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A COMPARISON OF HEAT EXPOSURE IN FIRE RESISTANCE TEST FURNACES CONTROLLED BY PLATE THERMOMETERS AND BY SHIELDED THERMOCOUPLES

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ABSTRACT

Harmonization of fire resistance furnaces is a major challenge facing the standard writing organizations. Efforts are being considered by the ASTM E05 committee to investigate the factors that affect such harmonization among test furnaces. The factors under consideration by ASTM include furnace specifications, the method used to control furnace temperature and structural load. This paper is a contribution to the efforts being made for identifying a method that can be used to control the fire resistance furnaces.

This paper presents and discusses the results of 12 heat exposure full-scale tests: 6 using a floor furnace and the other 6 using a wall furnace. These tests were conducted to investigate the use of two methods for controlling furnace temperature: one by use of the shielded thermocouples and the other by use of the so-called Plate Thermometers. Also, tests were conducted to investigate the heat exposure received by the specimen in fire resistance furnaces controlled by either the Plate Thermometers or by shielded thermocouples.

INTRODUCTION

In North America, the fire resistance rating of building elements such as walls, floors, beams and columns is determined by a full-scale fire resistance test conducted in accordance to either the CAN/ULC-S101¹ or ASTM E119² standards. These standards assume that different test furnaces will provide the same heat exposure to test specimens. Heat exposure in the fire resistance test furnaces depends on the type of fuel used, furnace wall materials and furnace depth³. Different attempts were made to provide tools for harmonization of the heat exposure in standard fire resistance test furnaces. One attempt by the author³ suggests that if the full-scale fire resistance test furnaces are lined with very low thermal conductivity materials, such as ceramic fibre insulation, the heat exposure to a test specimen in different furnaces heated with either liquid or gaseous fuels or furnaces with different depths would be comparable. Other attempts were made at the Swedish National Testing Institute by Wickstrom^{4,5,6} and by Olsson⁷ suggesting that by changing to controlling fire resistance test furnaces with the so-called Plate Thermometers (PT), the heat exposure in the furnaces would be harmonized. Wickstrom⁸ provided information on the theory and practical use of the PT. Currently, the ISO 834-1⁹ and European EN 1363-1¹⁰ standards require use of the PT to control the heat exposure in fire resistance test furnaces while the North American standards, CAN/ULC-S101 and ASTM E119, require use of the shielded thermocouples to control the heat exposure in fire resistance test furnaces.

Efforts are being considered by the ASTM E05.11 Subcommittee to investigate the harmonization of fire resistance test furnaces. In an attempt to harmonise fire resistance test furnaces, three Task Groups have been formed: one to investigate the effect of furnace specification, the second, to investigate the potential use of the so-called Plate thermometers for controlling furnace and the third to provide guidance on the load calculation and methodology of applying the load on a test specimen.

In contribution to these efforts, The National Research Council of Canada (NRC) conducted an experimental study to measure the heat exposure to a specimen and to measure the furnace temperature using both the shielded thermocouples and the Plate Thermometers in full-scale wall and floor furnaces when controlled by either the Plate Thermometer or by shielded thermocouples. The study includes 12 heat exposure experiments: 6 experiments using a full-scale wall furnace and the other 6 using a full-scale floor furnace.

To provide data on the potential use of the Plate Thermometers in the North American fire resistance standards, comparisons are presented for floor and wall furnace temperatures measured by both the shielded thermocouples, current standard, and by the Plate Thermometers, proposed, for furnaces controlled by either the shielded or by the Plate Thermometers. Also, comparisons of heat exposure in both floor and wall furnaces of different depths for furnaces controlled by either the Plate Thermometer or by shielded thermocouples are presented. In addition, comparisons of a heat exposure in wall and floor furnaces controlled by either the Plate Thermometers or by shield thermocouples are also presented.

EXPERIMENTAL WORK

Descriptions of heat flux sensor, Plate Thermometer, shielded thermocouple, test specimens, full-scale wall and floor furnaces and experimental procedure are given below.

Heat Flux Sensor

Five-heat flux sensors, water-cooled Gardon Gauge, were used to measure the heat exposure to a test specimen in the full-scale wall and floor furnaces. These gauges are 2.5 mm diameter and 2.5 mm long copper cylinder and have a stated accuracy of 63%. The water flow temperature was maintained during the entire test within the temperature range specified by the manufacturer for the sensors.

Plate Thermometers

The Plate Thermometers used in this study were made by Thermo-Elecra and they are described in detail in Ref. 8, however, for the reader's convenience, the Plate thermometer is a steel plate 100 mm by 100 mm by 0.7 mm thick with a surface emissivity greater than 0.7. On one side (back) facing the test specimen, a 1 mm Type K thermocouple is welded to the centre of the plate and covered with 10 mm thick ceramic fibreboard to protect it from radiative exchange with the specimen itself. The other side (front) of the steel plate is facing the furnace. The steel plate has a 15 mm diameter area around the centre and is specially treated to achieve a directional sensitivity to radiation. The Plate Thermometer is schematically shown in Figure 1. The Plate Thermometers were placed in both the floor and wall furnaces in locations similar to the shielded thermocouples required by the North American standards (see Figures 3 and 4) for fire resistance but at a distance of 100 mm away from the test specimen fire-exposed surface.

Shielded Thermocouples

The shielded thermocouple was fabricated by fusing the twisted ends of No. 18 gauge Chromel-Alumel wires, and mounting the leads inside a porcelain insulator. The thermocouple with the porcelain insulator was inserted inside a 12.7 mm diameter steel pipe so that the thermocouple bead was 12.7 mm away from a sealed end steel cap. The shielded thermocouple is schematically shown in Figure 2. The locations of these thermocouples are shown in Figures 3 and 4.

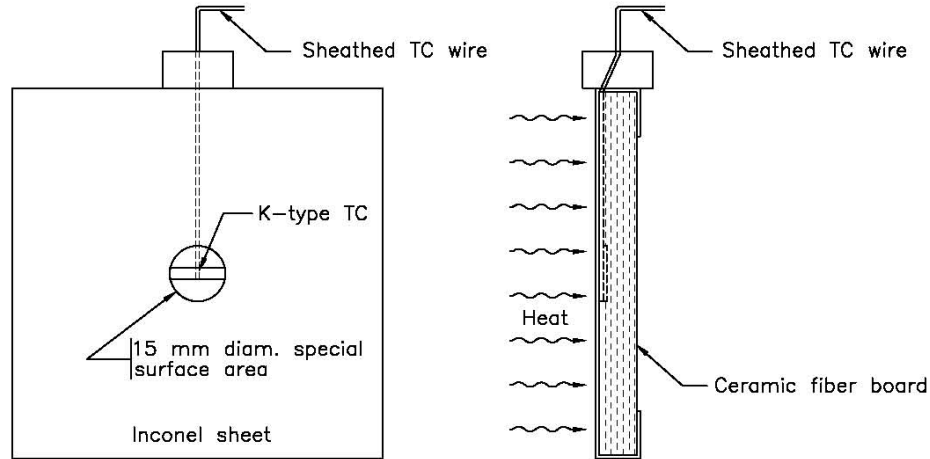


Figure 1. Plate Thermometer

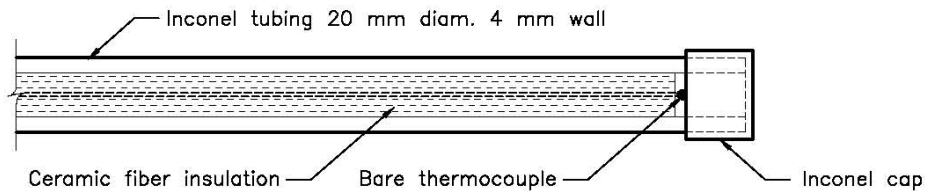


Figure 2. Shielded Thermocouple

Specimens

In the floor furnace, the test specimen used was a castable refractory slab, marketed as KS-4, composed of 20 rectangular slabs, 800 mm wide by 1200 mm long by 1500 mm thick, suspended on a steel beam. The slabs were tightly butted with a ceramic sheet along their perimeters to form a 4 m by 5 m unit. For measuring the heat flux received by the test specimen, 5 heat flux sensors were installed flush with the specimen surface: one at the centre of the furnace and one at the centre of each quarter section of the furnace to measure the receiving heat exposure to the specimen surface. Also, 5 thermocouples, 1 mm Type K, were installed at 40 mm from the specimen fire-exposed surface. The locations of the thermocouples are shown in Figure 4.

For the wall furnace, the test specimen composed of five so-called measuring specimens, blocks of KS-4 castable refractory brick, 600 mm square by 150 mm thick, were inserted in the simulated block brick wall covered with ceramic fire insulation, one at its centre and four at the centres of its quarter sections as shown in Figure 5. As in the floor furnace mentioned-above for measuring the

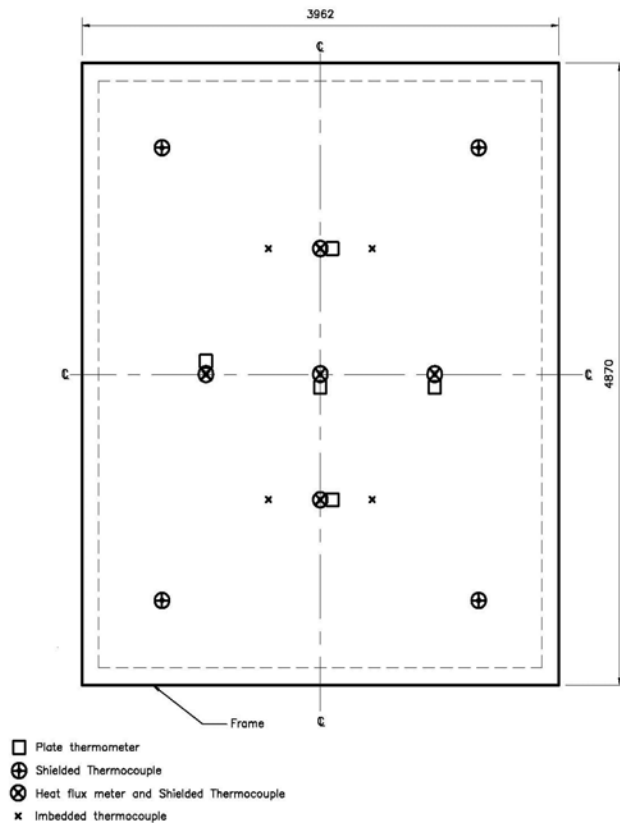


Figure 3 Full-scale Floor Furnace Specimen

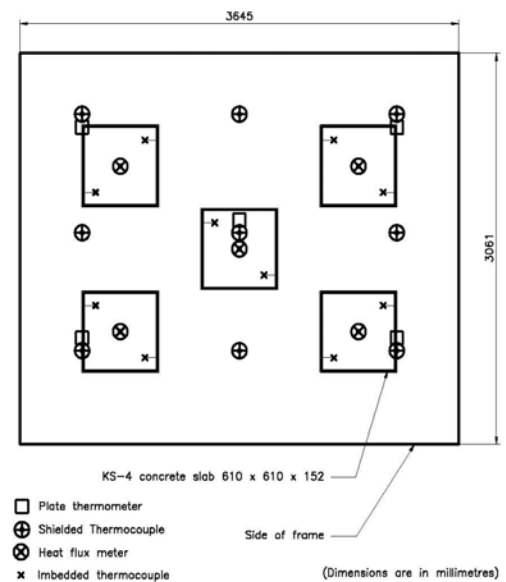


Figure 4 Full-scale Wall Furnace Specimen

heat flux received by the test specimen, one heat flux sensor, water-cooled Gardon Gauge, was installed flush with the specimen surface in the centre of each measuring specimen. The location of these sensors is also shown in Figure 3. Each specimen was sealed at the edges against the furnace using ceramic fibre blankets. The properties of these slabs are given in Table 1.

Table 1 Thermal Property of Furnace Lining and Specimen Materials

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

Full-scale Furnaces

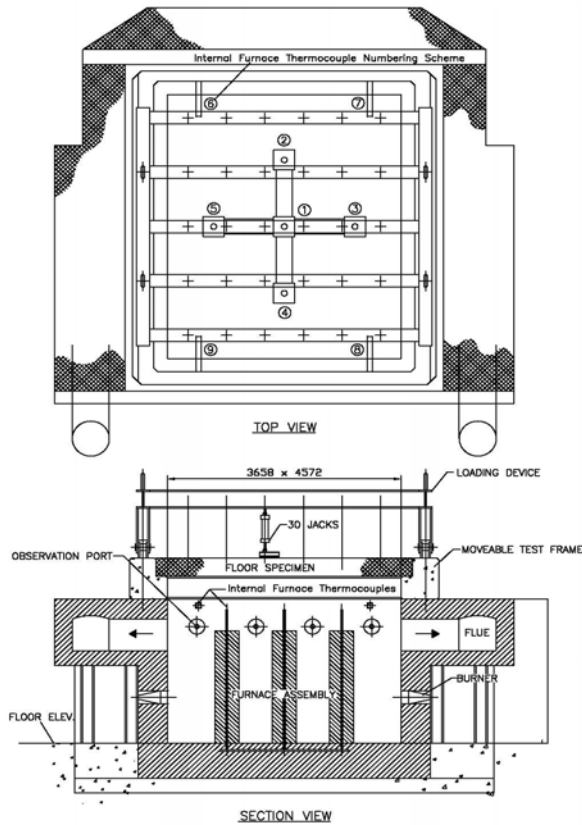


Figure 5 Full-scale Floor Furnace

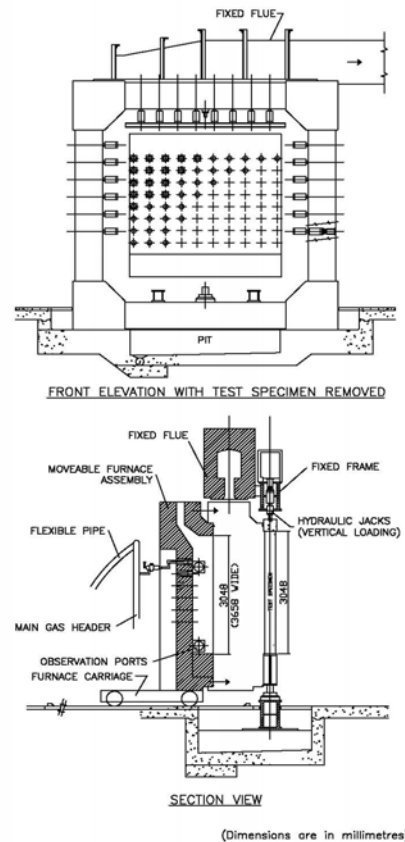


Figure 6 Full-scale Wall Furnace

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

Experimental Procedure

The heat exposure measurements for 12 experiments were carried out on a full-scale floor furnace and on a wall furnace using five water-cooled Gardon Gauge heat flux sensors shown in Figure 3. The experiment duration was 2 hours and the data were recorded every 10 seconds. Six tests were conducted using a floor furnace: 3 duplicate tests with a furnace controlled by the shielded thermocouples in accordance to ULC-S101/ASTME119 standards and the other three duplicate tests by a furnace controlled with PT in accordance to ISO 834-1 and European EN 1363-1 standards. The other 6 tests were conducted using a wall furnace: 3 duplicate tests with a furnace controlled by the shielded thermocouples in accordance to ULC-S101/ASTME119 standards and the other three duplicate tests by a furnace controlled with PT in accordance to ISO 834-1 and European EN 1363-1 standards. The furnace temperature was measured by 9 (20 gauge) shielded thermocouples in accordance with CAN/ULC-S101-M89^x. 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 specimen. The wall and floor furnaces are controlled electronically in

such a way that the furnace temperature follow as closely as possible, the CAN/ULC-S101-M89 standard time-temperature curve. This curve is similar to the ASTM E119⁴ time temperature curve.

RESULTS AND DISCUSSION

The effects of furnace temperature measurement methods and heat exposure to test specimens in fire resistance furnaces controlled by either the shielded thermocouples or by the Plate Thermometers are discussed below.

Furnace Temperature control Methods

Furnace temperature measurements in a floor and a wall furnace controlled by either the shielded thermocouples or by Plate Thermometers are given below.

Floor Furnace

Comparisons of furnace temperature in a floor furnace controlled by either the shielded thermocouples or by Plate thermometers are shown in Figures 7 and 8, respectively.

The results of the average furnace temperature measured by both the 9 shielded thermocouples and by 5 Plate Thermometers in a floor furnace controlled by either the Plate Thermometer or by shielded thermocouples as well as the ULC S101/ASTM E119 curve are given in Figures 7 and 8. The furnace temperature measurements shown in Figure 7 for a floor furnace controlled by shielded thermocouples, the Plate Thermometer temperature measurements are much higher (up to 100%) in the first 10 min of the fire exposure than those measured by the shielded thermocouples. This could be due to a larger time constant for the shielded thermocouples that fail to respond to a rapid change in the furnace temperature, however, the Plate Thermometers were able to respond faster to change. After 10 min of fire exposure, the difference in furnace temperature measurements by using two different methods for controlling the furnace temperature, is insignificant.

For a floor furnace temperature controlled by the Plate Thermometers (see Figure 8), the shielded thermocouples temperature measurements are much lower (up to 100%) in the first 10 min of fire exposure than those measured by the Plate Thermometers. This is due to a larger time constant for shielded thermocouples than for Plate Thermometers. After 10 min, the shielded thermocouples temperature measurements are slightly lower (up to 5%) than those measured by the Plate Thermometers. As in the case when the floor furnace is controlled by the shielded thermocouples mentioned-above, the difference in furnace temperature measurements by using two different methods for controlling the furnace temperature, is also insignificant.

Wall Furnace

Figures 9 and 10 show comparisons of furnace temperature in a wall furnace controlled by either the shielded thermocouples or by Plate Thermometers.

The results of the average furnace temperature measured by both the 9 shielded thermocouples and by 5 Plate Thermometers in a wall furnace controlled by either the Plate thermometer or by shielded thermocouples as well as the ULC S101/ASTM E119 curve are presented in Figures 9 and 10. The furnace temperature measurements shown in Figure 9 are more or less similar to those measured in the floor furnace mentioned above. In a wall furnace controlled by shielded thermocouples, the Plate Thermometer temperature measurements are much higher (up to 100%) in

the first 10 min of fire exposure than of those measured by the shielded thermocouples. This could be due to a larger time constant for the shielded thermocouples that fail to respond to the rapid change in the furnace temperature, however, the Plate Thermometers were able to respond faster to the changes. After 10 min fire exposure, the difference in furnace temperature caused by using two different methods for controlling the furnace temperature is insignificant.

For a wall furnace temperature controlled by Plate thermometers (see Figure 10), the shielded thermocouples temperature measurements are much lower (up to 100%) in the first 10 min of fire exposure than those measured by the Plate Thermometers. This is due to a larger time constant for the shielded thermocouples as explained above. After 10 min, the shielded thermocouple temperature measurements are slightly higher (up to 5%) than those measured by the Plate Thermometers. The difference in furnace temperature caused by using two different methods for controlling the furnace temperature, is insignificant. Based on the results mentioned-above for assemblies tested for 15 min, the use of shielded thermocouples to control the furnace is questionable.

Heat Exposure Measurements

Heat exposure measurements in a floor and a wall furnace with the furnace temperature controlled by either the shielded thermocouple or by Plate Thermometers are discussed below.

Floor Furnace

Figure 11 shows a comparison of the heat exposure received by a specimen in a floor furnace controlled by either the shielded thermocouples or by the Plate Thermometers.

The results shown in Figure 11 indicate that when a floor furnace is controlled by shielded thermocouples, the specimen received about up to 100% more heat flux in the first 10 min than when the same furnace is controlled by Plate Thermometers. Similarly, after 10 min when the furnace is controlled by the shielded thermocouples, the specimen received about 12% more heat flux than when the furnace is controlled by Plate Thermometers. These results are consistent with the increase of the furnace temperature measured by the Plate Thermometer than those measured by the shielded thermocouples for a floor furnace controlled by the shielded thermocouples.

Wall Furnace

A comparison of heat exposure received by a specimen in a wall furnace controlled by either the shielded thermocouples or by the Plate Thermometers is given in Figure 12.

The results shown in Figure 12 indicate that when a furnace is controlled by shielded thermocouples, the specimen received peaks of up to 100% more heat flux in the first 10 min than when the same furnace is controlled by the Plate Thermometers. After 10 min, when the furnace is controlled by the shielded thermocouples, the specimen received about 5% less heat flux than when the furnace is controlled by the Plate Thermometers. These results are consistent with the increase of the furnace temperature measured by the Plate Thermometer than those measured by the shielded thermocouples for a floor furnace controlled by the shielded thermocouples.

Wall/Floor Furnaces controlled by Shielded Thermocouples

Figure 13, shows a comparison of the heat flux received by a specimen in a floor and a wall furnace controlled by shielded thermocouples.

For a wall and a floor furnace controlled by shielded thermocouples, the results shown in Figure 13 indicate that in the first 10 min of fire exposure, the wall furnace specimen received more heat flux than the floor furnace specimen. In this period, the furnace must achieve a rapid increase in temperature in order to follow the time-temperature curve specified by the standard; as a result, more fuel is used and the furnace flame likely touched the shielded thermocouple due to a smaller depth in the wall furnace (0.5 m) than in the floor furnace (3m). However, after 10 min, the heat flux received by either a floor or a wall specimen is more or less the same. These results are consistent with the findings in temperature measurement shown in Figures 7 and 9.

Wall/Floor Furnaces controlled by Plate Thermometers

A comparison of the heat flux received by a specimen in a floor and a wall furnace controlled by the Plate thermometers is given in Figure 14.

For a wall and a floor furnace controlled by the Plate Thermocouples, the results shown in Figure 14 indicate that the heat flux received by a specimen in a wall furnace is 15 % more than in a floor furnace specimen. As the two furnaces were controlled by the Plate Thermometers, this could be caused by one or more of the two following reasons: first, the furnace lining in the wall furnace was ceramic fibre blankets while in the floor furnace it was firebrick, so that the heat exposure to the specimen could be affected by the furnace walls material type. Second, the furnace depth: the floor furnace is 3 m deep and the wall furnace is 0.5 m deep. Further research is needed to investigate the effect of furnace depth and furnace lining material on heat flux received by a specimen in floor and wall furnaces.

CONCLUSIONS

This paper discusses two methods for controlling the furnace temperature in a floor and a wall fire resistance furnace. It also discusses the heat flux received by a specimen in a floor and wall furnace controlled by either shielded thermocouples or by the Plate Thermometers. Based on the results mentioned above, the following key trends can be highlighted:

1. For the initial fire exposure (10 min) in either a floor or a wall furnace controlled by either the shielded thermocouples or by the Plate Thermometers, the difference between furnace temperatures measured by shielded thermocouples and by the Plate Thermometer is significant. However, after 10 min, the difference is insignificant.
2. In the initial fire exposure (10 min) in either a floor or a wall furnace controlled by the shielded thermocouples, the specimen received peaks of up to 100% more heat flux than when the same furnace is controlled by the Plate Thermometers. However, after 10 min, the floor and wall furnace specimen received 12% and 5%, respectively, more heat flux than when the same furnace is controlled by the Plate Thermometers.
3. For furnaces controlled by the shielded thermocouples, the specimen in the wall furnace receives a similar heat flux as for the specimen in the floor furnace.
4. In furnaces controlled by Plate Thermometers, the specimen in the wall furnace received about 15% more heat flux than the specimen in the floor furnace.

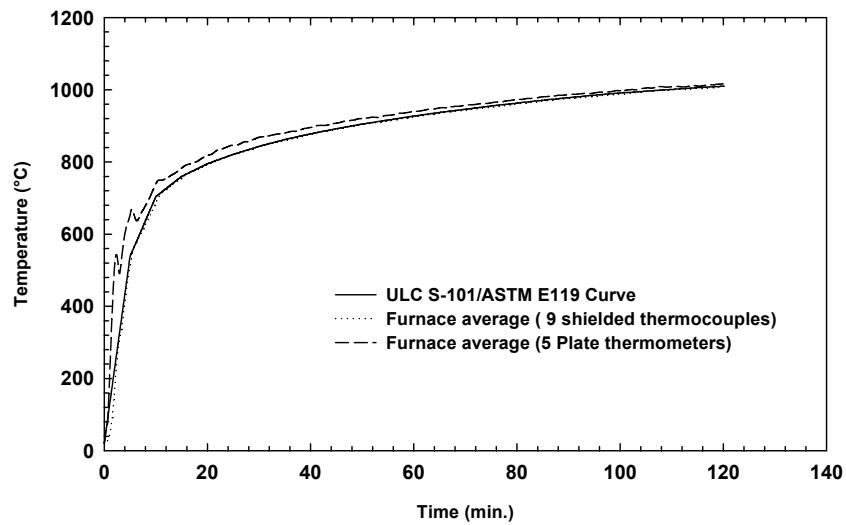


Figure 7 Comparison of Floor Furnace Temperature (Shielded Thermocouples)

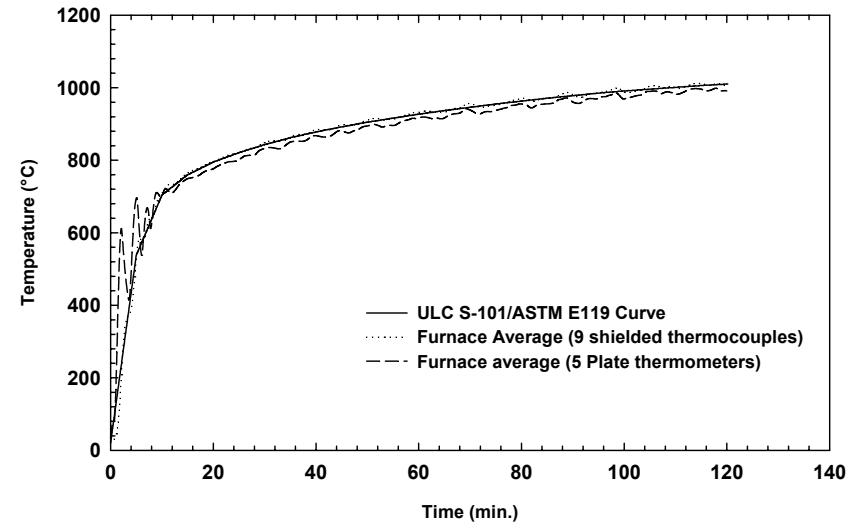


Figure 9 Comparison of Floor Furnace Temperature (Plate Thermometers)

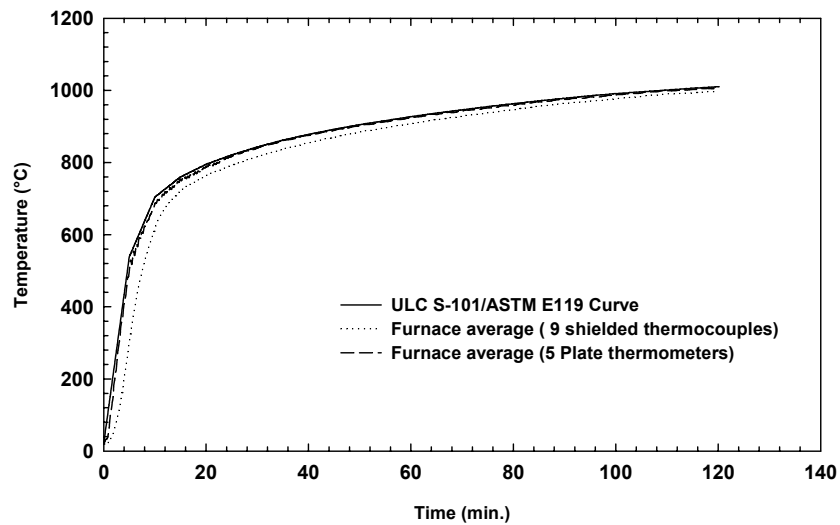


Figure 8 Comparison of Wall Furnace Temperature (Shielded Thermocouples)

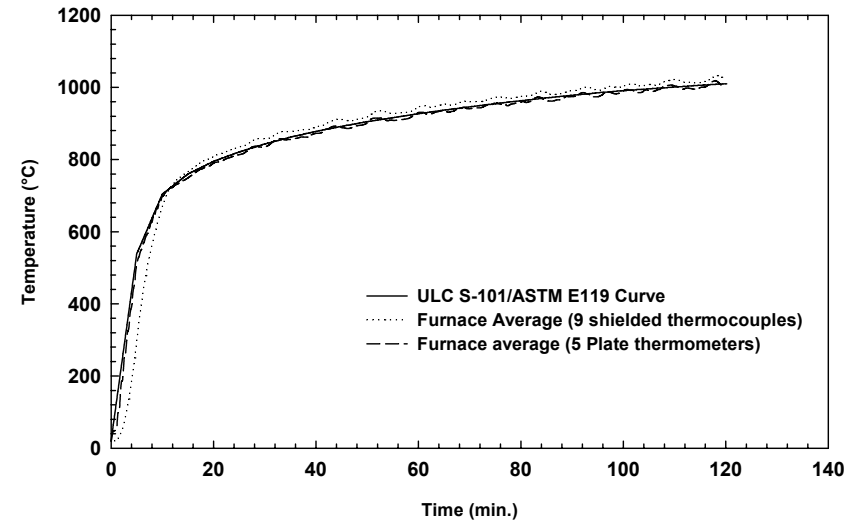


Figure 10 Comparison of Wall Furnace Temperature (Plate Thermometers)

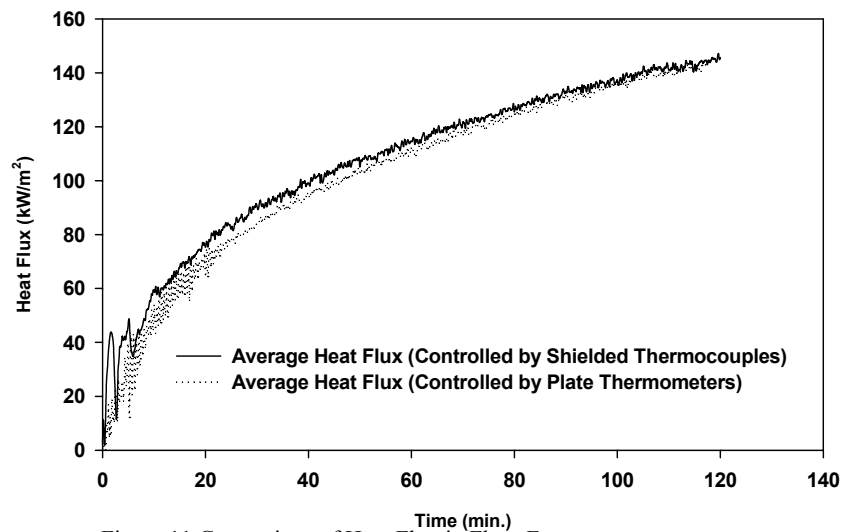


Figure 11 Comparison of Heat Flux in Floor Furnace

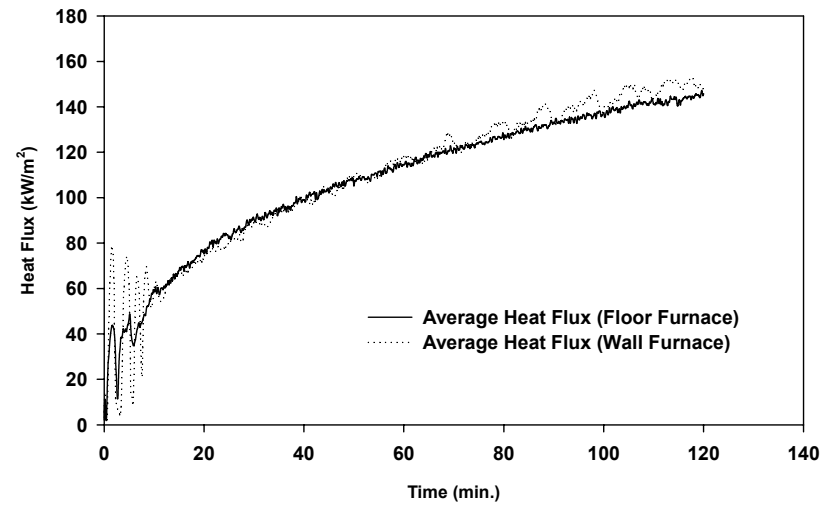


Figure 13 Comparison of Heat Flux (Shielded Thermocouples)

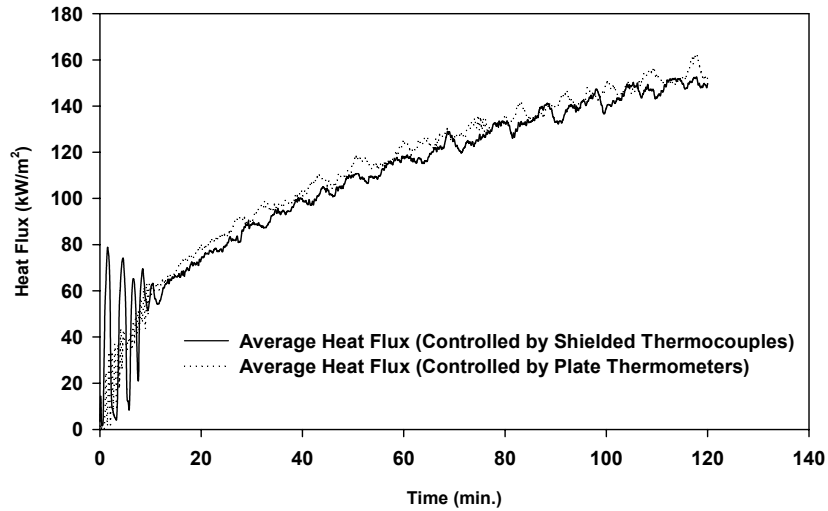


Figure 12 Comparison of Heat Flux in Wall Furnace

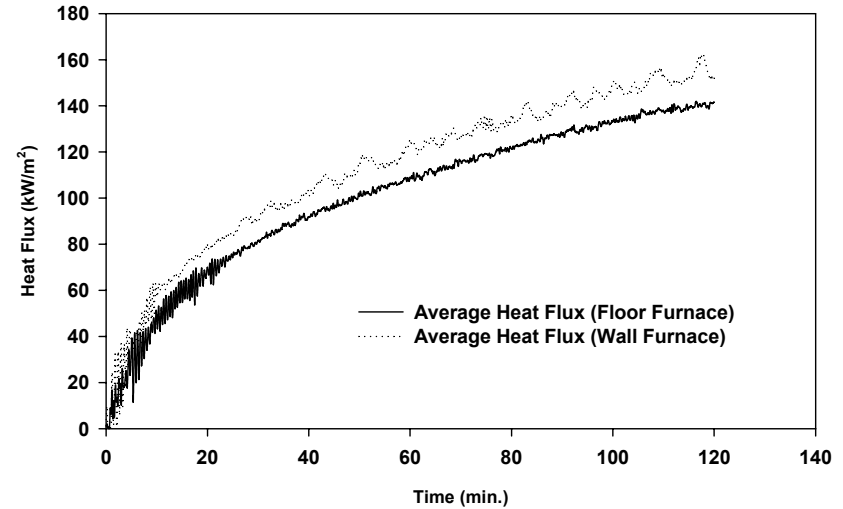


Figure 14 Comparison of Heat Flux (Plate Thermometers)

ACKNOWLEDGEMENTS

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