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Incident Heat Flux Measurements in Floor and Wall Furnaces of Different Sizes

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ABSTRACT

This paper presents the results of incident heat flux experiments in standard (full-scale) and non-standard (intermediate-scale) wall and floor fire resistance furnaces. These experiments were conducted to investigate the effects of full-scale furnace depth (wall and floor furnaces), furnace size (full-scale and intermediate-scale furnaces) and intermediate-scale furnace orientation (vertical and horizontal positions) on the incident heat flux in fire resistance test furnaces.

KEYWORDS: fire resistance, furnace, wall, floor, full-scale, intermediate-scale, incident heat flux

INTRODUCTION

Fire-rated floor and wall building systems formed with new materials and designs have been increasingly used in residential and non-residential buildings. To determine the fire resistance performance of these systems, full-scale tests are required. However, these tests are expensive and time consuming and there is a need by building designers and architects, at least in the initial design stage, to find alternative solutions. To satisfy this need, the National Research Council of Canada (NRC) has been developing simpler and less expensive experiments and models to assess the fire resistance of building systems such as walls and floors. Along with these efforts, NRC has recently completed the construction of an intermediate-scale furnace, 1.2 m wide by 1.8 m long by 0.5 m deep, that can be used to test loaded and unloaded wall and floor systems. However, to ensure that the intermediate-scale furnace can be used to reflect full-scale experimental results, it must be characterized in relation to a full-scale furnace. Incident heat flux in fire resistance test furnaces is one of the critical parameters in determining the fire resistance performance of building systems. A number of investigations of heat exposure in full-scale standard fire resistance furnaces were carried out for furnace harmonization. Sultan et al[1] examined factors that affect the “test efficiency” in fire resistance testing. It was shown in that, the convective heat transfer in test chamber is important in small furnace size. Paulsen et al[2], presented a method of calibrating specimens in fire resistance furnaces by measuring the concrete specimen temperature at 15 mm under the fire exposed surface as basis for characterizing fire resistance furnaces. Wickström et al[3,4] suggested that in furnaces controlled with the so-called Plate Thermometers (PT), the heat exposure to test specimen in the furnaces would be comparable. Wickstrom[5] provided information on the theory and practical use of the PT in fire resistance test furnaces. Harmathy[6] examined the characteristics of fire resistance test furnaces. In that study, it was shown that the efficiency of a furnace, as measured in terms of heat load it imposes on a test specimen, depends markedly on the size of the furnace. Wickström [7] provided an interesting approach for determining the heat transfer by radiation and convection in fire testing based on the furnace temperature measured by the so-called plate thermometer. Wickström in Ref. 7 also, mentioned that the Gardon gauges and the Schmidt-Boelter heat flux meters may be used to measure the incident heat radiant flux in furnaces.

To characterize the heat flux for an intermediate-scale furnace in relation to a full-scale furnace of the same furnace lining material, a number of parameters need to be investigated such as the effects of full-scale furnace depth (wall and floor), furnace size (full-scale and intermediate-scale) on the incident heat flux in fire resistance test furnaces. As the intermediate-scale furnace was designed to be used as a wall and a floor furnace by rotating the furnace to a vertical and a horizontal position, respectively, the effect of furnace orientation (vertical or horizontal) on the heat flux is also investigated. Any mentioned in this paper on heat flux, the reader should consider it as incident heat flux.

The paper presents the results of heat flux experiments conducted at the NRC on 6 full-scale and 6 intermediate-scale specimens to investigate the heat flux in intermediate-scale and full-scale furnaces. Comparisons of heat flux in a full-scale and intermediate-scale fire resistance furnaces to address the effects of furnace size and furnace depth on the heat flux in wall and floor fire resistance surfaces is presented. In addition, a comparison of heat flux in an intermediate-scale furnace in both wall and floor configuration is also presented. The results reported in this paper can also be used as data for the development of fire resistance models for floor and wall assemblies.

EXPERIMENTAL WORK

This experimental study was carried out at the National Research Council of Canada using full- and intermediate-scale wall and floor fire resistance furnaces. Heat flux experiments include: 3 repeat experiments using the full-scale floor furnace, 3 repeat experiments using the full-scale wall furnace, 3 repeat experiments using the intermediate-scale furnace in its floor configuration and 3 repeat experiments using the intermediate-scale furnace in its wall configuration. The duration of each experiment was two hours and measurements were recorded every minute.

The descriptions of the heat flux sensor used to measure the heat flux in the furnaces, full-scale and intermediate-scale, and details of the full-scale and intermediate-scale specimens are given below. Also, the temperature at 40 mm from the fire-exposed surface was measured but results are not reported in this paper.

Heat Flux Sensor

Heat flux to the test specimen was measured in the intermediate-scale furnace by two water-cooled Gardon Gauge heat flux sensors (see Figure 1) and in the full-scale wall and floor furnaces by 5 water-cooled Gardon Gauge heat flux sensors. These gauges are 2.5 mm in diameter and 2.5 mm long copper cylinder and has a stated accuracy of ±3%. The water flow temperature was maintained during the entire experiment within the temperature range specified by the manufacturer for the sensors.

Standard Full-scale Wall and Floor Furnaces

The full-scale fire resistance floor furnace (see Figure 2) is approximately 4 m wide by 5 m long by 3 m deep and the wall furnace (see Figure 3) is 3.6 m wide by 3 m high by 0.5 m deep. In the wall furnace, the boundaries were covered with ceramic fibre insulation, however in the floor furnace, the furnace walls were made of insulated firebrick, however, the floor of furnace was covered with ceramic fibre insulation. Thermal properties of the firebrick and ceramic fibre insulation are given in Table 1.

Experiments were carried out by exposing castable refractory specimens to heat using propane-fired horizontal and vertical furnaces. The specimens were instrumented with 5 heat flux meters in both the full-scale wall and floor furnaces. These meters were installed flush to the specimen surface to measure the heat flux received by a specimen in fire resistance test furnaces. Each specimen was sealed at the edges against the furnace using ceramic fibre blankets. The furnace temperature was measured by 9 (20 gauge) shielded thermocouples in accordance with CAN/ULC-S101[8]. The average of the 9-thermocouple temperatures was used to control the furnace. These thermocouples were located 0.3 m below the fire-exposed surface of the sample, following, as closely as possible, the CAN/ULC-S101 standard time-temperature curve. This curve is similar to the ASTM E119[9] time-temperature curve.

Non-standard Intermediate-scale Wall and Floor Furnace

Intermediate-scale fire resistance furnace shown in Figure 4 is approximately 1.2 m wide by 1.8 m long by 0.5 m deep. The furnace boundaries were made of insulated firebrick. The intermediate-scale furnace can be oriented vertically to become a wall furnace or oriented horizontally to become a floor furnace.

Wall and floor heat flux experiments were carried out by exposing the castable refractory specimen to heat using propane as in the full-scale. The specimen was sealed at the edges against the furnace using ceramic fibre blankets. The furnace temperature was measured by 3 (20 gauge) shielded thermocouples. The average of the 3 thermocouple temperatures was used to control the furnace. These thermocouples were located 0.3 m below the exposed surface of the sample, following, as closely as possible, the CAN/ULC-S101 standard time-temperature curve.

Full-scale Specimens

The specimen used in the floor furnace was a castable refractory slab, marketed as KS-4, composed of 20 rectangular slabs, 0.8 m wide by 1.2 m long by 0.15 m thick, suspended on a steel beam. The slabs were tightly butted with ceramic sheet along their perimeters to form a 4 m by 5 m unite. The properties of these slabs are given in Table 1. Five heat flux meters were installed flush with the specimen surface: one at the centre of the specimen and one at the centre of each quarter section of the specimen to measure the receiving heat flux to the specimen surface. The location of the heat flux sensors is shown in Figure 5.

Full-scale wall specimen, composed of five so-called measuring specimens, blocks of castable refractory brick, 600 mm square by 150 mm thick, were inserted in the simulated block brick wall, one at its centre and four at the centres of its quarter sections as shown in Figure 6. One water-cooled Gardon Gauge heat flux sensor was installed flush with the specimen surface in the centre of each measuring specimen. The location of the heat flux sensors is shown in Figure 6.

Intermediate-scale Specimen

In intermediate-scale floor furnace, the specimen was also a castable refractory slab as those used in the full-scale floor and wall specimen and composed of one rectangular slab 0.8 m wide by 1.2 m long by 0.15 m thick. It was mounted in the centre of a concrete frame 1.2 m wide by 1.8 m long around the specimen. The location of the heat flux sensors is shown in Figure 7.

RESULTS AND DISCUSSION

The effects of furnace depth (full-scale wall and floor furnaces), furnace size (full-scale and intermediate-scale) and intermediate-scale furnace orientation (vertical and horizontal) on the heat flux in fire resistance furnaces are given below. The heat flux measurements for all full-scale and intermediate-scale wall and floor furnaces experiments are given in Ref. 10.

Effect of furnace depth (full-scale wall and floor furnaces)

The averages of heat flux for the 3 experiments using the full-scale floor furnace and the 3 experiments using the full-scale wall furnace are provided in Figures 8 and 9, respectively. In the first 5 min for both the wall and floor furnaces, the heat flux measurements were peaks up and down as the furnace was tried to meet the standard rapid temperature increase. After 5 min, the heat flux increases with the increase in furnace temperature and it follows a similar trend to the furnace temperature. A comparison of the heat flux in full-scale wall and floor furnaces of different depths is shown in Figure 10. The heat flux in a full-scale floor furnace with a larger depth (3 m) is slightly higher (8%) than in a wall furnace with a smaller depth (0.5 m). This slight increase in heat flux in the case of a floor furnace could be caused by the presence of a thicker hot layer gas facing the specimen's fire exposed surface.

Effect of Furnace Size (full-scale vs intermediate-scale for wall and floor furnaces)

The average heat flux results for the intermediate-scale furnace in its floor and wall orientation are shown in Figures 11 and 12, respectively. Comparisons of the average heat flux in full- and intermediate-scale floor and wall furnaces are shown in Figures 13 and 14, respectively. The results in Figure 13 indicate that, when either the full-scale or the intermediate-scale fire resistance floor furnace is heated up using the CAN/ULC-S101 or ASTM E119 time-temperature curve, the heat flux in the intermediate-scale floor furnace is approximately 15% higher than in the full-scale floor furnace. Similarly, the results in Figure 14 indicate that, when either the full-scale or the intermediate-scale fire resistance wall furnace is heated up using the CAN/ULC-S101 or ASTM E119 time-temperature curve, the heat flux in the intermediate-scale wall furnace is approximately 18% higher than in the full-scale wall furnace. These results suggest that the effect of furnace size on heat flux is somewhat significant. Generally, the heat received by a specimen in fire resistance furnaces is by radiation and convection. The radiative part is much greater than the convective part. In the full-scale furnaces, convective heat occurs by natural convection while, in the smaller size furnaces, forced convection could occurs as the burners are closed to the test specimen and might impinging on it. Heat transfer by forced convection is greater than by natural convection. As the furnace size increases, the convective heat to the specimen decreases and this may explain why the heat flux in an intermediate-scale furnace is higher than in a full-scale furnace. For a heat flux parameter, an assembly tested in an intermediate-scale furnace will provide a conservative fire resistance performance compared to a similar assembly tested in a full-scale furnace.

Effect of Furnace Orientation (Vertical vs Horizontal)

The average heat flux results for the intermediate-scale furnace in the horizontal position and in the vertical position are shown in Figures 11 and 12, respectively. A comparison of the average heat flux in the horizontal and in the vertical furnace position is shown in Figure 16. The results showed that, when an intermediate-scale fire resistance furnace (1.2 m wide by 1.8 m long by 0.5 m deep) is heated up using the CAN/ULC-S101 or ASTM E119 time-temperature curve, the heat flux to a specimen in a furnace oriented horizontally is slightly higher (6%) than in a furnace oriented vertically. This difference in heat flux is considered insignificant.

CONCLUSIONS

This paper discussed the effects of full-scale furnace depth (floor vs wall), furnace size (full-scale vs intermediate-scale) and intermediate-scale furnace orientation (vertical vs horizontal) on the heat flux in fire resistance experiment furnaces. Based on the results mentioned above, the following key trends can be highlighted:

1. The effect of full-scale furnace depth on the heat flux is insignificant.
2. The heat flux in either intermediate-scale wall or floor furnace, 1.2 wide by 1.8 m long by 0.5 m deep, is 15% and 18% higher than in the full-scale wall and floor furnace, respectively.
3. For the intermediate-scale furnace, 1.2 m wide by 1.8 long by 0.5 m deep, the effect of furnace orientation, whether vertical (wall) or horizontal (floor), on the heat flux is insignificant.

ACKNOWLEDGEMENTS

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Table 1 Thermal Property of Furnace Lining and Specimen Materials

	Furnace Lining Material		Specimen Material
	Firebrick	Ceramic Fibre	Castable Refractory Slab
Thermal Conductivity ($W\ m^{-1}K^{-1}$)	1.15	0.04	0.9
Specific Heat ($J\ kg^{-1}\ K^{-1}$)	900	1150	1000
Density ($kg\ m^{-3}$)	2600	160	2085

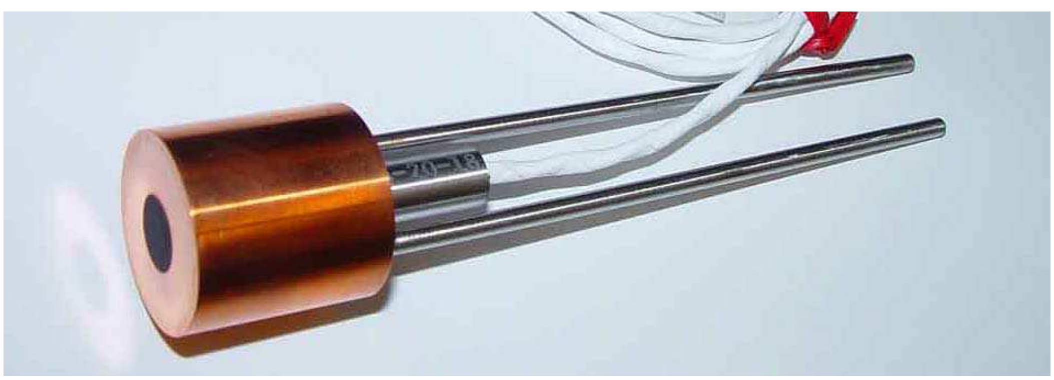

Figure 1 Water Cooled Gardon Gauge Heat Flux Sensor

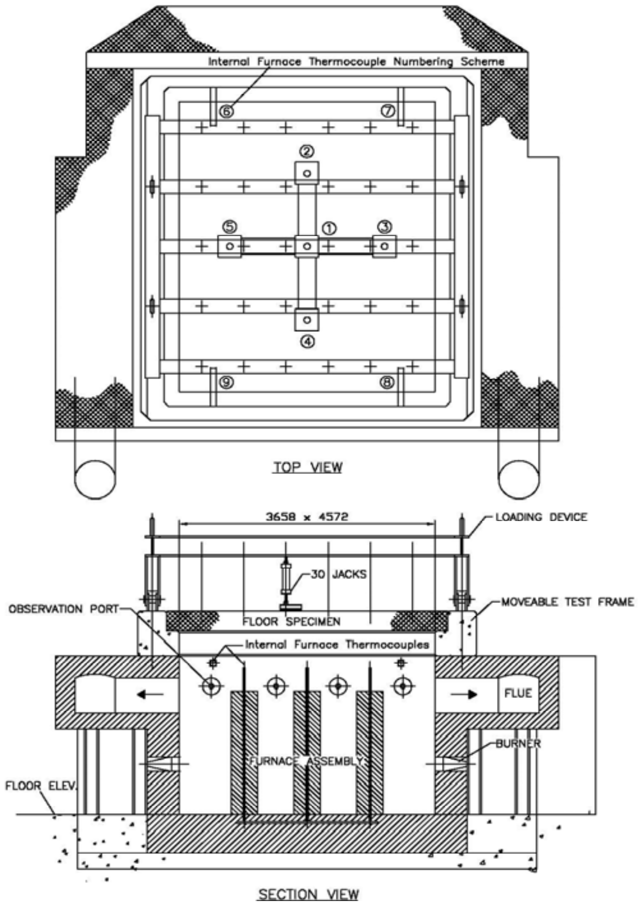

Figure 2 Full-scale Floor Furnace

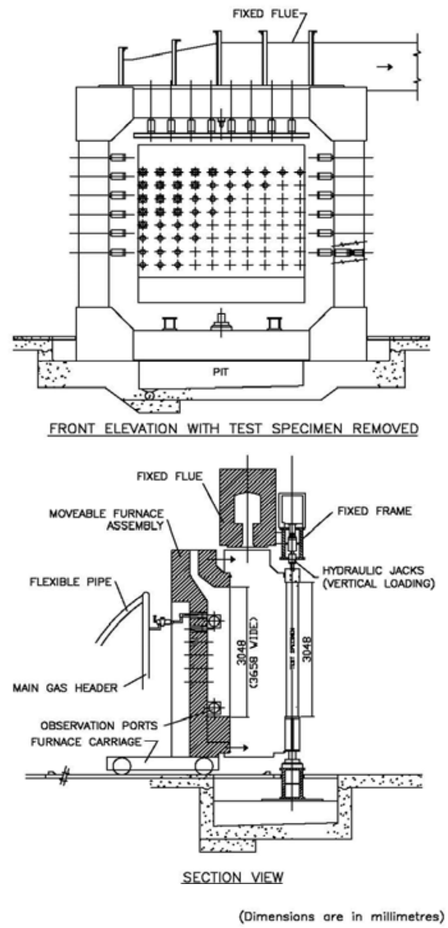

Figure 3 Full-scale Wall Furnace

Figure 4 Intermediate-scale Wall and Floor Furnace

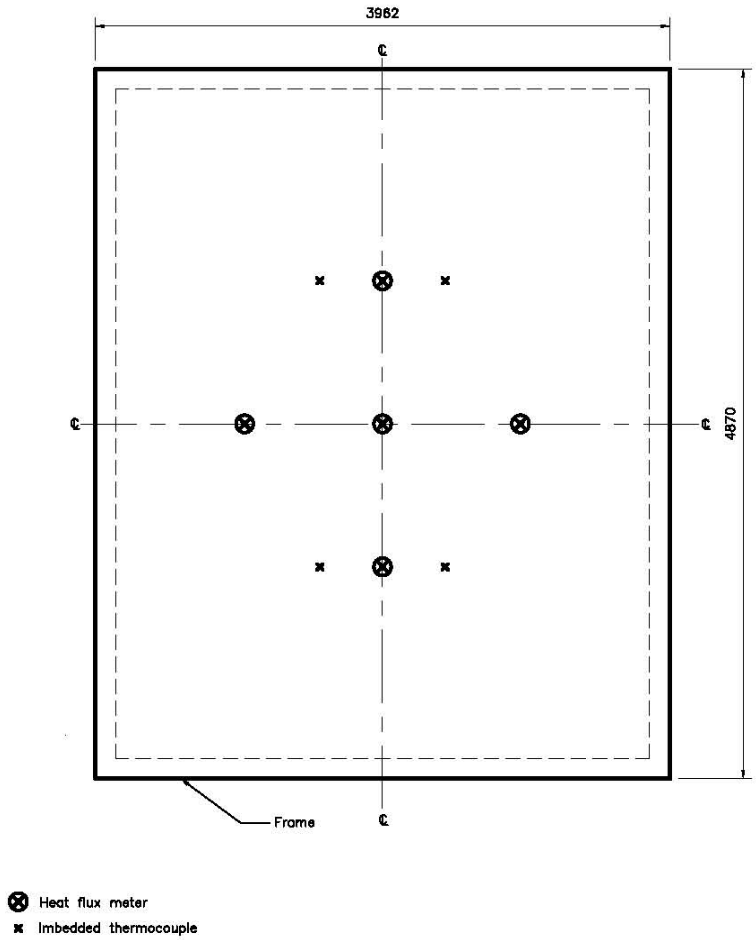

Figure 5 Full-scale Floor Specimen

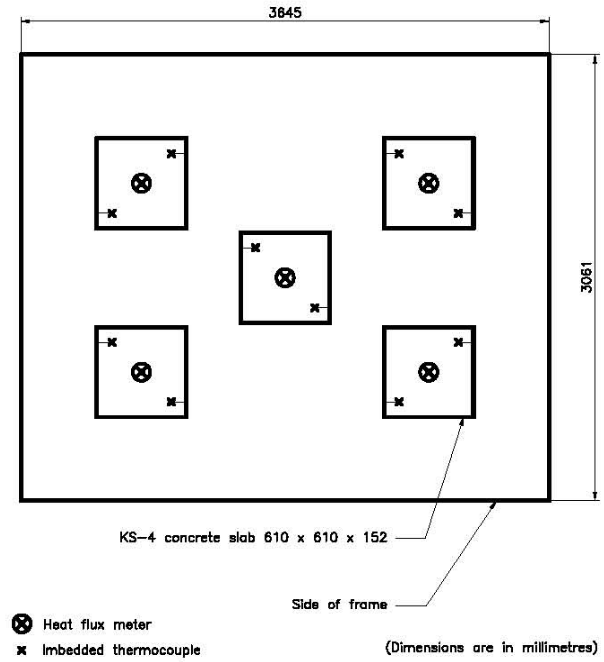

Figure 6 Full-scale Wall Specimen

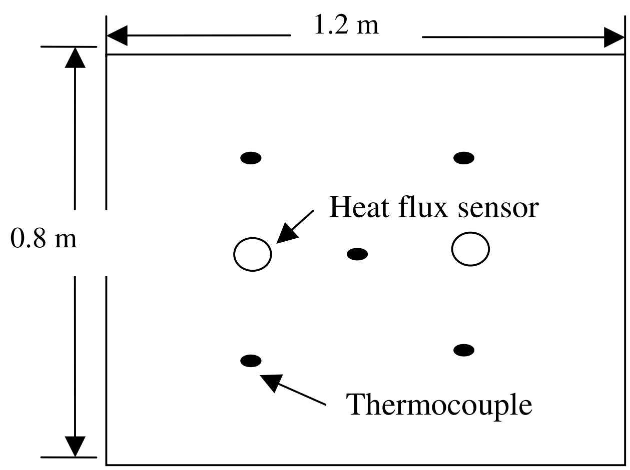

Figure 7 Intermediate-Scale Wall and Floor Specimen

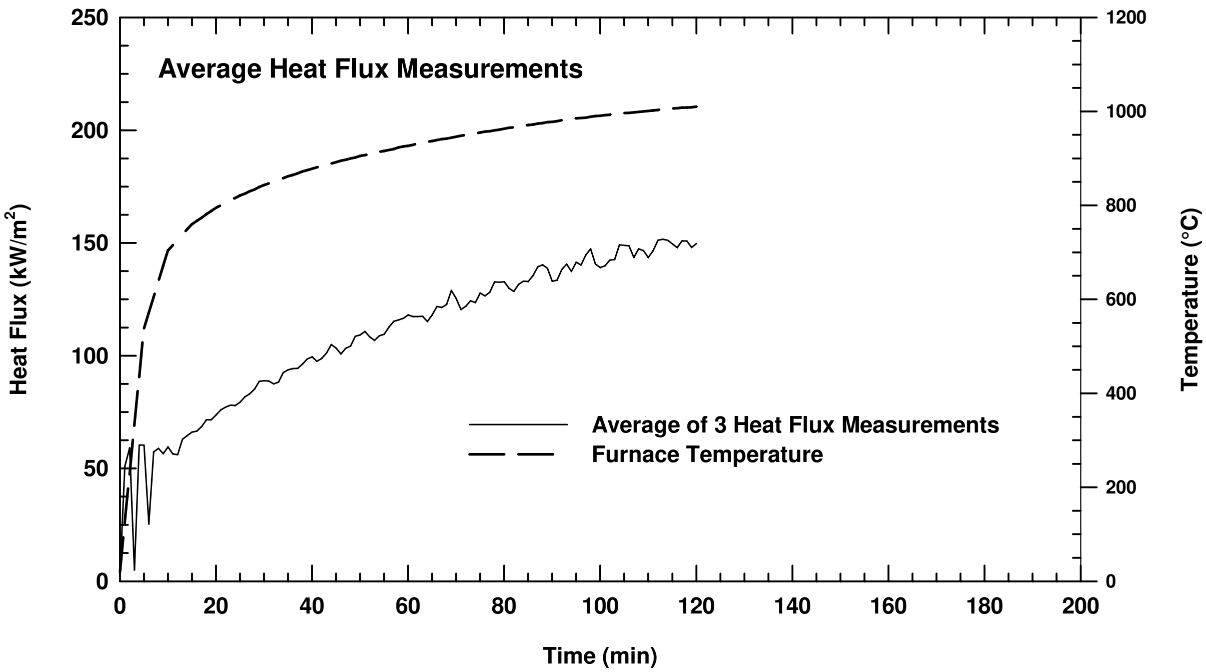

Figure 8 Heat flux in Full-scale Floor Furnace

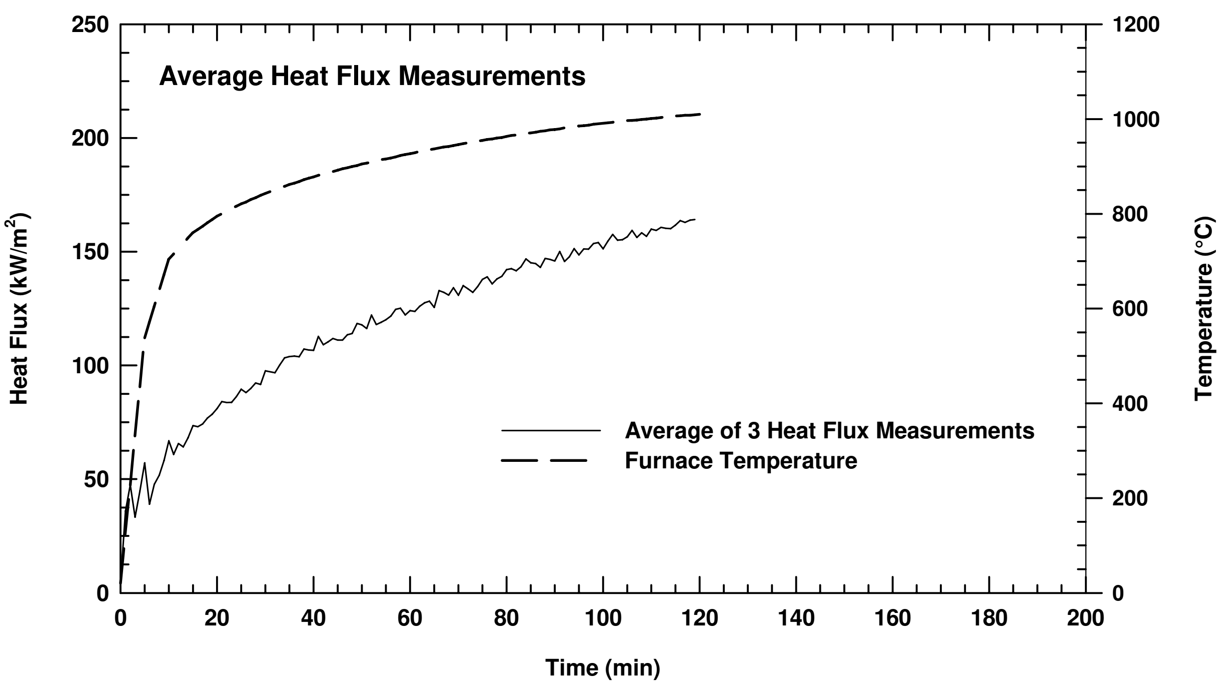

Figure 9 Heat flux in Full-scale Wall Furnace

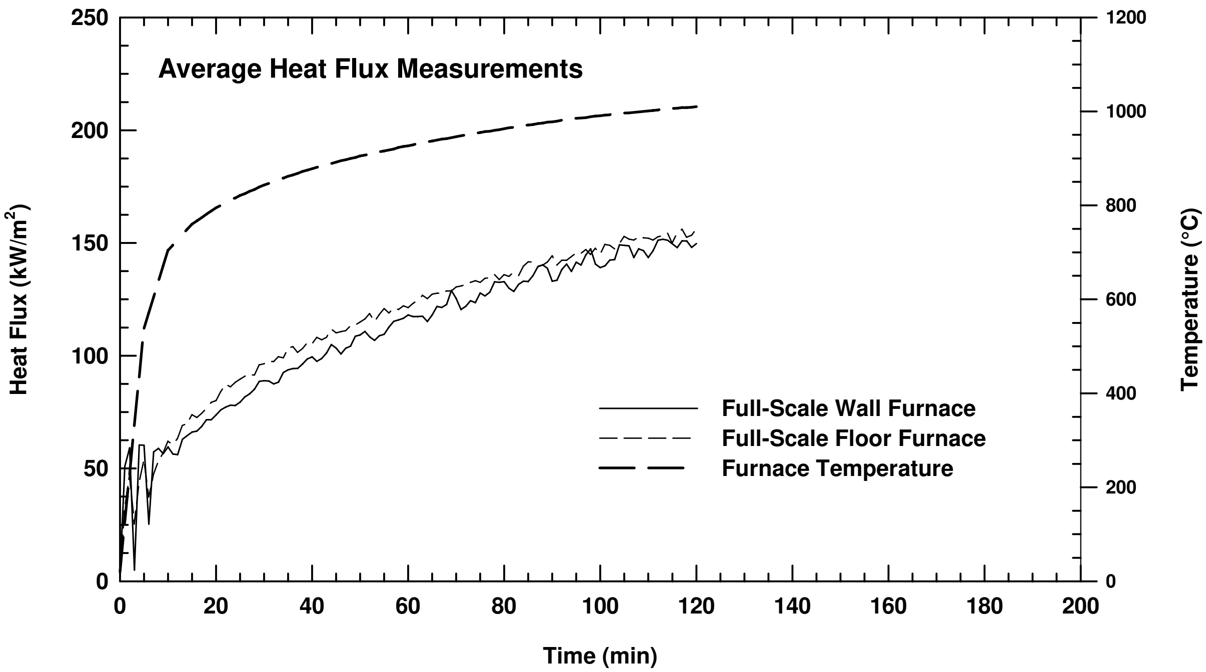

Figure 10 Comparison of Heat flux in Full-scale Furnaces of Different Depths (Floor vs Wall Furnace)

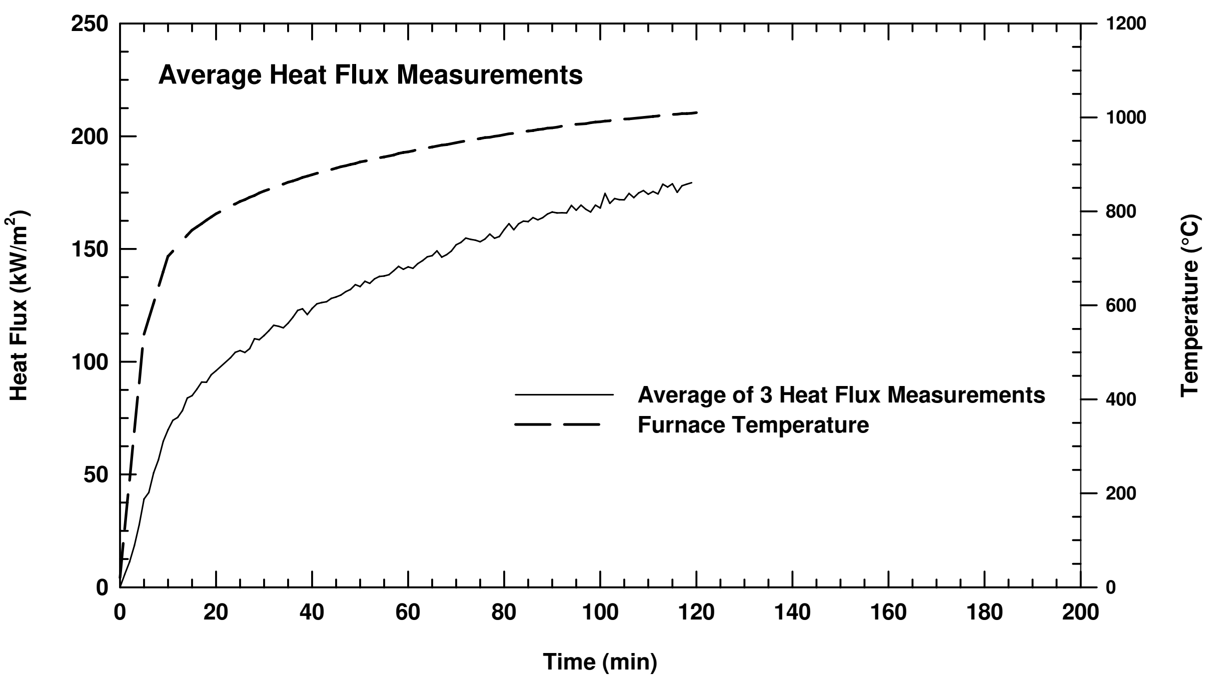

Figure 11 Heat flux in Intermediate-scale Floor Furnace

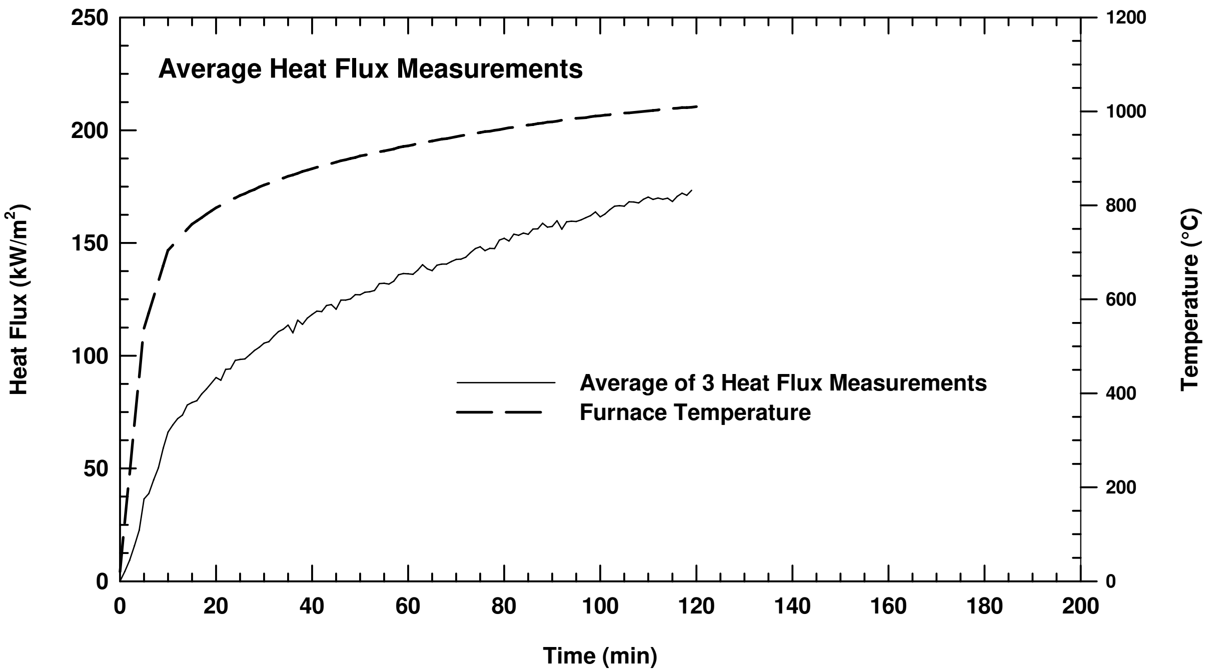

Figure 12 Heat flux in Intermediate-scale Wall Furnace

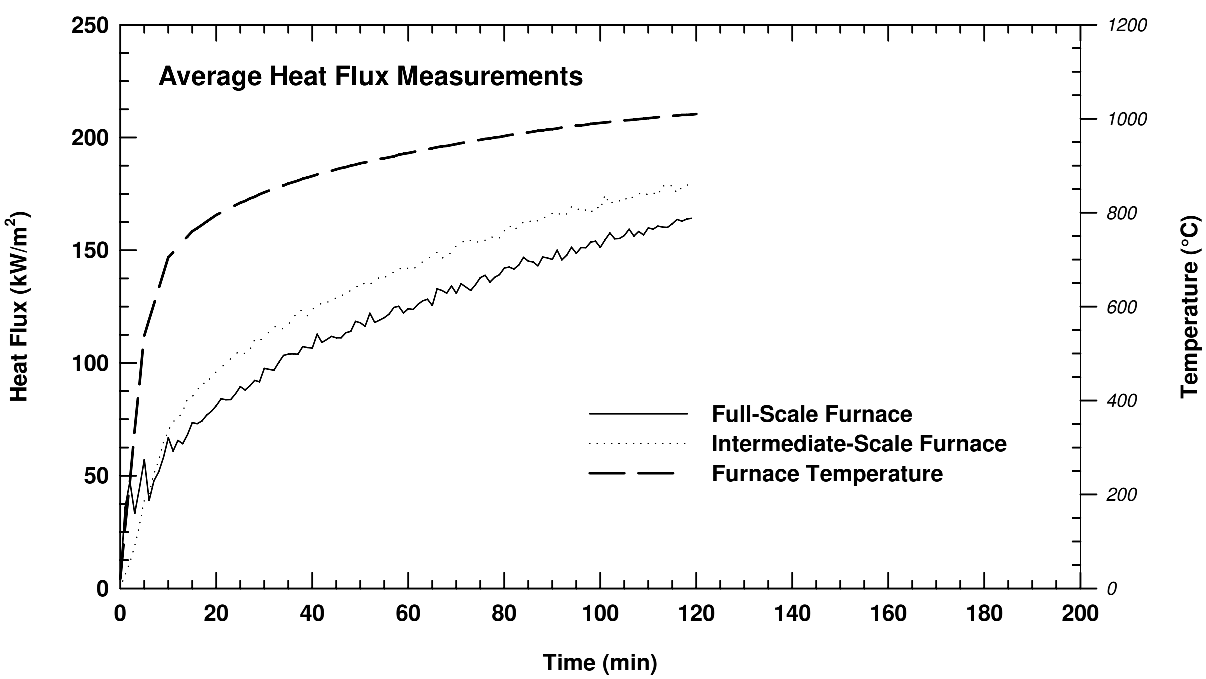

Figure 13 Comparison of Heat flux in Floor Furnaces
(Full-scale vs Intermediate-scale)

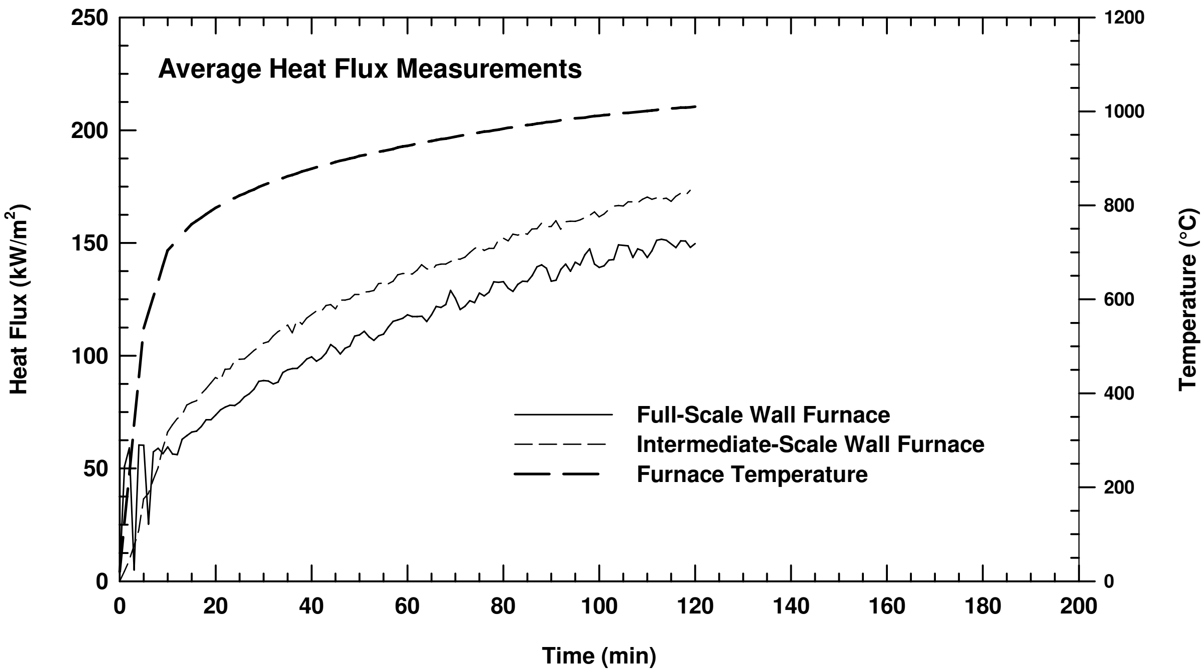

Figure 14 Comparison of Heat flux in Wall Furnaces
(Full-scale vs Intermediate-scale)

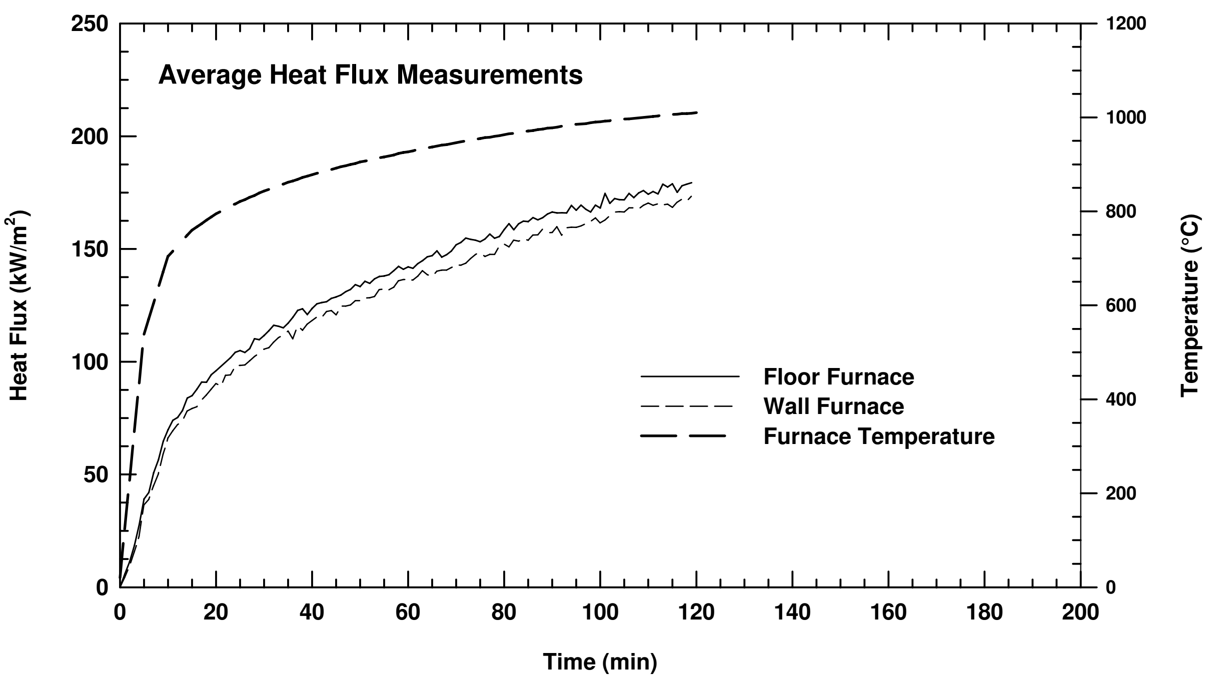

Figure 15 Comparison of Heat flux in Intermediate-scale Furnace
(Wall vs Floor)