Structural Load.**

APPENDIX B

CLT #1

TEST PHOTOGRAPHS

(CONSISTING OF 13 PAGES)

Figure B-1. **CLT #1 Prior to Testing.**

Figure B-2. CLT #1 Test at 1 min.

Figure B-3. CLT #1 Test at 12 min.

Figure B-4. CLT #1 Test at 14 min 5 s: Ignition of Gypsum Board Paper at Burner.

Figure B-5. CLT #1 Test at 14 min 40 s: Flames on Floor Spread to Door.

Figure B-6. CLT #1 Test at 37 min.

Figure B-7. CLT #1 Test at 39 min.

Figure B-8. **CLT #1 Test at 57 min 45 s.**

Figure B-9. CLT #1 Test at 60 min 25 s.

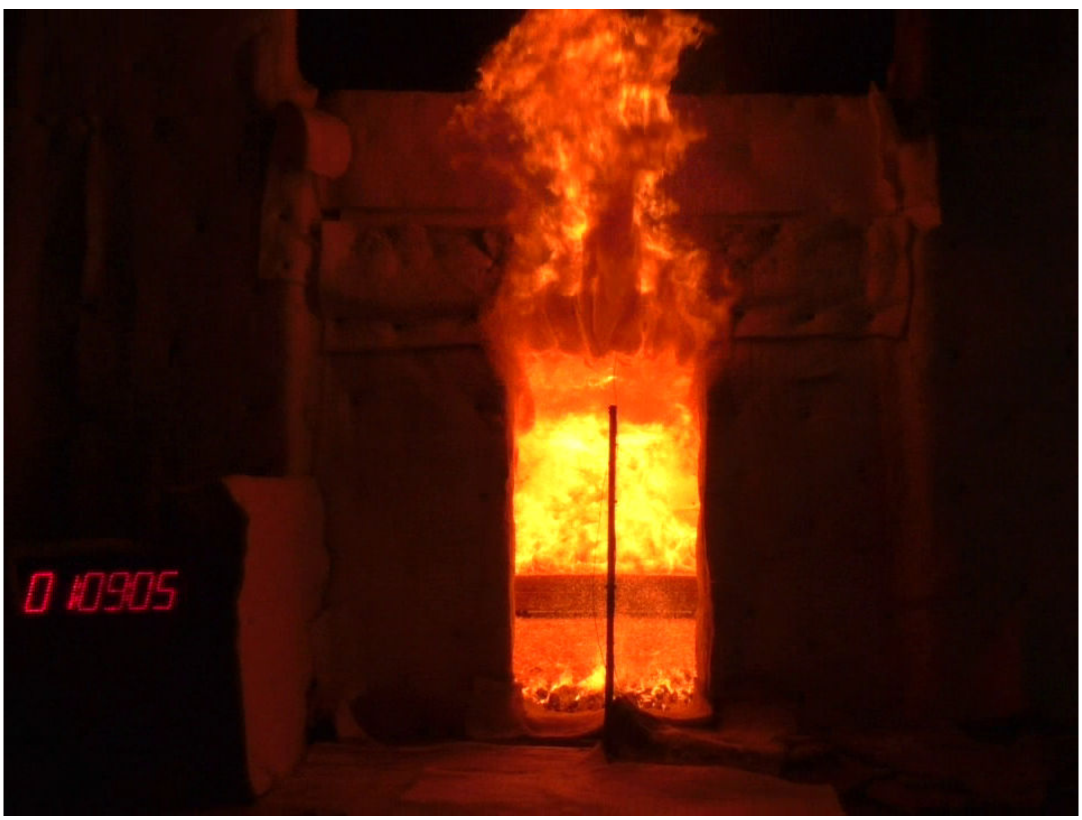

Figure B-10. **CLT #1 Test at 69 min 5 s.**

Figure B- 11. CLT #1 Test at 87 min.

Figure B- 12. CLT #1 Test at 89 min.

Figure B-13. CLT #1 Test at 140 min.

Figure B-14. CLT #1 Test at 140 min 30s.

Figure B-15. **CLT #1 Test at 144 min.**

Figure B-16. CLT #1 Test at 179 min.

Figure B- 17. CLT #1 Test at 179 min 45 s.

Figure B-18. CLT #1 Test at 188 min.

Figure B-19. CLT #1 Test at 190 min 35 s.

Figure B-20. CLT #1 Test at 191 min 30 s: Start of Extinguishment.

Figure B-21. **CLT #1 Test at 191 min 33 s: Ceiling Fire Extinguished.**

Figure B-22. CLT #1 Test: Post-Test Picture of CLT Following Extinguishment.

Figure B-23. **CLT #1 Test: Post-Test Picture of Charred Wood on Floor.**

Figure B- 24. **CLT #1 Test: Post-Test Picture of CLT Removed from Test Structure.**

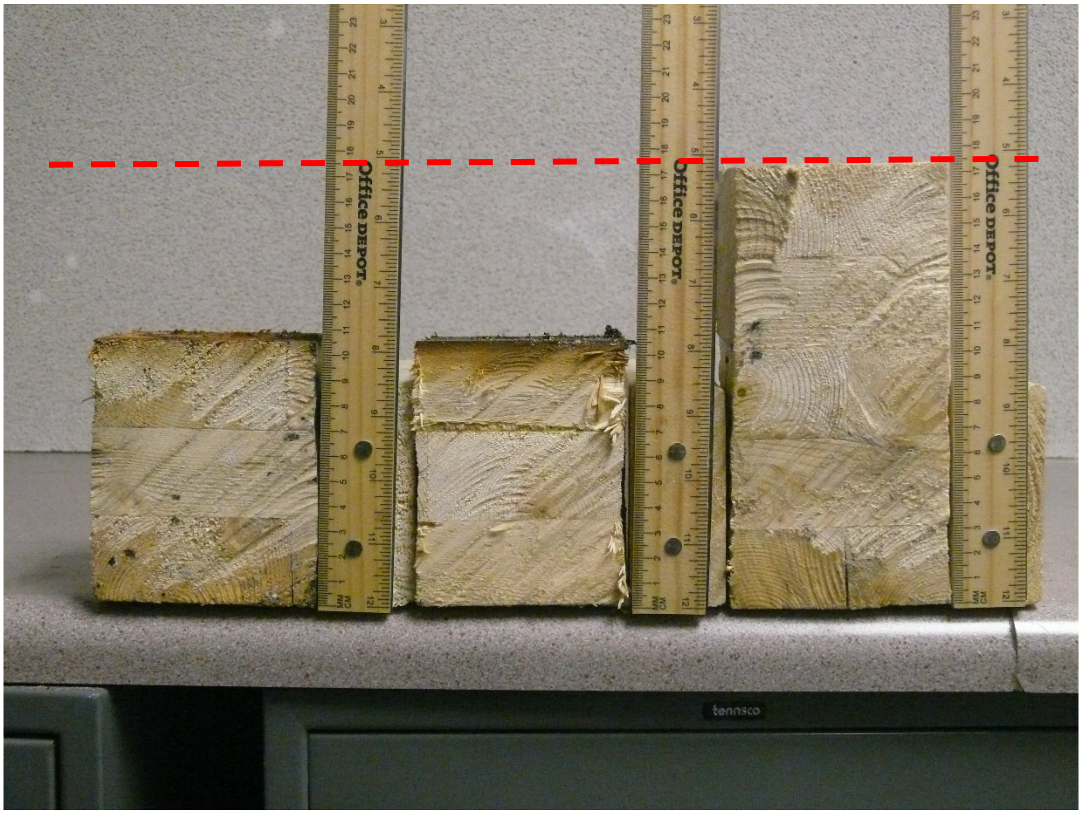

Figure B- 25. **CLT #1 Char Depth: Front Left – Front Right - Original.**

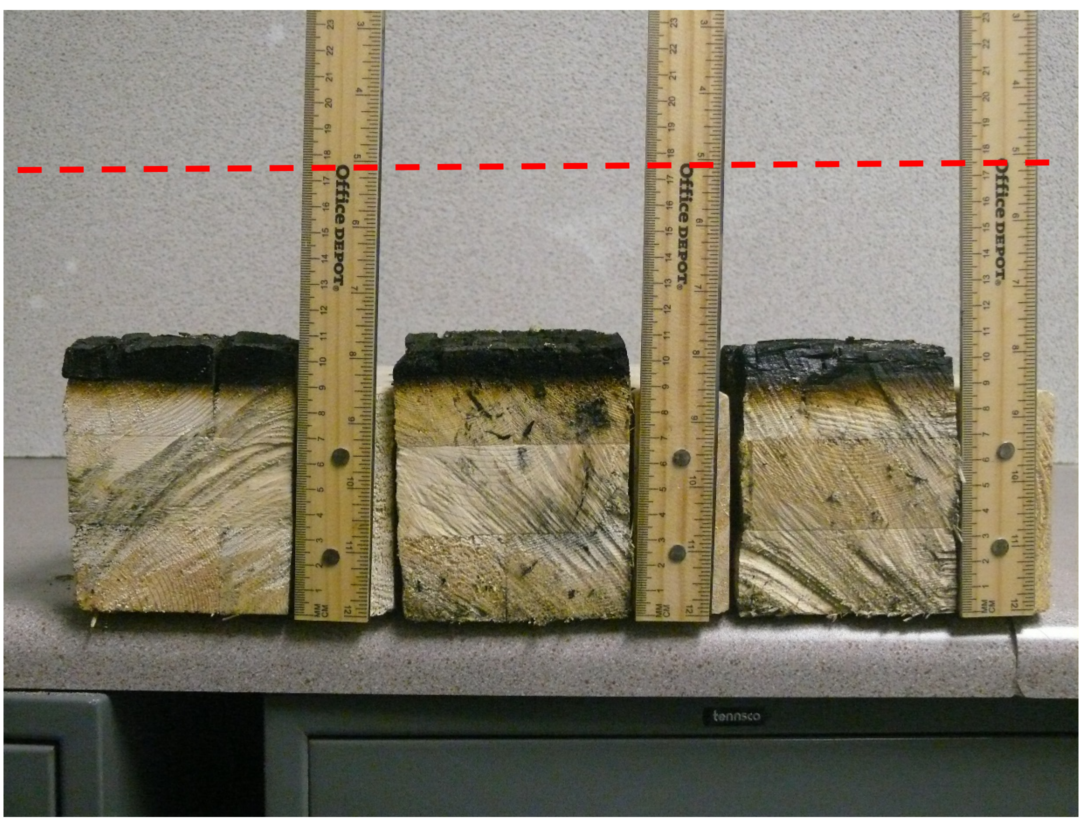

Figure B- 26. **CLT #1 Char Depth: Back Left – Ceiling Center – Back Right.**

APPENDIX C

CLT #1

GRAPHICAL TEST RESULTS

(CONSISTING OF 5 PAGES)

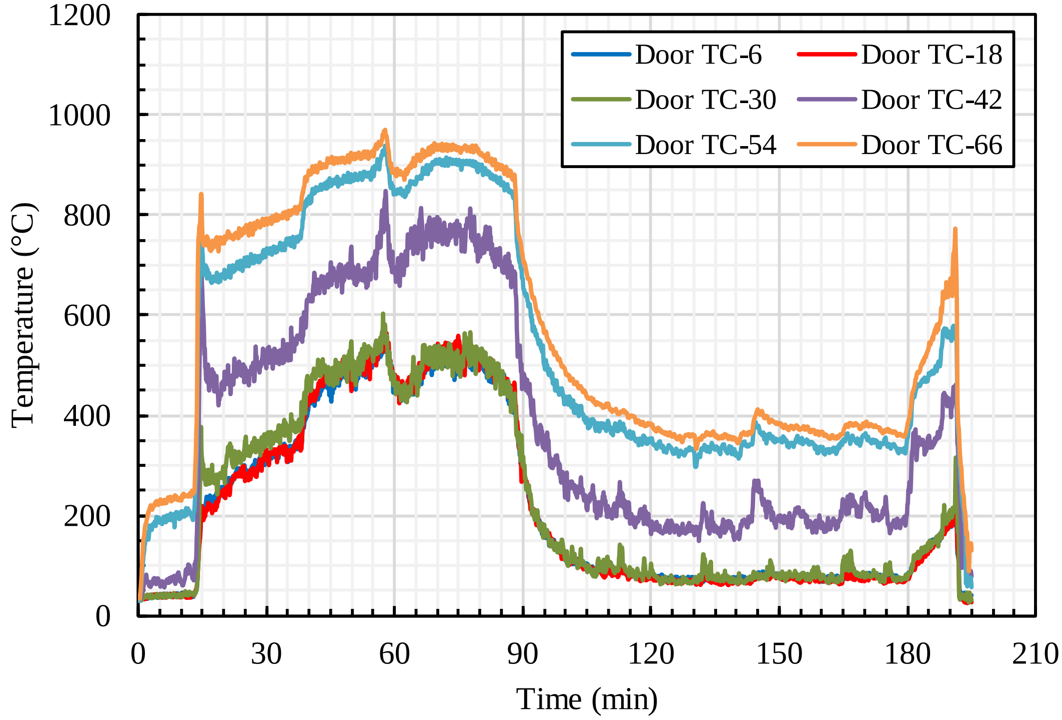

Figure C-1. CLT #1 Test: Door TC Tree Temperatures.

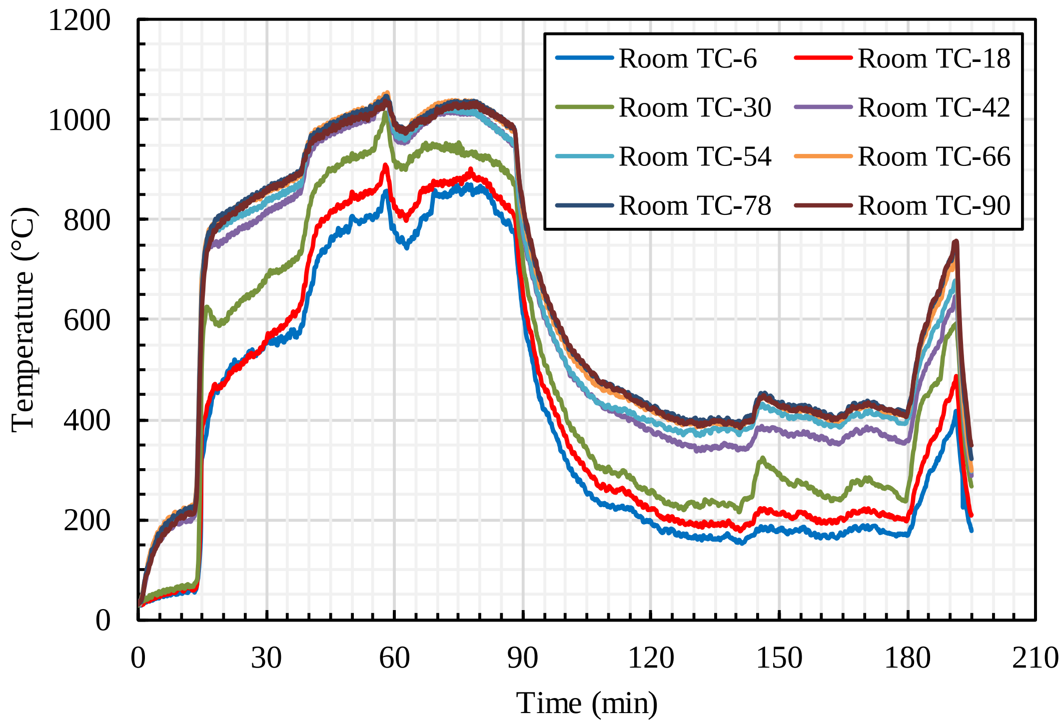

Figure C-2. CLT #1 Test: Room TC Tree Temperatures.

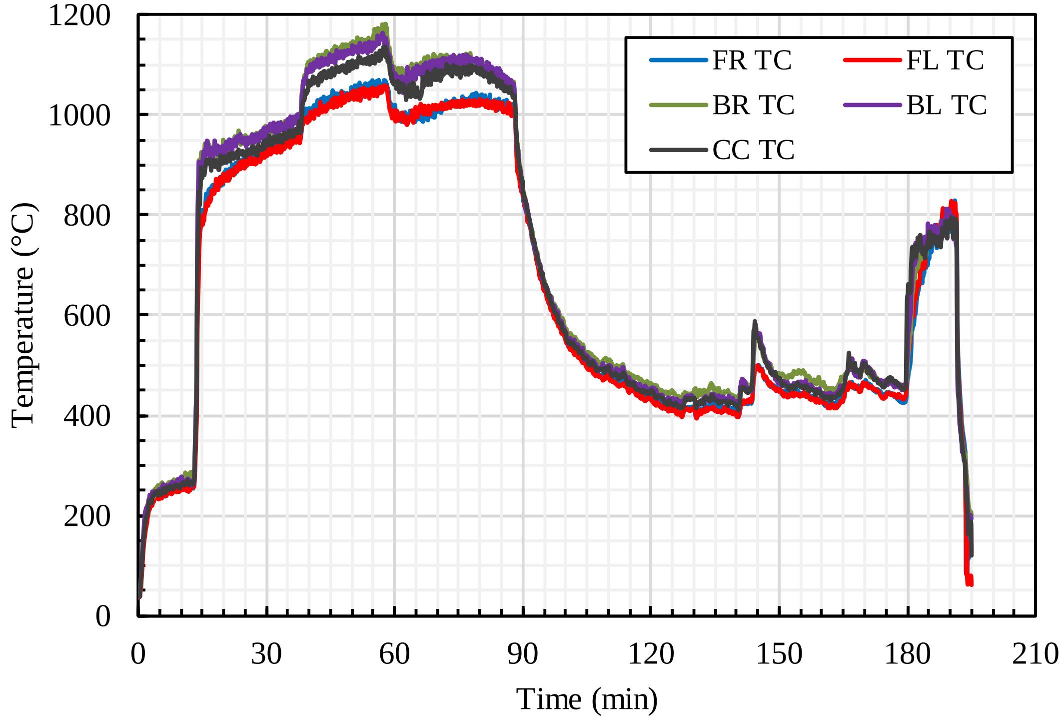

Figure C-3. CLT #1 Test: Ceiling TC Temperatures.

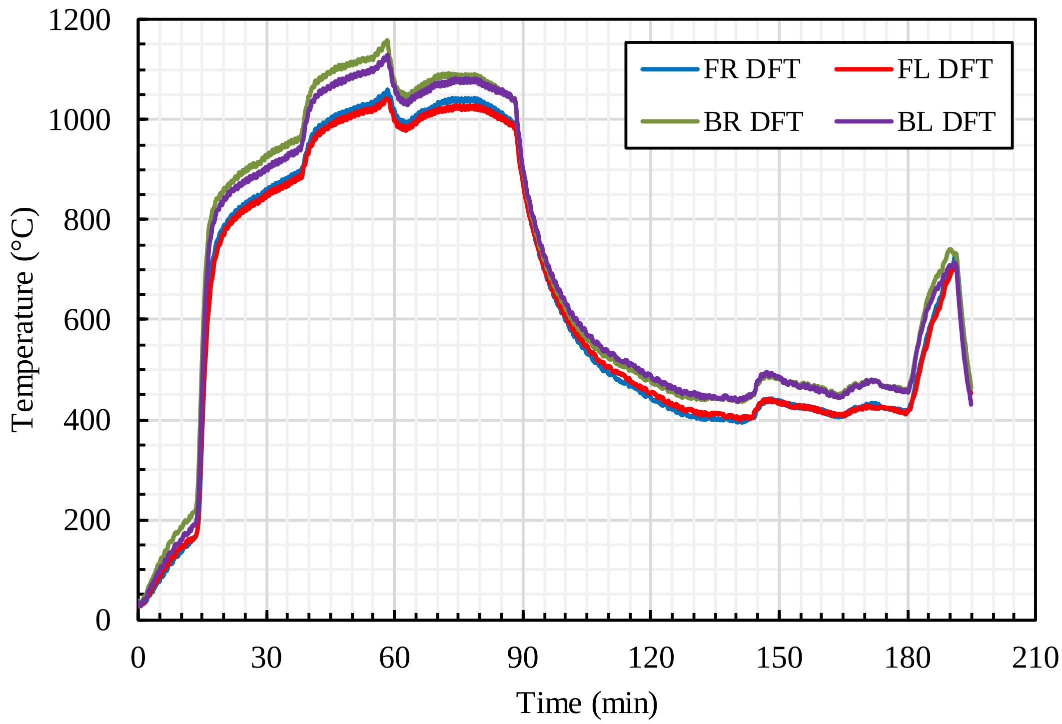

Figure C-4. CLT #1 Test: DFT Exposed Plate Temperatures.

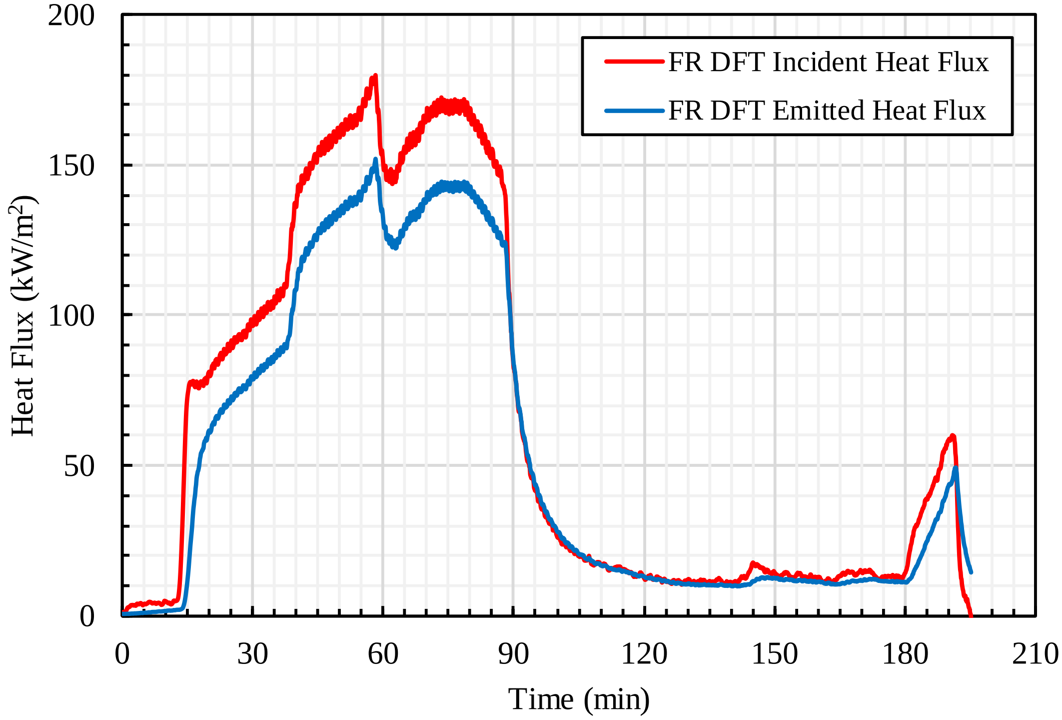

Figure C-5. CLT #1 Test: Front Right DFT Heat Flux.

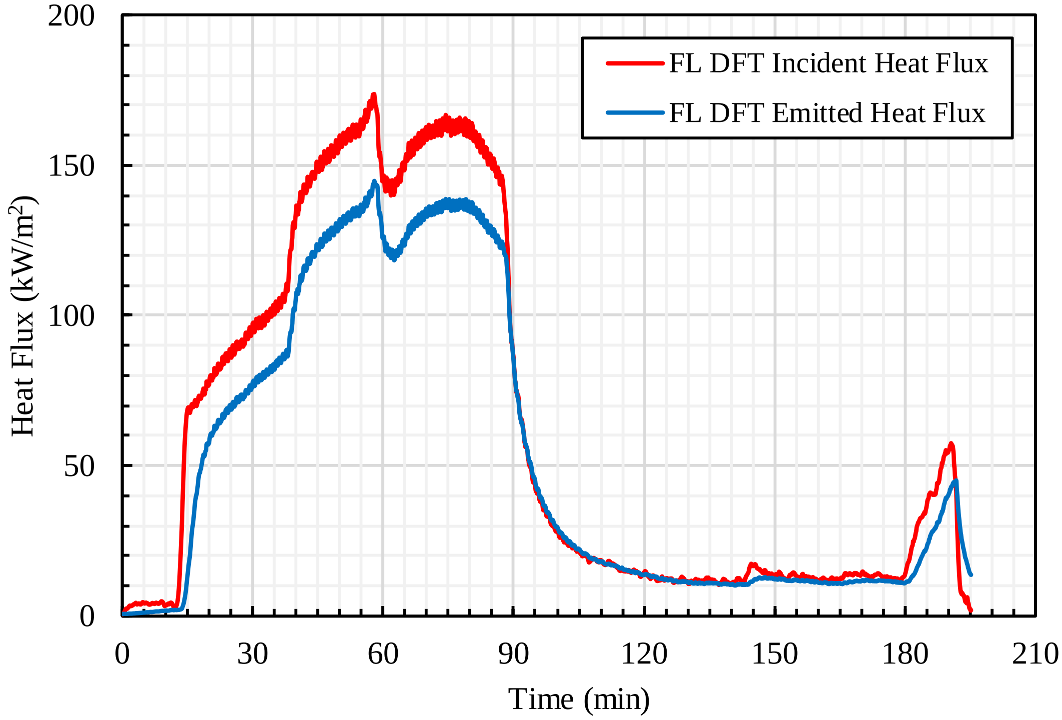

Figure C-6. CLT #1 Test: Front Left DFT Heat Flux.

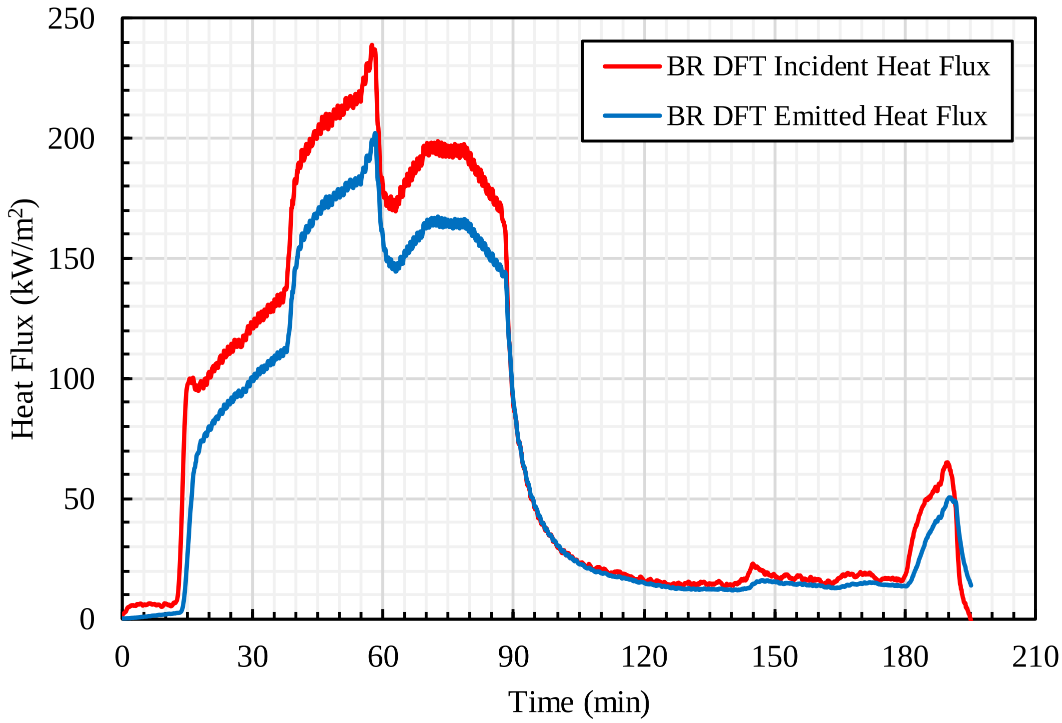

Figure C-7. CLT #1 Test: Back Right DFT Heat Flux.

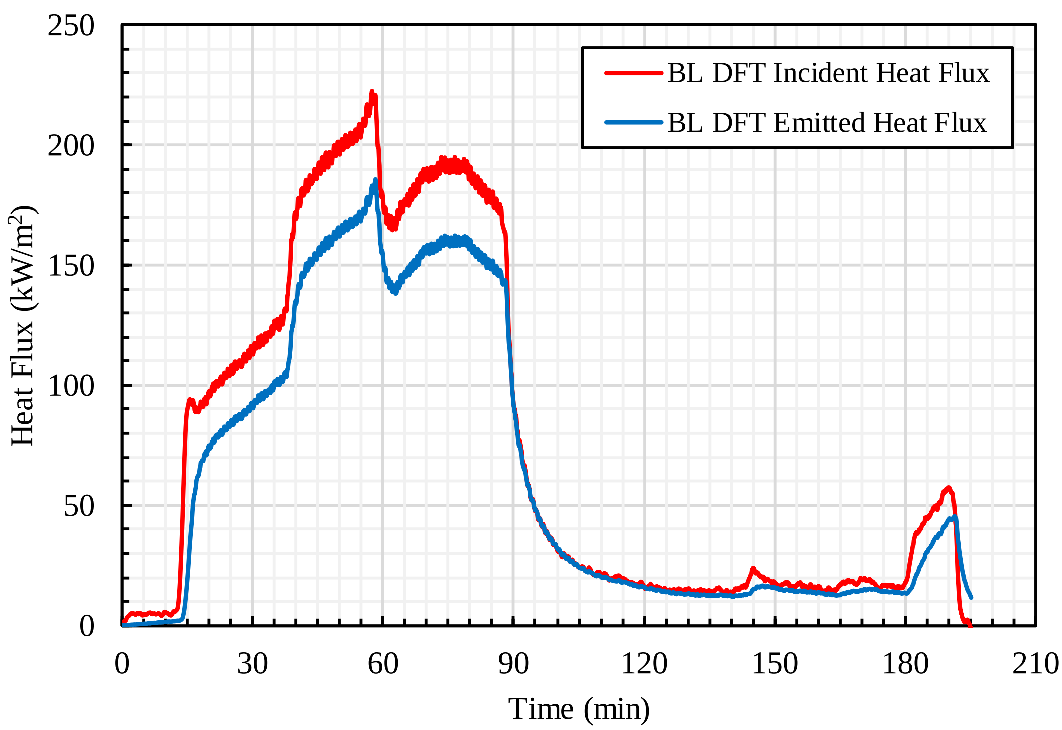

Figure C-8. CLT #1 Test: Back Left DFT Heat Flux.

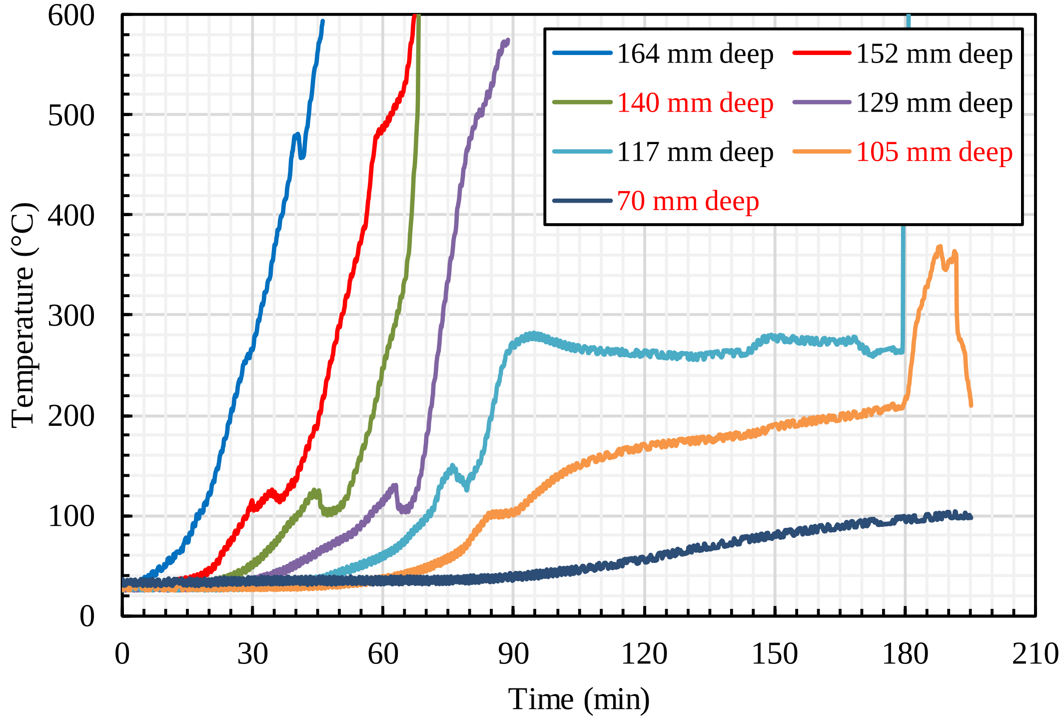

Figure C-9. CLT #1 Test: Embedded TC Temperatures.

APPENDIX D

CLT #2

TEST PHOTOGRAPHS

(CONSISTING OF 11 PAGES)

Figure D-1. CLT #2 Prior to Testing.

Figure D-2. CLT #2 Test at 1 min.

Figure D-3. CLT #2 Test at 12 min.

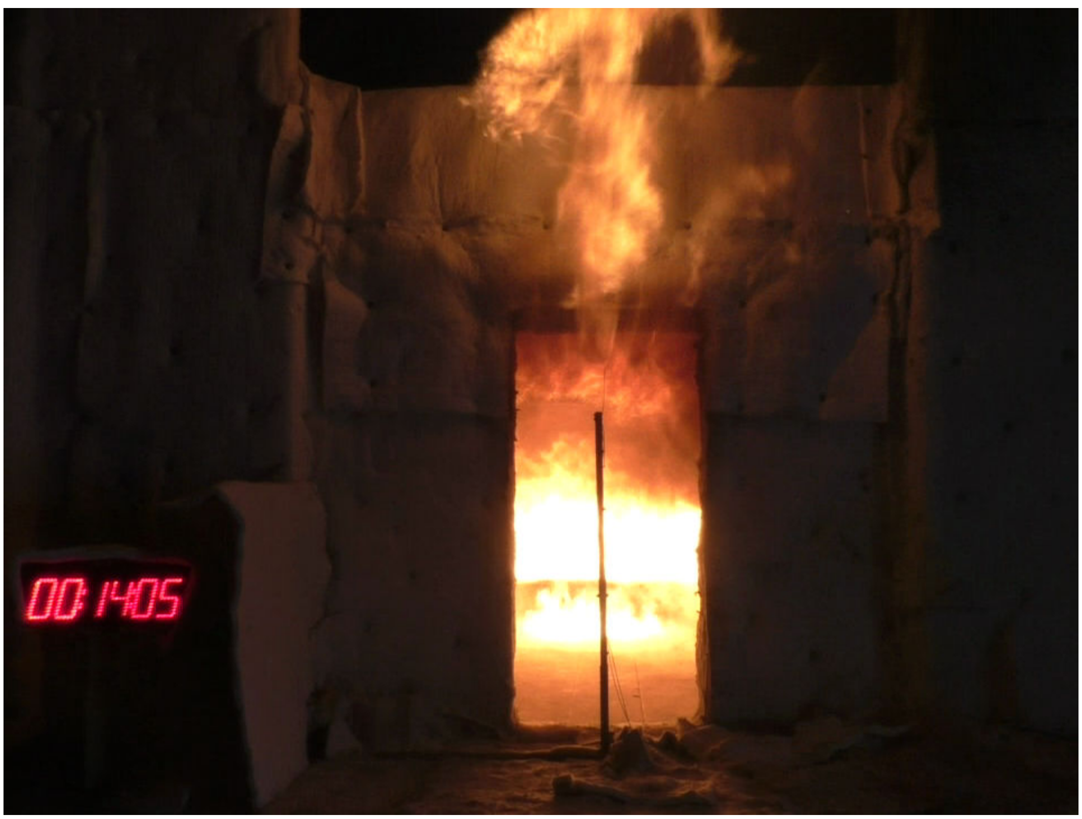

Figure D-4. CLT #2 Test at 14 min 5 s: Ignition of Gypsum Board Paper at Burner.

Figure D-5. CLT #2 Test at 14 min 40 s: Flames on Floor Spread to Door.

Figure D-6. CLT #2 Test at 37 min.

Figure D-7. CLT #2 Test at 39 min.

Figure D-8. CLT #2 Test at 57 min.

Figure D-9. CLT #2 Test at 59 min.

Figure D-10. CLT #2 Test at 87 min.

Figure D-11. CLT #2 Test at 89 min.

Figure D-12. CLT #2 Test at 120 min.

Figure D-13. CLT #2 Test at 150 min.

Figure D-14. CLT #2 Test at 180 min.

Figure D-15. CLT #2 Test at 210 min.

Figure D-16. End of CLT #2 Test at 212 min.

Figure D-17. CLT #2 Test: Post-Test Picture of CLT Following Extinguishment.

Figure D-18. CLT #2 Test: Post-Test Picture of Charred Wood on Floor.

Figure D-19. CLT #2 Test: Post-Test Picture of CLT Removed from Test Structure.

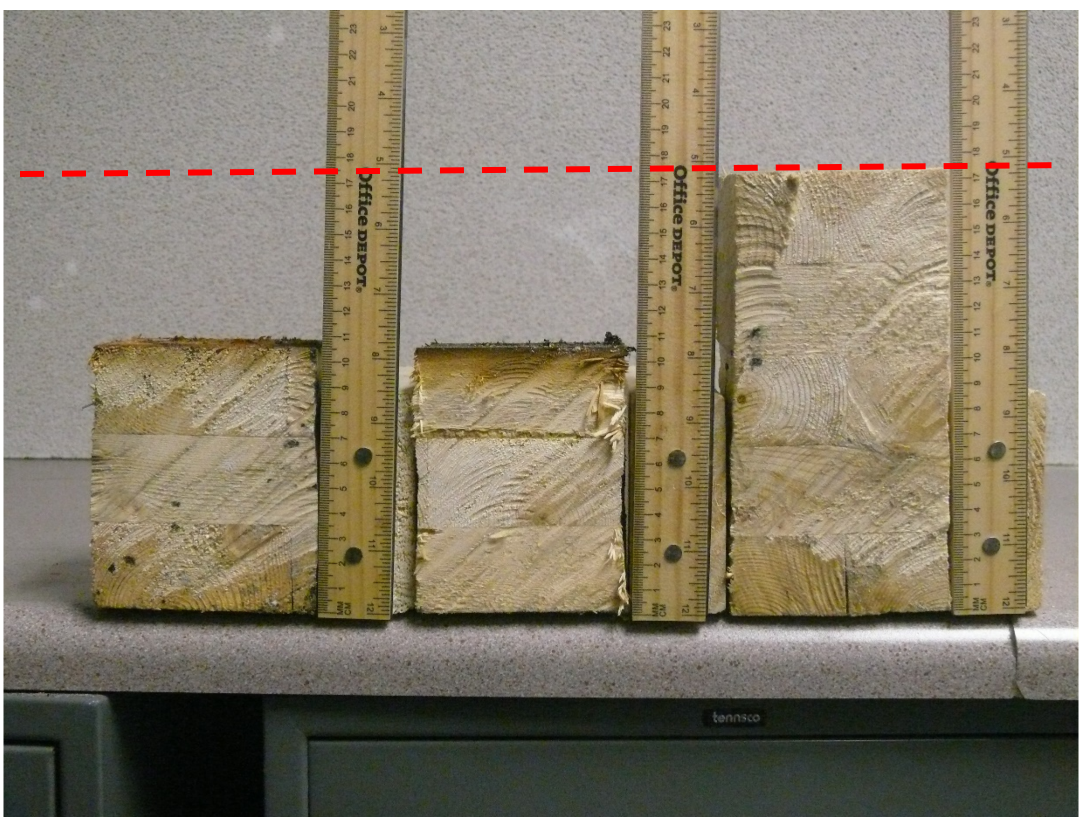

Figure D-20. CLT #2 Char Depth: Front Left – Front Right - Original.

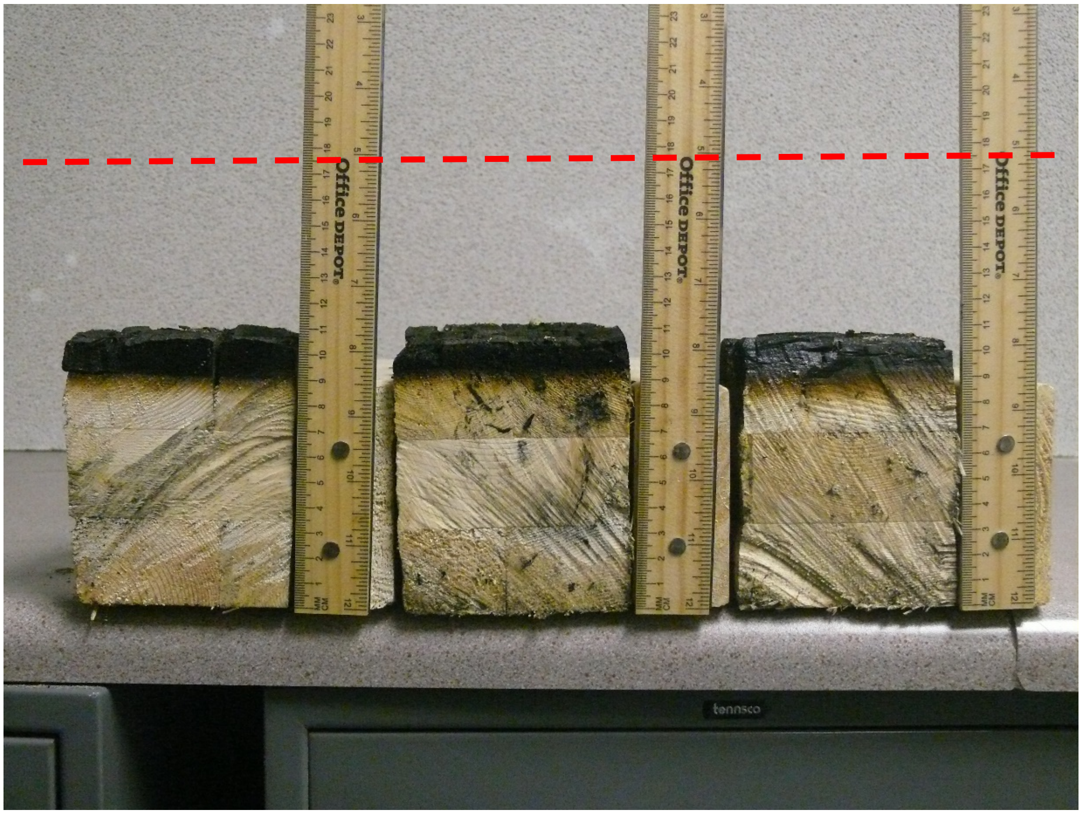

Figure D-21. CLT #2 Char Depth: Back Left – Ceiling Center – Back Right.

APPENDIX E

CLT #2

GRAPHICAL TEST RESULTS

(CONSISTING OF 5 PAGES)

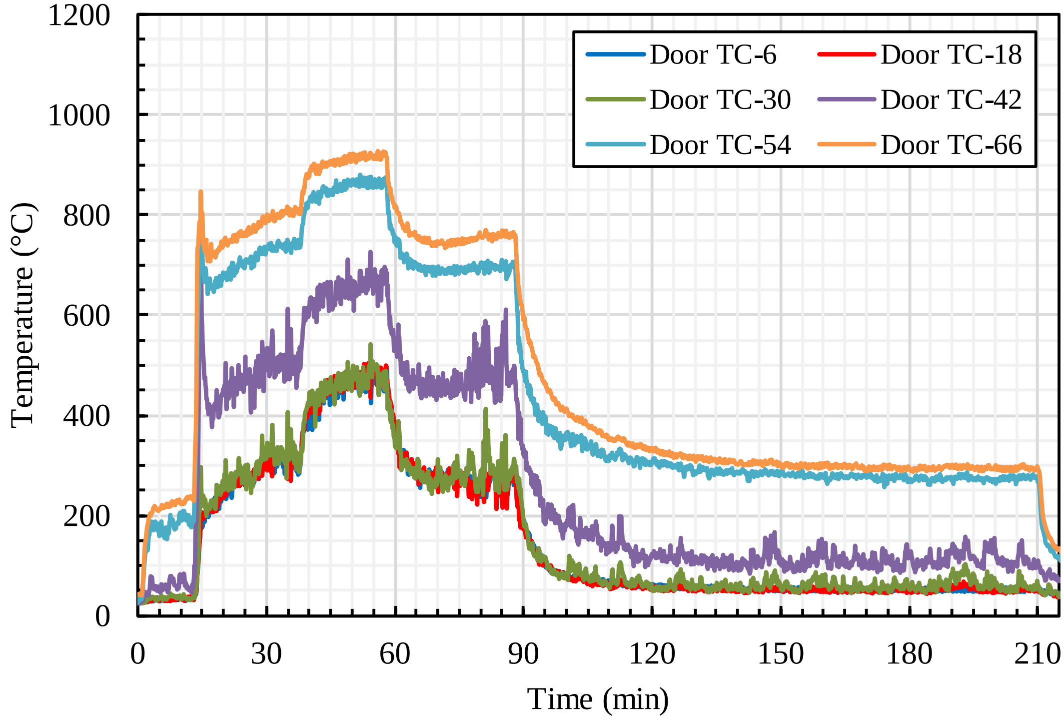

Figure E-1. CLT #2 Test: Door TC Tree Temperatures.

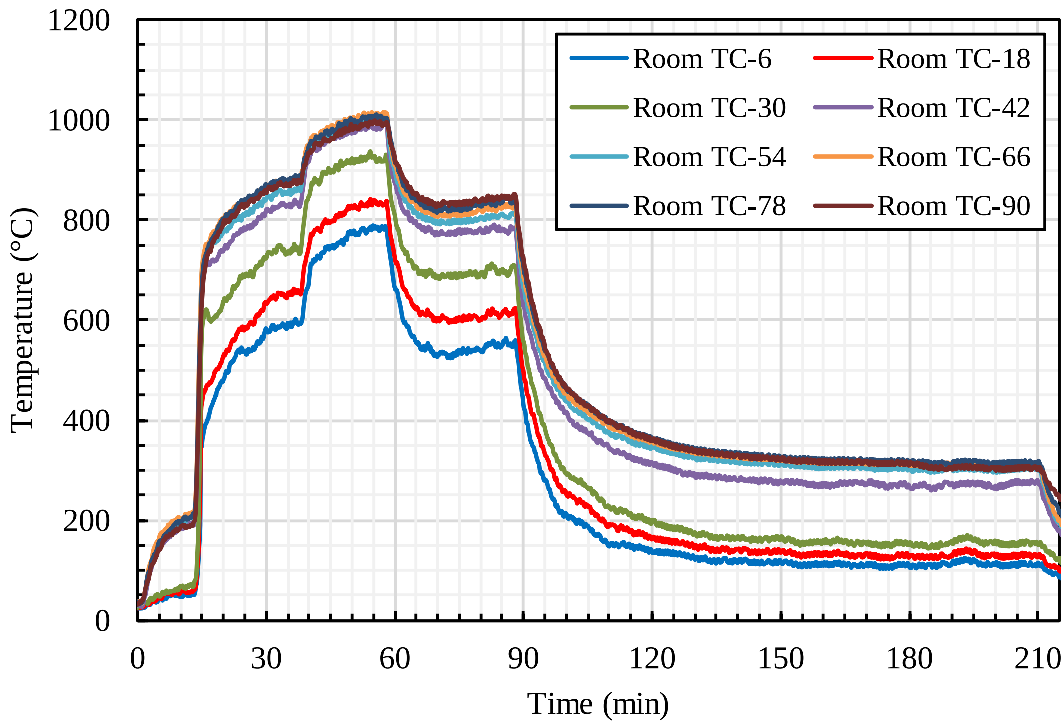

Figure E-2. CLT #2 Test: Room TC Tree Temperatures.

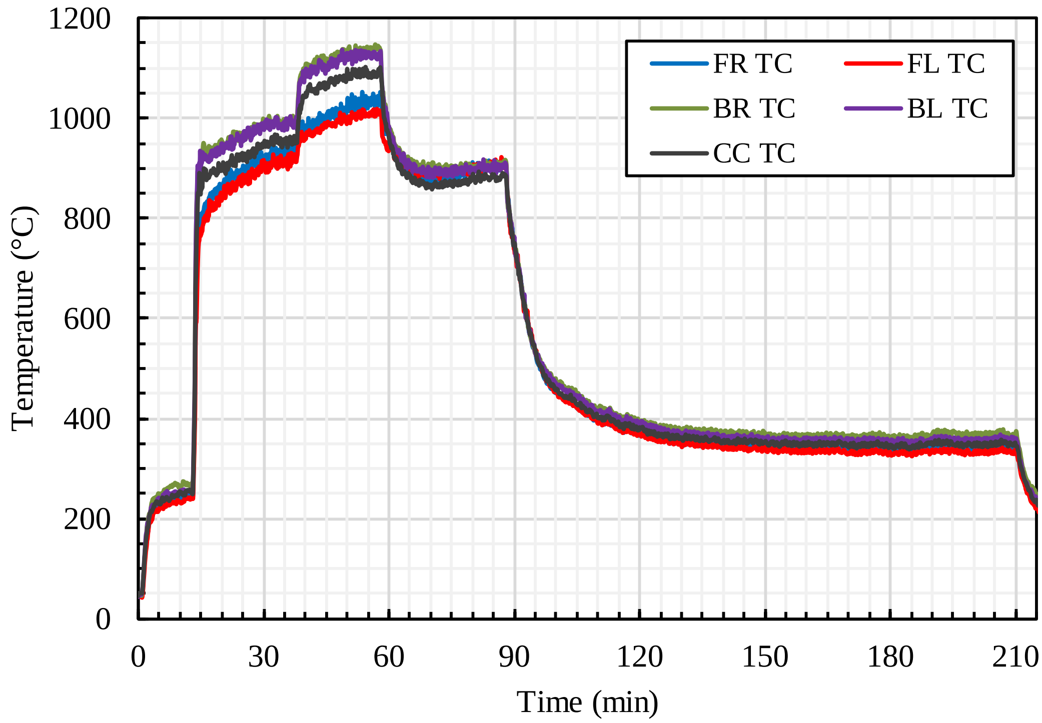

Figure E-3. CLT #2 Test: Ceiling TC Temperatures.

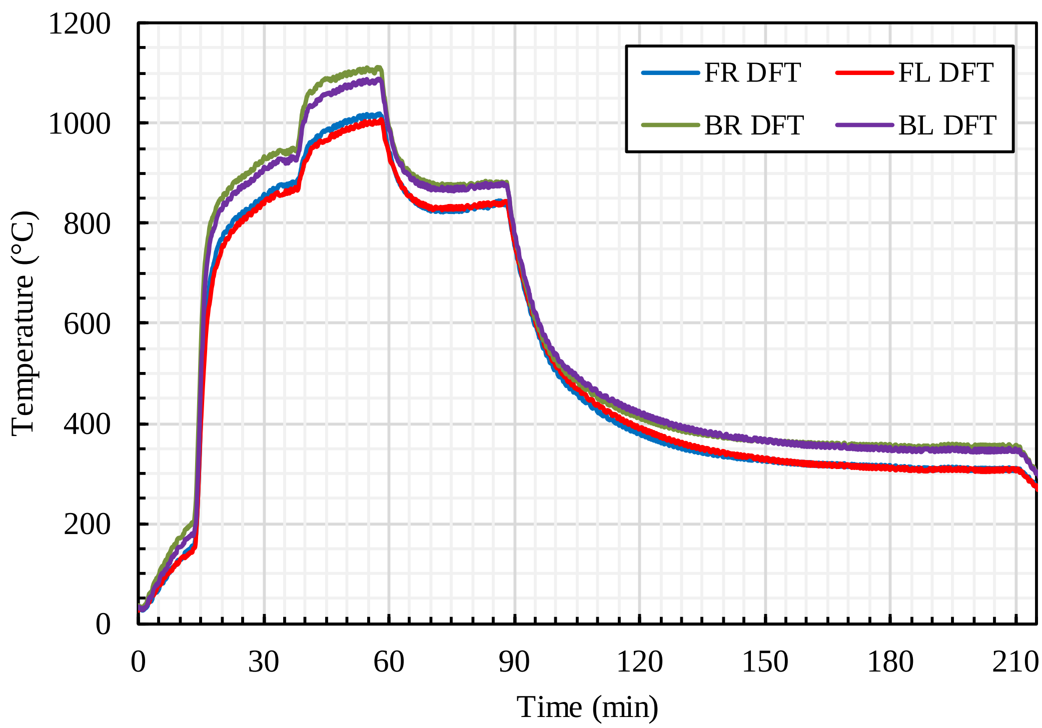

Figure E-4. CLT #2 Test: DFT Exposed Plate Temperatures.

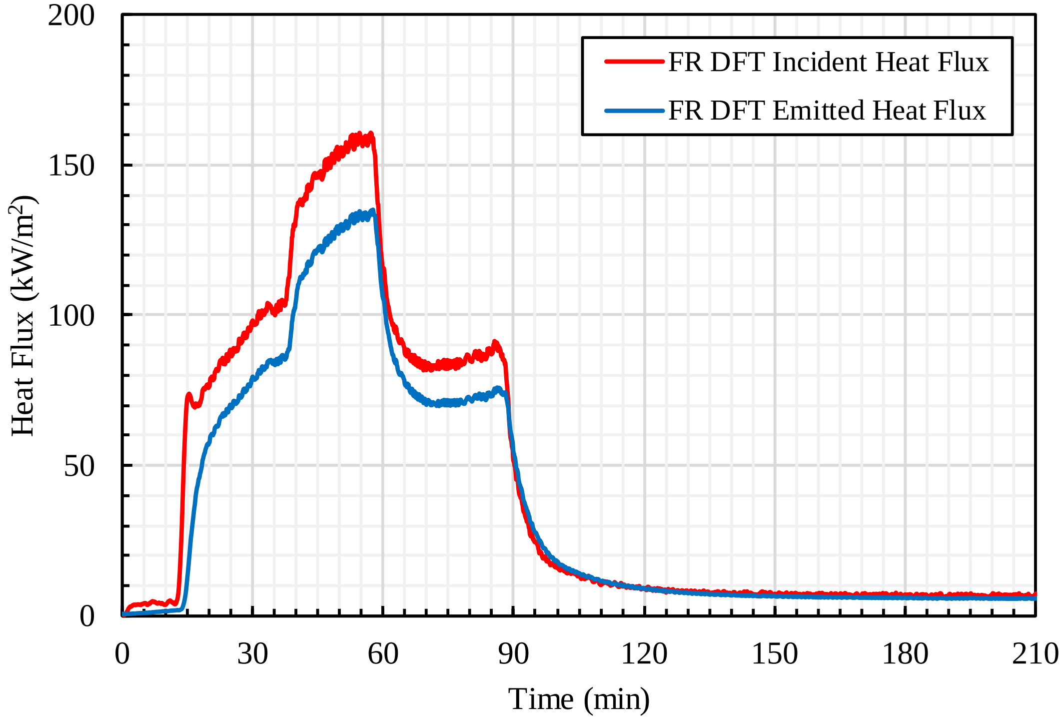

Figure E-5. CLT #2 Test: Front Right DFT Heat Flux.

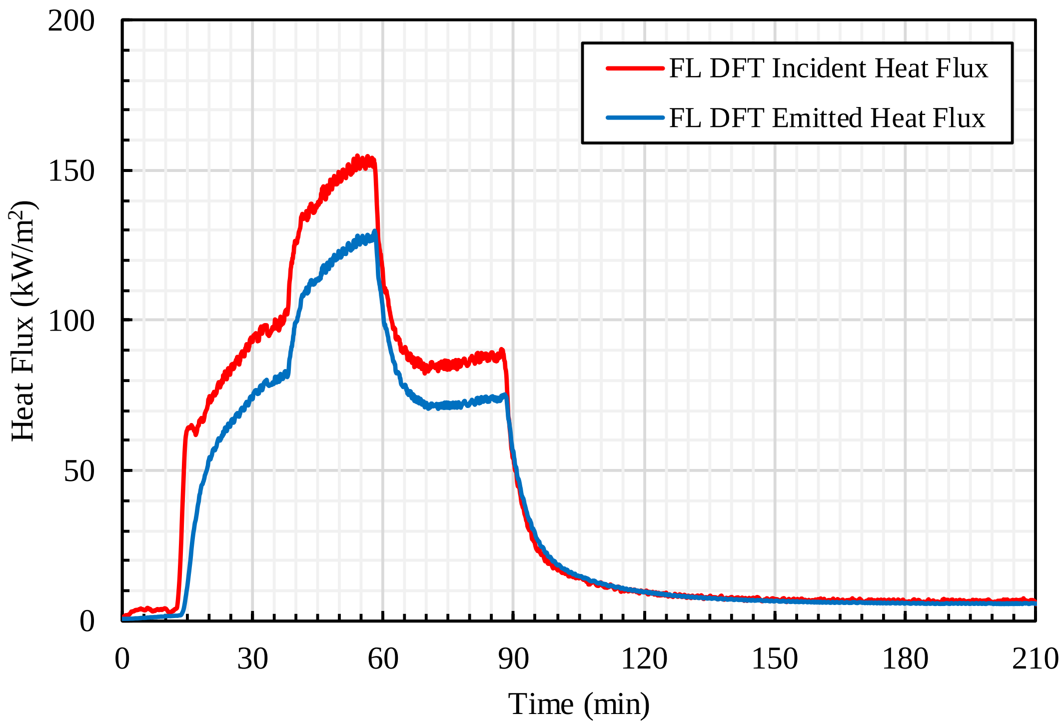

Figure E-6. CLT #2 Test: Front Left DFT Heat Flux.

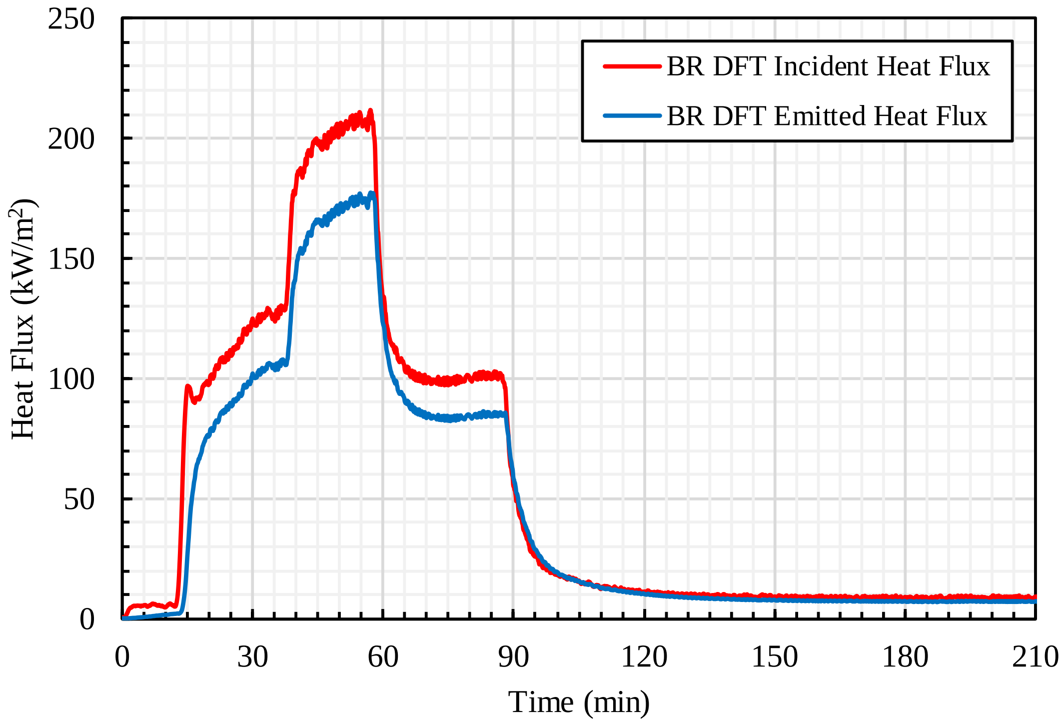

Figure E-7. CLT #2 Test: Back Right DFT Heat Flux.

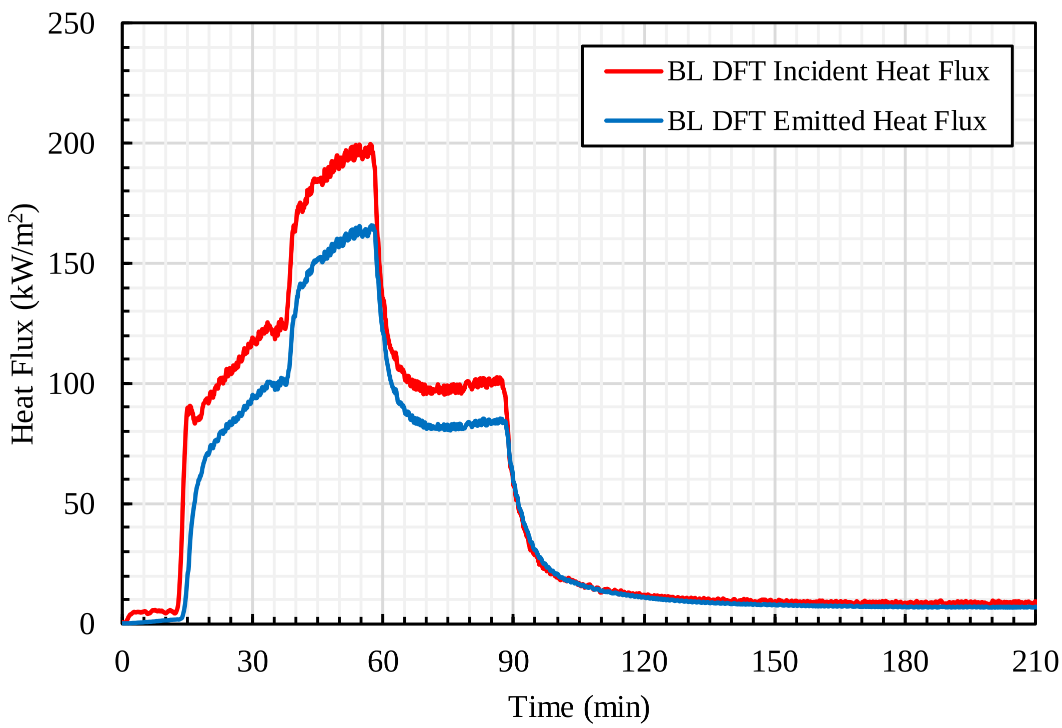

Figure E-8. CLT #2 Test: Back Left DFT Heat Flux.

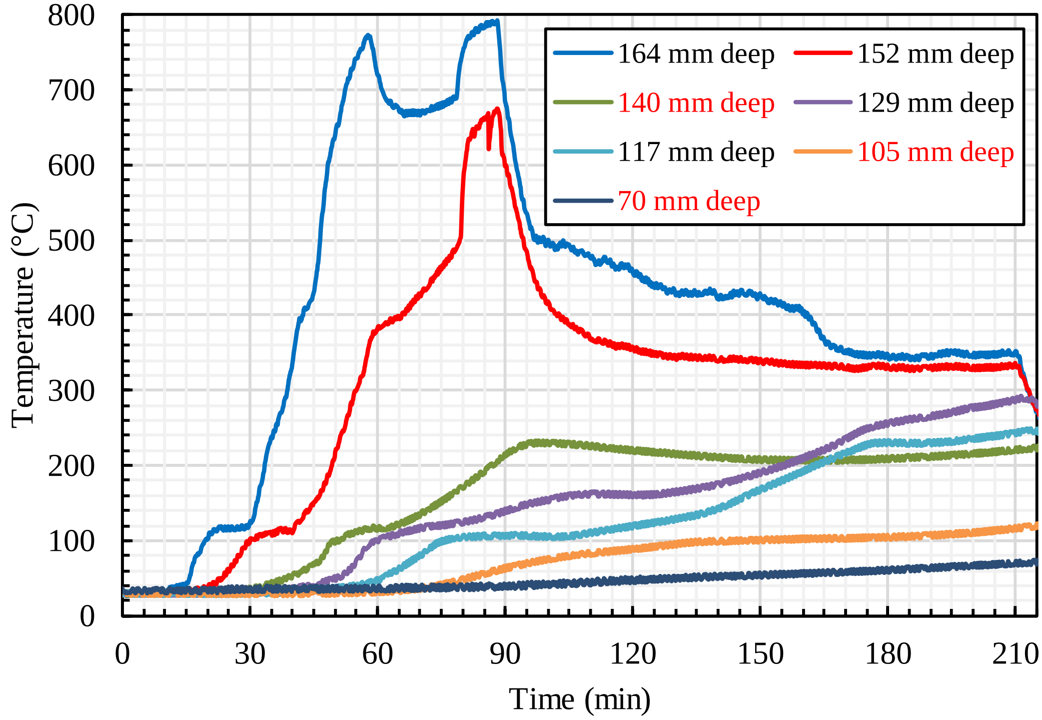

Figure E-9. CLT #2 Test: Embedded TC Temperatures.

APPENDIX F

CLT #3

TEST PHOTOGRAPHS

(CONSISTING OF 11 PAGES)

Figure F-1. CLT #3 Prior to Testing.

Figure F-2. CLT #3 Test at 1 min.

Figure F-3. CLT #3 Test at 12 min.

Figure F-4. CLT #3 Test at 13 min 47 s: Ignition of Gypsum Board Paper at Burner.

Figure F-5. CLT #2 Test at 14 min 30 s: Flames on Floor Spread to Door.

Figure F-6. CLT #3 Test at 37 min.

Figure F-7. CLT #3 Test at 39 min.

Figure F-8. CLT #3 Test at 57 min.

Figure F-9. CLT #3 Test at 59 min.

Figure F-10. CLT #3 Test at 87 min.

Figure F-11. CLT #3 Test at 89 min.

Figure F-12. CLT #3 Test at 120 min.

Figure F-13. CLT #3 Test at 150 min.

Figure F-14. CLT #3 Test at 180 min.

Figure F-15. CLT #3 Test at 210 min.

Figure F-16. CLT #3 Test at 240 min

Figure F-17. End of CLT #3 Test at 242 min.

Figure F-18. CLT #3 Test: Post-Test Picture of CLT Following Extinguishment.

Figure F-19. CLT #3 Test: Post-Test Picture of CLT Removed from Test Structure.

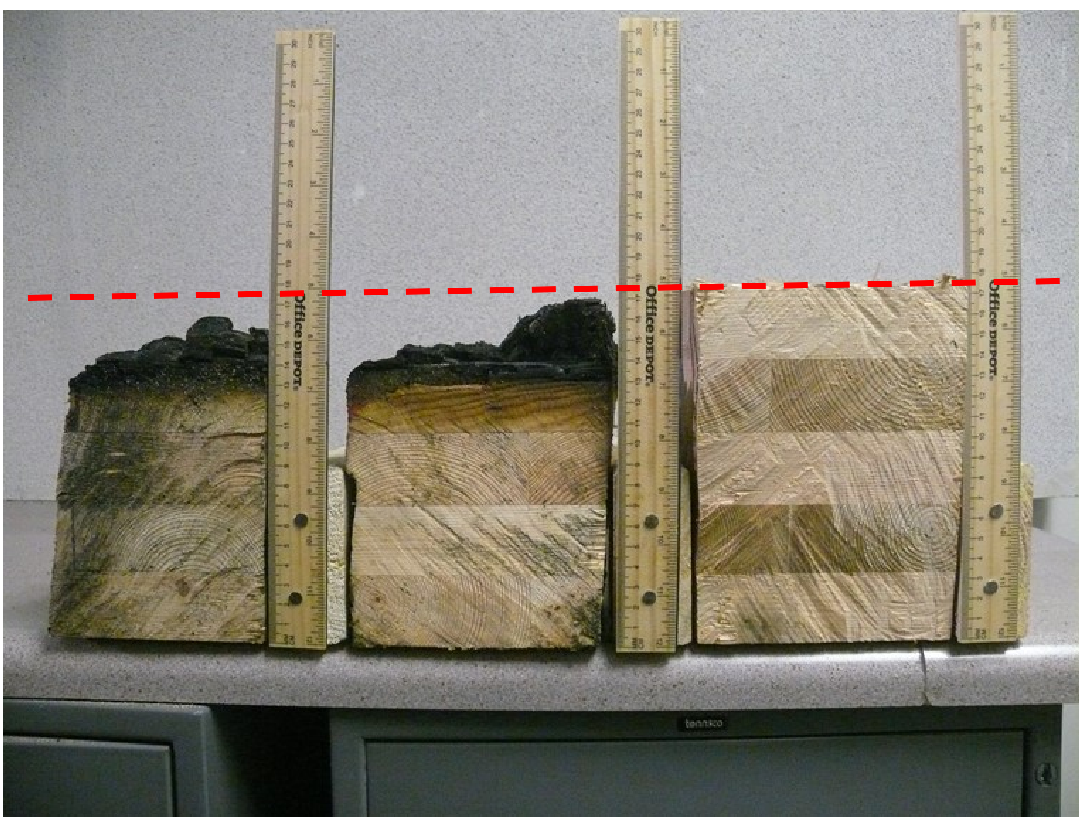

Figure F-20. CLT #3 Char Depth: Front Left – Front Right - Original.

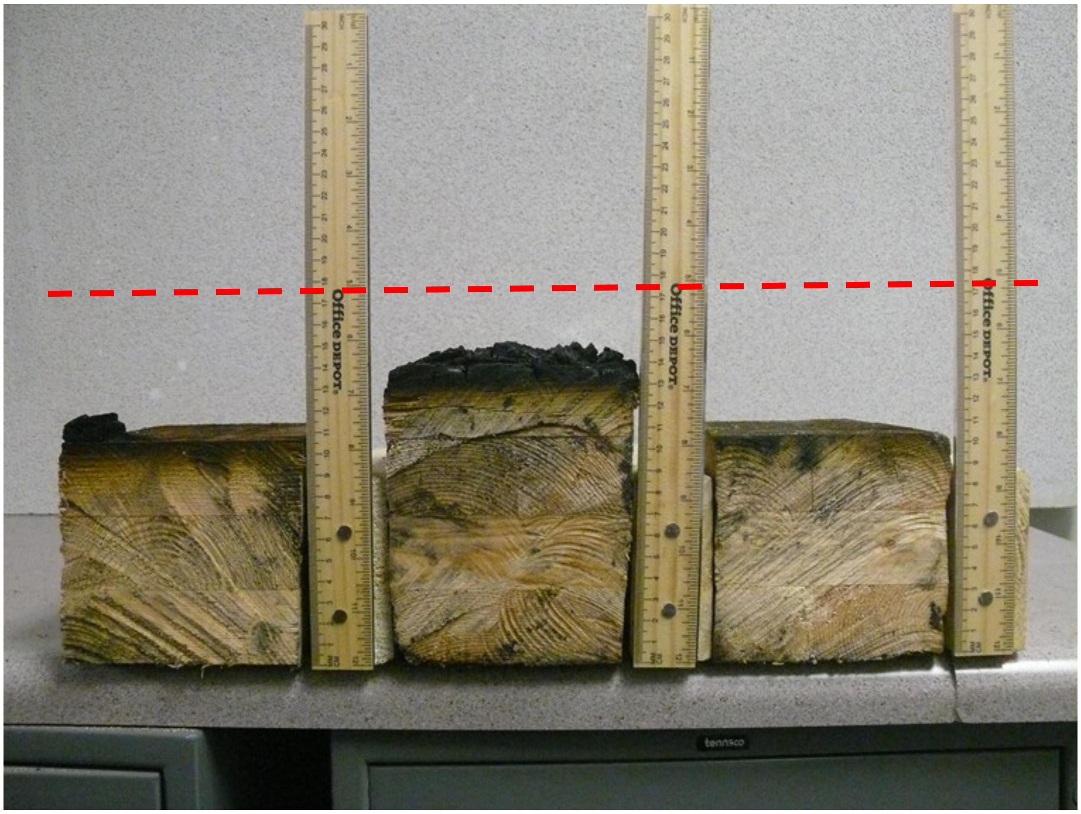

Figure F-21. CLT #3 Char Depth: Back Left – Ceiling Center – Back Right.

APPENDIX G

CLT #3

GRAPHICAL TEST RESULTS

(CONSISTING OF 5 PAGES)

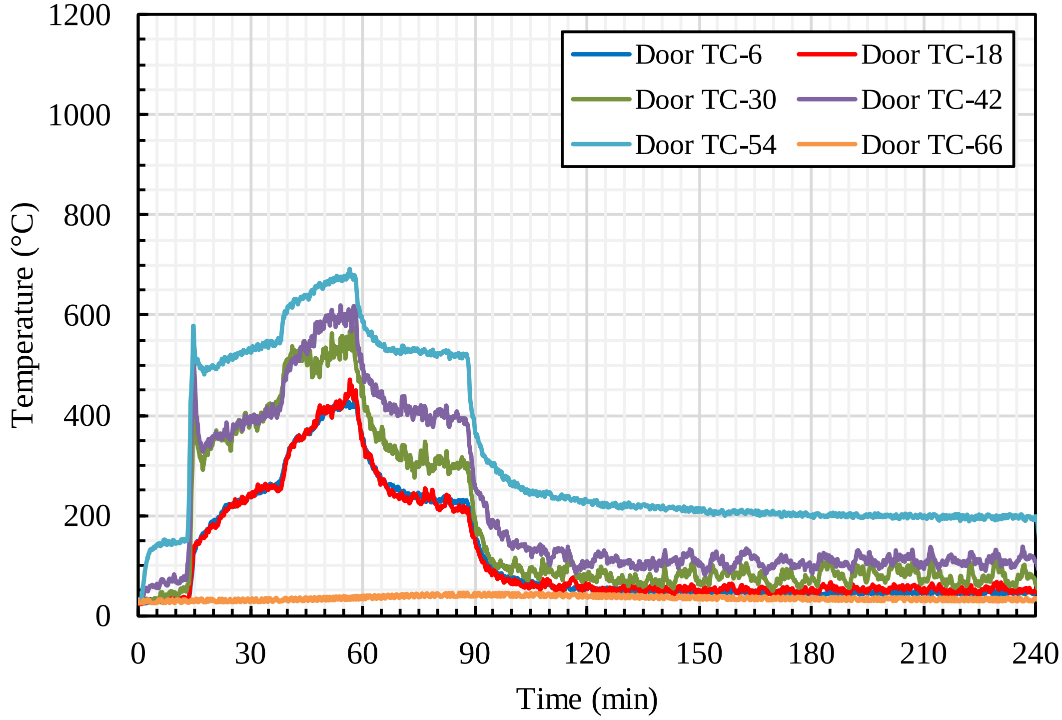

Figure G-1. CLT #3 Test: Door TC Tree Temperatures.

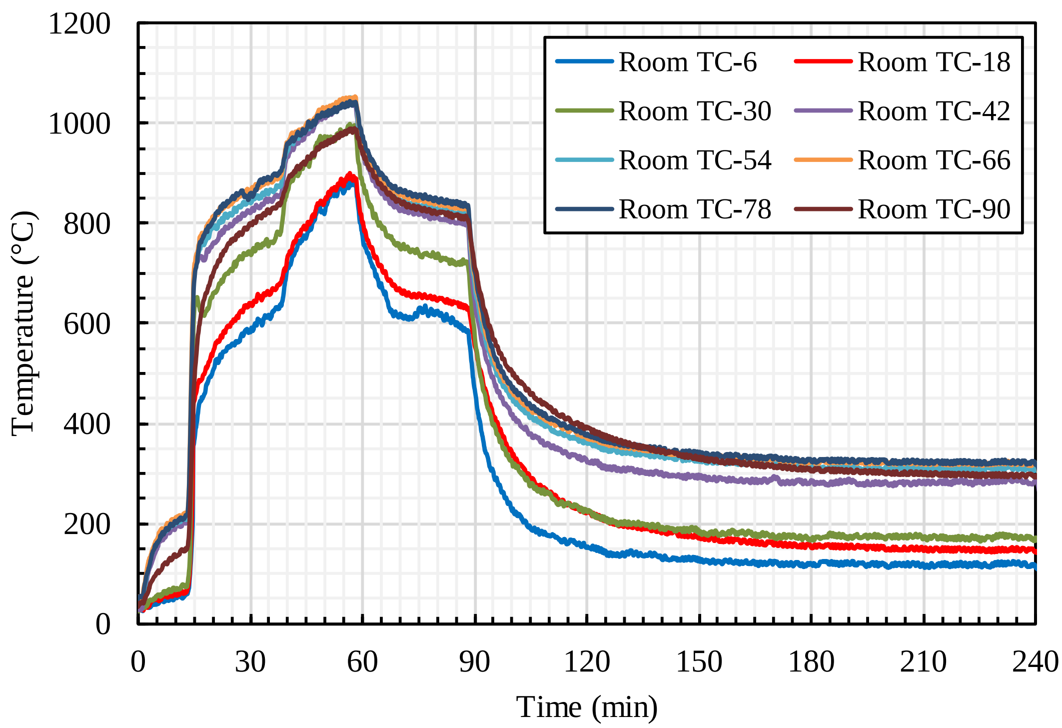

Figure G-2. CLT #3 Test: Room TC Tree Temperatures.

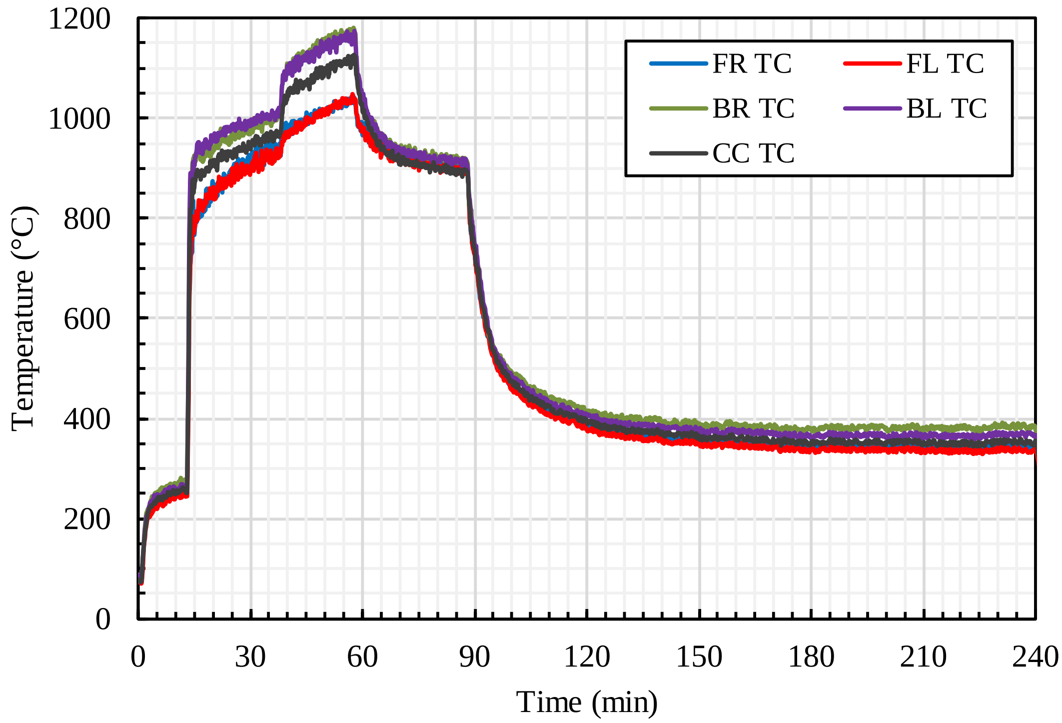

Figure G-3. CLT #3 Test: Ceiling TC Temperatures.

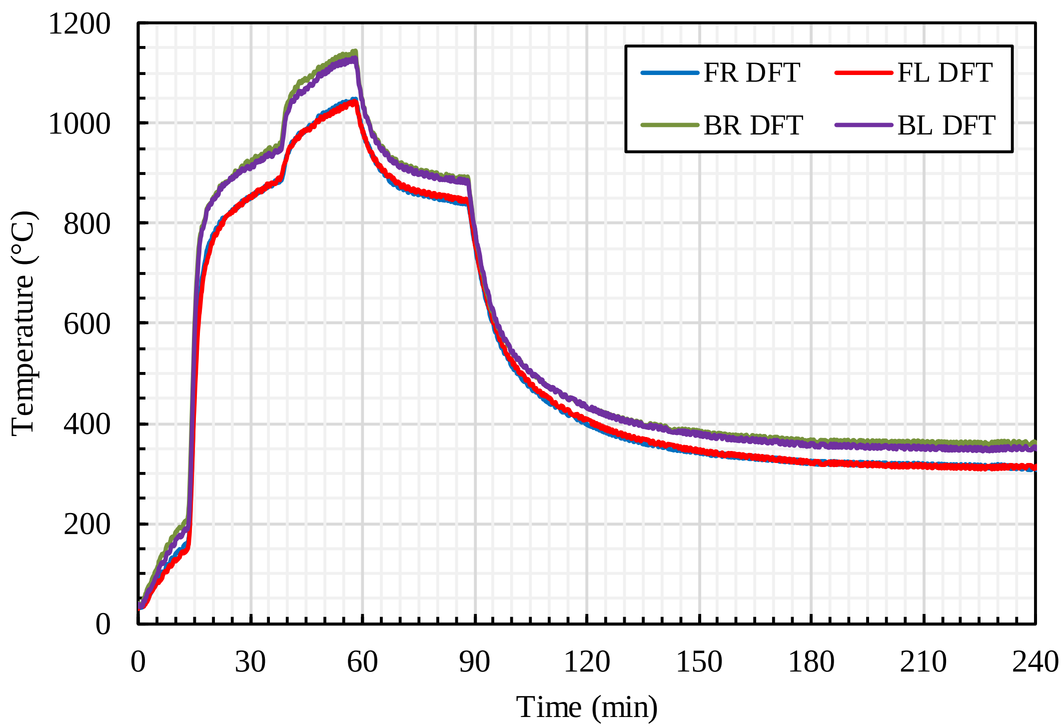

Figure G-4. CLT #3 Test: DFT Exposed Plate Temperatures.

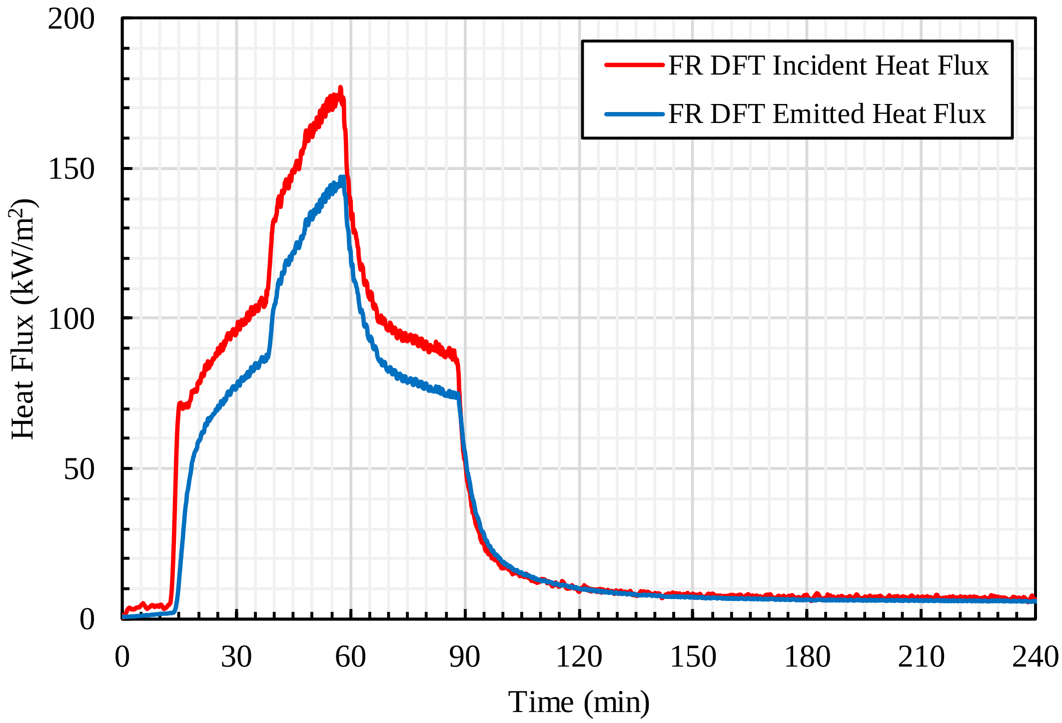

Figure G-5. CLT #3 Test: Front Right DFT Heat Flux.

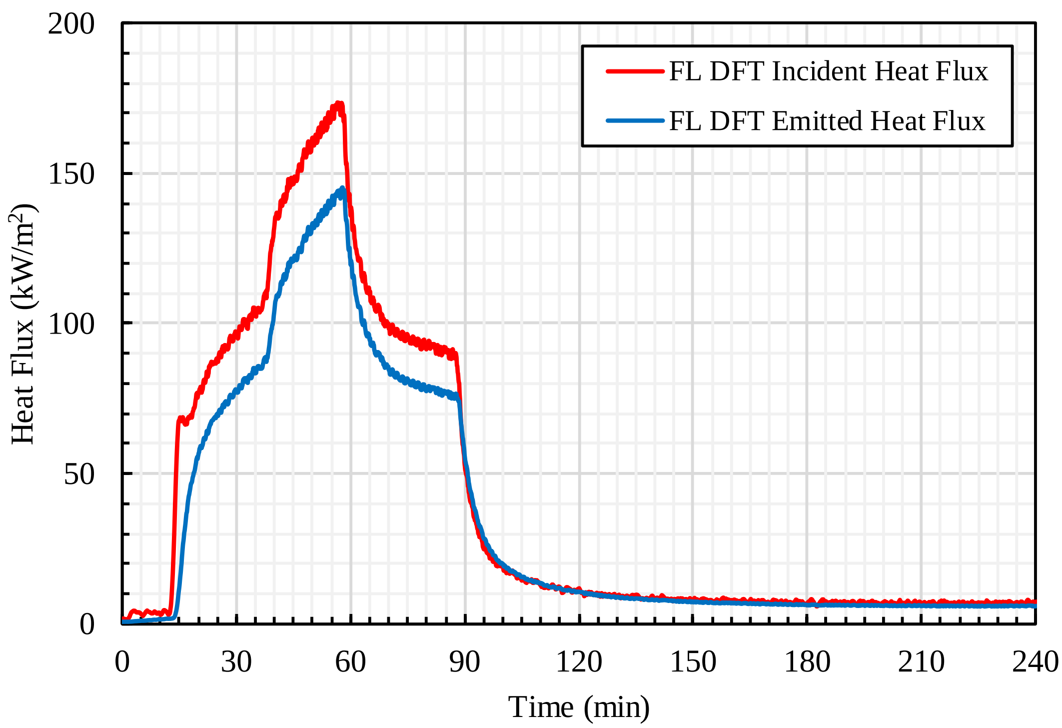

Figure G-6. CLT #3 Test: Front Left DFT Heat Flux.

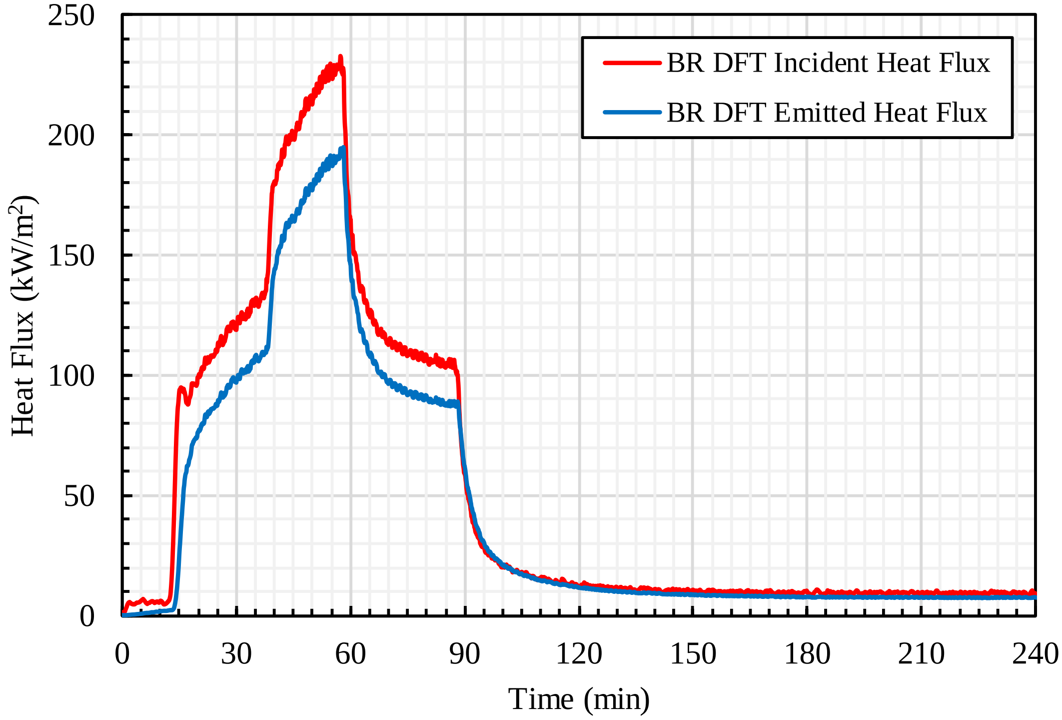

Figure G-7. CLT #3 Test: Back Right DFT Heat Flux.

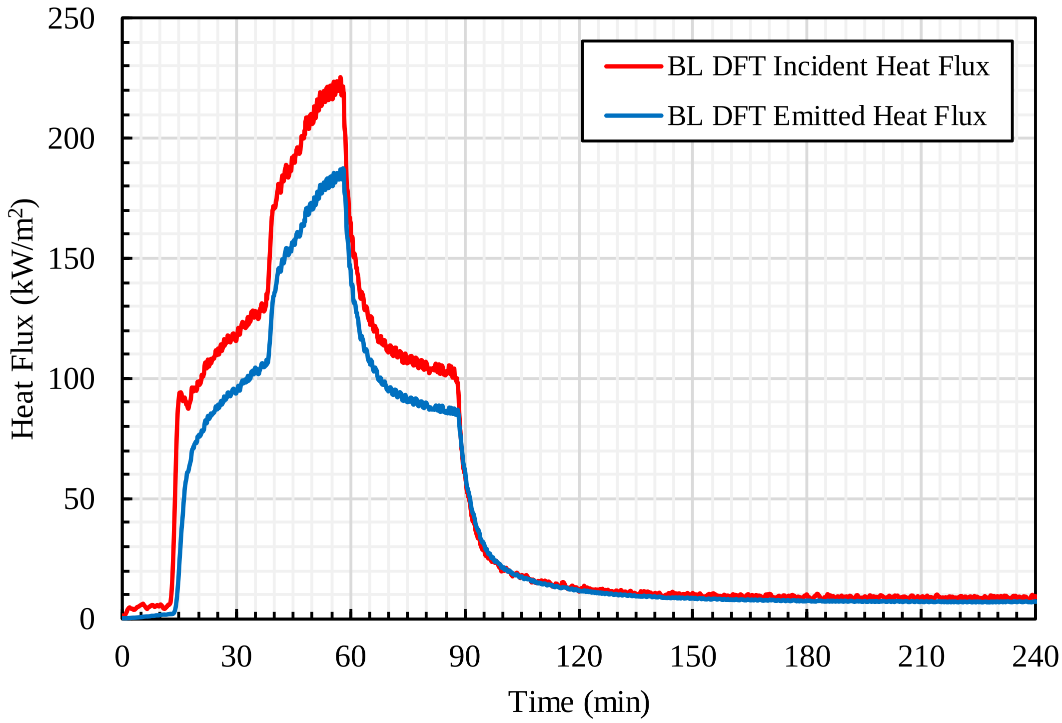

Figure G-8. CLT #3 Test: Back Left DFT Heat Flux.

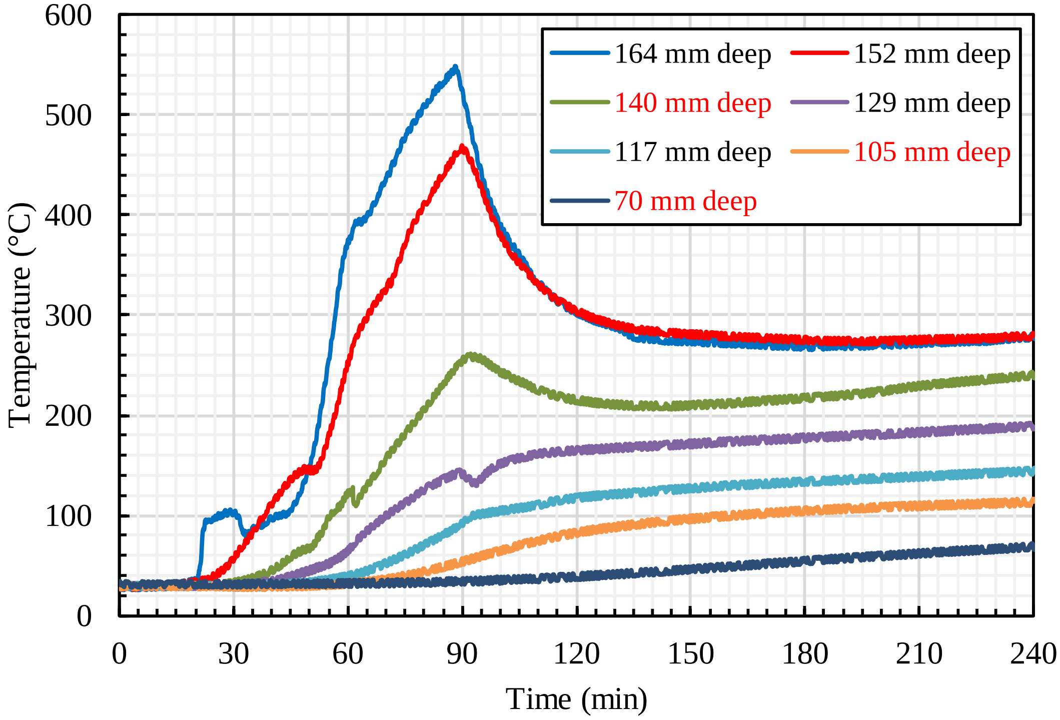

Figure G-9. CLT #3 Test: Embedded TC Temperatures.