STUDY REPORT

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Effective Passive Roof Venting using Roof Panels in the Event of a Fire

Part 2: Preliminary Experimental Results

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BUILDING RESEARCH

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Preface

This report was prepared as a result of a preliminary modelling and experiment investigation of materials, general designs and test methods for passive roof venting during a fire event to determine appropriate standard test methods, performance criteria and any other design requirements for regulation. This report summarises the preliminary experimental investigation.

Acknowledgments

This work was funded by the Building Research Levy.

Note

This report is intended for regulatory authorities, researchers, manufacturers, fire engineers and designers.

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Part 2: Preliminary Experimental Results

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Reference

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Abstract

This report comprises Part 2 of a three-part series on aspects investigating passive buoyancy-driven roof fire vents in large floor area single storey buildings.

The primary objective of this report is to describe the preliminary small-scale test apparatus developed to assess fire venting potential of roof sheeting. Recommendations based on the analysis of this investigation are presented.

The scope of this report is limited to the development of a potential test method for assessing the potential fire venting characteristics of roof sheeting. Assessment of specific materials and proprietary systems was outside the scope of this project, since roof construction method, specific engineering additives to the base material and geometry (e.g. thickness) contribute to the fire venting performance of the sheeting.

Since there are no current standard test methods for determining the performance of roof sheeting to be used as passive roof fire venting, a test method was developed. This new test method was based on modifying an existing standard test method for dedicated buoyancy driven roof fire vents, AS 2428.3 (2004). The only attribute of fire venting that was considered as part of this project is the formation of openings for venting of hot products. Other requirements for roofing materials or roof vents (such as durability, rain leakage, etc.) were considered outside of the scope of this project.

The general concept of the test method is to subject a specimen (2.7 x 1.4 m), which represents a section of roof, including a potential venting panel, to hot combustion gases on a reduced scale and the potential venting characteristics are observed and recorded.

The results from the analysis presented here alone are not designed to provide a definitive answer as to the appropriateness of the potential use of plastic panels for passive fire venting. This is discussed in Part 3 of this series of reports. However several important aspects highlighted in the results of this study include:

1. The reduced-scale test described here would be suitable for determining the venting characteristics of a roof sheeting panel for temperature rate increases in the range of the moderate (10 ± 2°C per minute average) and rapid (200 ± 20°C per minute average) temperature increases used here.
2. Pass criteria for the reduced-scale test must be carefully selected to incorporate the fundamental processes involved in the formation of an opening in a panel material and the desired overall performance in a building design. One example is the selection of a maximum temperature, such that the gas temperatures

below the roof section test specimen must be maintained below this maximum temperature while subjected to a pre-determined gas flow rate over the duration of the test. Another example is a minimum effective open area (e.g. 1 m^2) that forms before the end of the test.

3. The test specimen must be constructed in accordance with the intended installation in a building. This is to include rafters, purlins, surrounding roof cladding (e.g. iron sheeting), fasteners, etc, and mesh, condensation wrap, etc, where required.

4. The appropriate portion of the roof area required to be constructed of tested venting roofing panels needs to be assessed based on the building design.

5. Tested venting panels do not have the same venting characteristics as dedicated venting systems.

6. Appropriate concessions for the inclusion of tested venting roofing panels in a building needs to be assessed.

It is noted here that the experiments performed here were designed to develop a potential test method for roof panels that might be used for fire venting. The materials tested were not assessed as to their appropriateness for fire venting. Testing of individual products could be tested in the future, after discussion and establishment of the appropriateness of this, or another test method, and the associated pass criteria.

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Acronyms

C/AS1	Fire Safety Compliance Documents (C Clauses), Acceptable Solution
GRP	Glass-fibre Reinforced Polyester
NZ	New Zealand
NZBC	New Zealand Building Code
NZFS	New Zealand Fire Service

1. INTRODUCTION

This report comprises one part of a series on aspects investigating passive buoyancy-driven roof fire vents in large floor area single storey buildings.

In large area single storey buildings, "…although a fire may involve only a relatively small area of the floor, the smoke and hot gases will quickly fill the building and experience has shown that the fire can be completely concealed before the arrival of the fire brigade." (Thomas et al 1963) Fire-fighting is then difficult and dangerous, since the fire must be located within the building and the smoke and heat conditions may be sufficiently severe to limit the fire brigade to conducting an external fire attack. External attacks are ineffective as fire hose streams rarely reach the seat of the fire to extinguish it and this only results in more water damage and contaminated run-off. The temperature of the hot smoke layer trapped beneath the roof may also be sufficiently high to cause softening or failure of unprotected roof construction or ignite flammable roof materials.

A passive fire venting system relying on buoyancy of the hot fire products to provide the driving force for removal of the hot gases has advantages: simplicity, effectiveness in a wide range of fire conditions and independence from any available power supply that may be disrupted during a fire. For example, the rate of removal of hot gases is largely dependent upon the depth and temperature of smoke. Therefore if a fire grows larger than the assumed design point used to calculate the venting, then a larger depth and higher temperature of gases would lead to an increased flow rate through the vent (i.e. venting of the hot products would still occur, but the desired level of 'effectiveness' may not be achieved). Thus a passive fire venting system has an element of self-compensation (Morgan and Gardner 1990). However, as with all 'reliable' and "effective" systems, the reliability and effectiveness must be determined through demonstration of design.

1.1 Motivation

The motivation for this series of reports includes:

- The New Zealand Building Act (2004) does not require building owners to consider owner property protection and consequently most industrial buildings have been constructed in the expectation that insurers will cover the fire loss.
- Fires in large industrial buildings can be very difficult for the fire service to control and extinguish. To assist fire service operations, the Building Code Compliance Document C/AS1 (2001, with Amendments up to October 2005) places a limit on the maximum compartment floor area in unsprinklered buildings (typically 1500 m²). This is designed to limit the total fire load in a firecell to less than 2 million MJ.
- No subdivision of the building is required if at least 15% of the roof area (distributed evenly throughout the firecell) is designed for effective fire venting. Subdividing large industrial buildings is often undesirable for functional reasons, and therefore the roof venting option is a popular one.
- No detailed specification or standard is currently referenced in the compliance document to ensure that fire venting is 'effective'. The current performance and effectiveness of these systems is therefore not well understood.
- There is also the question of the location or distribution of the panels over the area of the roof. An even distribution across the roof area is appropriate for flat

or very shallow roofs, but venting in steep roofs would be more effective if located near the apex.

Detailed guidance on how to assess the effectiveness of roof venting systems leading to appropriate specifications for them is desperately needed. Mechanically operated smoke and heat venting systems for fire are established technology overseas and various codes and standards do exist that may be suitable for use in NZ. Passive systems such as dedicated units utilising drop out panels are less common.

1.2 Objective

The objectives of this report are to:

1. Report on the preliminary small-scale test apparatus developed to assess fire venting potential of roof sheeting.
2. Present recommendations based on the analysis of this investigation.

1.3 Scope

The scope of this series of reports is limited to researching the appropriateness of buoyancy-driven fire venting relying on the passive failure and subsequent openings formed in plastics roofing materials to create an opening for the roof to vent hot combustion gases. Other roofing related criteria, such as durability, rain leakage, etc. that are important factors in roof performance, are considered to be outside of the scope of this project. Active or mechanically operated venting systems are also outside the scope.

The scope of this report is limited to the development of a potential test method for assessing the potential fire venting characteristics of roof sheeting. Assessment of specific materials and proprietary systems is outside the scope of this project, since roof construction method, specific engineering additives to the base material and geometry (e.g. thickness) contribute to the performance of the sheeting.

2. INTENT OF 'EFFECTIVE FIRE VENTING'

Following on from the above discussion of the current C/AS1 (2001) requirements, the intent of fire venting is assumed, for the purposes of this research, to be defined as:

Fire venting is a system designed for the removal of hot fire gases during the initial growth phase of the fire in order to reduce the hot smoke logging and thermal loading of the compartment to facilitate fire-fighting operations (in terms of rescue, if necessary, and protection of other property).

That is fire venting contributes directly to the New Zealand Building Code directive to facilitate fire-fighting operations and indirectly to the directive of protection of other property.

Fire venting may operate within or after the maximum permitted escape times have been surpassed coincidentally, as fire venting design is not related to occupant escape time. Furthermore passive fire venting is not interlinked with smoke or heat detection used for alerting occupants and is thus potentially related to facilitation of escape. Therefore fire venting is assumed to not contribute to life safety of the initial occupants of a building.

2.1 Performance Criteria for Fire Venting

As for the preliminary modelling part of this study (Robbins & Wade, 2008a), the performance criteria for fire venting was defined as:

At the time first fire suppression activities begin the conditions within the building are:

- *a maximum radiation of 4.5 kW/m² at 1.5 m above the floor, and*
- *a minimum height to the bottom of the smoke layer of 2.0 m.*

The time to first fire suppression activities was taken as 1,000 s.

The background for the parameter values for these performance criteria is discussed in detail in the preliminary modelling section of this study (Robbins & Wade, 2008a).

For this preliminary reduced-scale experimental study, the performance criteria are defined in terms of a single roofing sheet instead of building conditions. These were selected as forming an opening for hot gases to pass through unimpeded before the end of a test when subjected to a heating regime up to 300°C. The details of the definitions of "opening" and the heating regimes are discussed in the following section.

3. PRELIMINARY EXPERIMENT SETUP

3.1 Test Apparatus Description

Since there are no standard test methods for determining the performance of roof sheeting to be used as passive roof fire venting, a test method was developed based on modifying an existing standard test method for dedicated buoyancy driven roof fire vents, AS 2428.3 (2004). The only attribute of fire venting that was considered as part of this project is the formation of openings for venting of hot products. Other requirements for roofing materials or roof vents (such as durability, rain leakage, etc.) were considered outside of the scope of this project.

The general concept of the test method is to subject a section of a roof to hot combustion gases on a reduced scale and to observe the venting behaviour

A variable output propane gas burner (as in ISO 9705 1993) is used to provide hot combustion gases to the underside of the roof section. The burner is located centrally beneath the test specimen.

A sheet metal draught curtain with a depth of 300 mm is fitted below the test specimen. The lower edge of the draught curtain was initially 600 mm above the floor height. After analysis of initial tests, the height of the lower edge of the draught curtain was increased to 900 mm above the floor height to reduce visible flames above the second layer of baffles.

The potential vent is shielded from direct flame impingement and radiation by a non-combustible shield (25 mm thick cement fibre board). Flames are not to extend beyond the lower level of the smoke curtains. This is important since

1. a fire vent is unlikely to be positioned directly over a fire and therefore have reduced incident radiation to assist in the formation of any potential openings, and
2. flame impingement on the roof during a the early stages of a fire is a highly unlikely scenario.

The vent is shielded by two layers of segmented baffles to distribute the hot gases over the area of the test specimen. The layout of the layers of baffles is included in Appendix A, Figure 17. In the test apparatus, the baffles are suspended between two ledges directly below the bottom edge of the smoke curtain, with the lower layer of baffles located 75 mm below the first, as shown in Figure 1.

The roof is constructed with the panel for testing incorporated as would be used in practice. This includes rafters, purlins, sections of non-venting roofing construction either side of the potential venting panel, fasteners and safety mesh, and may include condensation wraps, etc., such that the centre section of the specimen demonstrates the minimum spacing between each of the components as would be expected in use. The available dimensions for the test specimen were 2700 x 1400 mm, as shown in Figure 1.

A grid of 12 K-type thermocouples is located 100 mm below the top edge of the smoke curtain, where the test specimen is attached. The spacing of the thermocouple grid is shown in Figure 3. A small hole in the corner of the smoke curtain is for the thermocouple wiring.

A schematic of the overlap of the upper and lower baffles and the thermocouples is included in Appendix A, Figure 19.

Photographs of the test apparatus are shown in Figure 2.

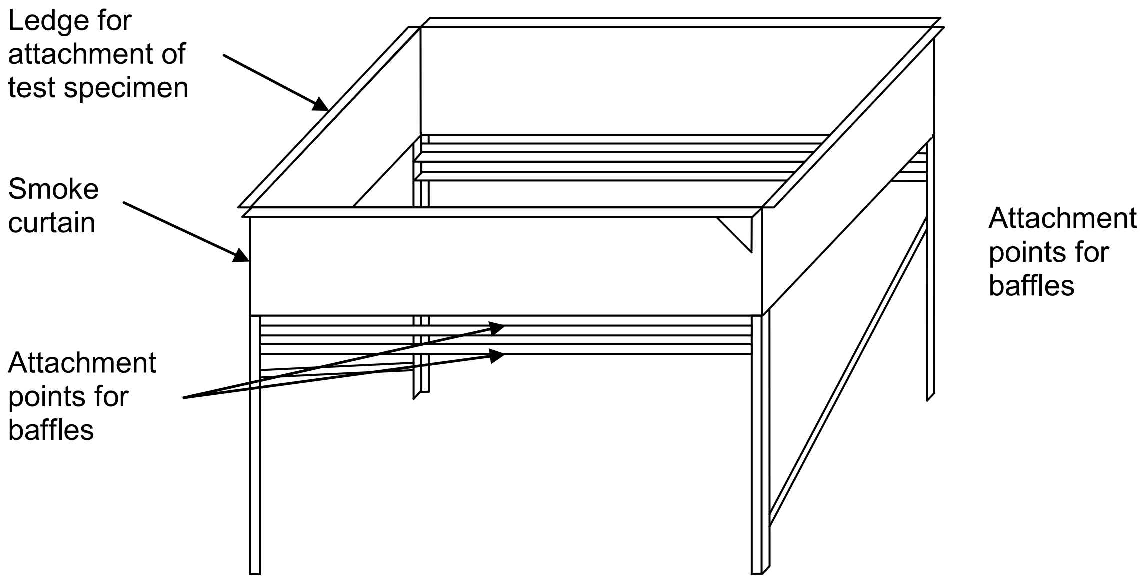
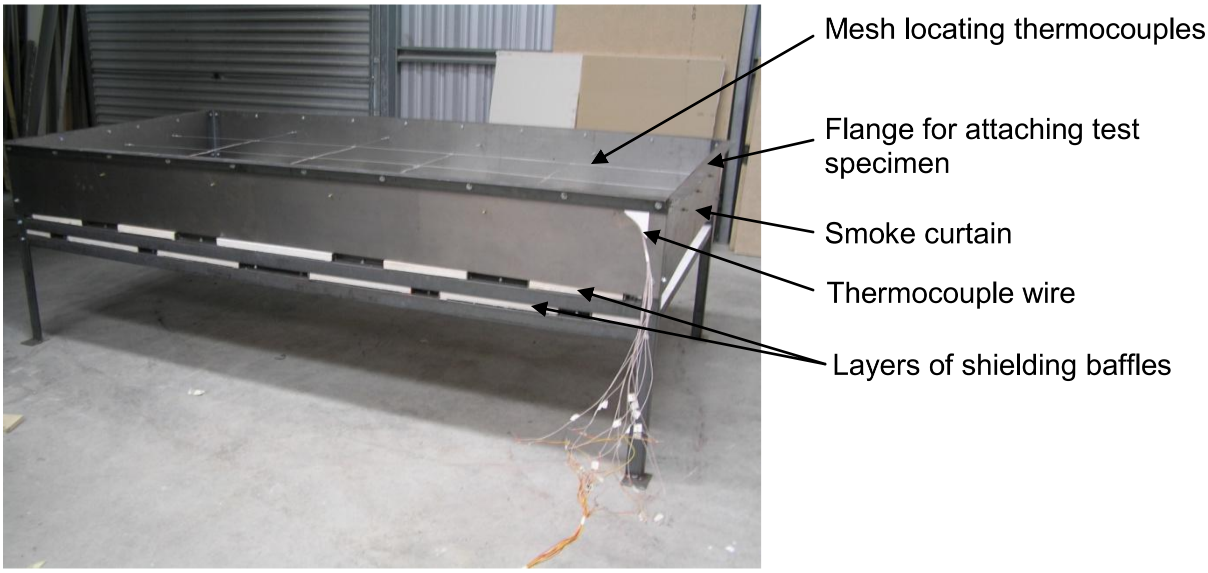
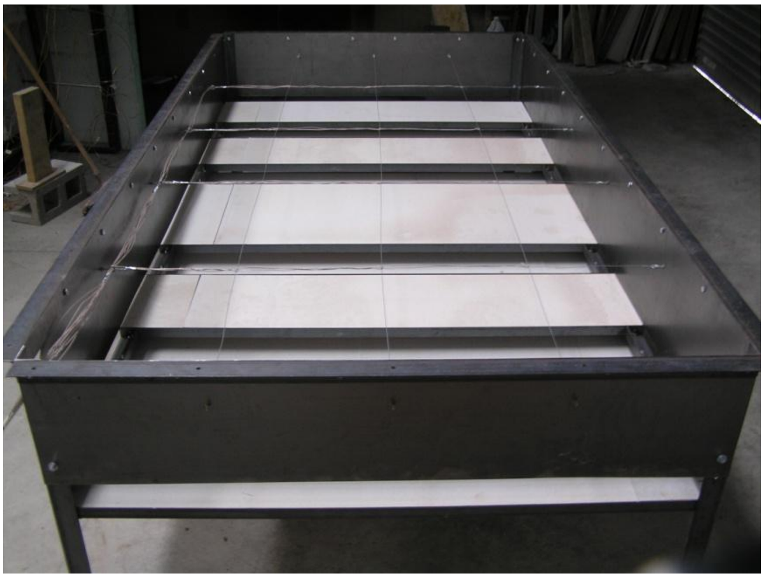


Figure 1: Schematic of the test frame. Not to scale.



(a)



(b)

Figure 2: Test apparatus.

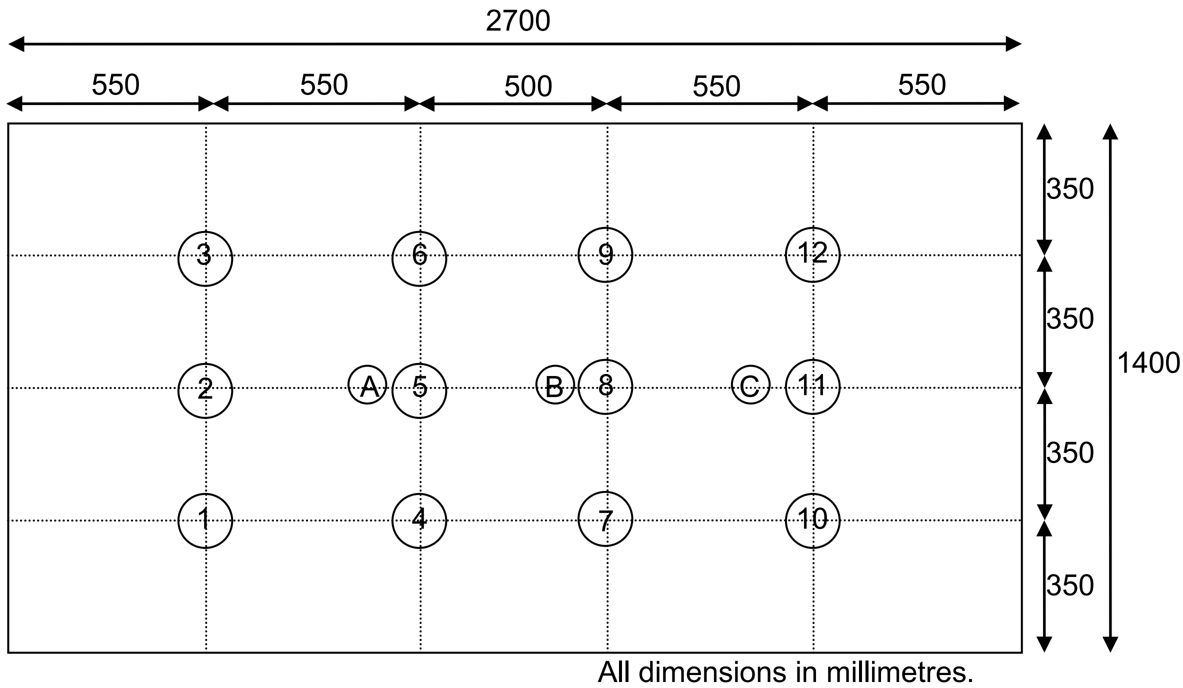


Figure 3: Schematic of thermocouple locations on the inside of the test apparatus.

3.2 Test Matrix

3.2.1 Temperature Conditions

Two rates of temperature increase were considered: a rapid heating rate and a slow heating rate, similar to the conditions required for AS 2428.3 (2004). For the rapid heating rate, the average temperature of the thermocouples located 100 mm below the underside surface of the test material is raised from ambient temperature to a maximum temperature of 300°C at a rate of 200±20°C per minute. For the slow heating rate, the average temperature of the thermocouples located 100 mm below the underside surface of the test material is raised from ambient temperature to a maximum temperature of 300°C at a rate of 10±2°C per minute. These conditions are summarised in Table 1.

Table 1: Summary of test temperature conditions considered

Rate of Temperature Increase	Rate of Average Temperature Rise	Maximum Temperature Reached
Rapid Heating Rate	200±20°C per minute	300°C
Slow Heating Rate	10±2°C per minute	300°C

3.2.2 Test Specimens

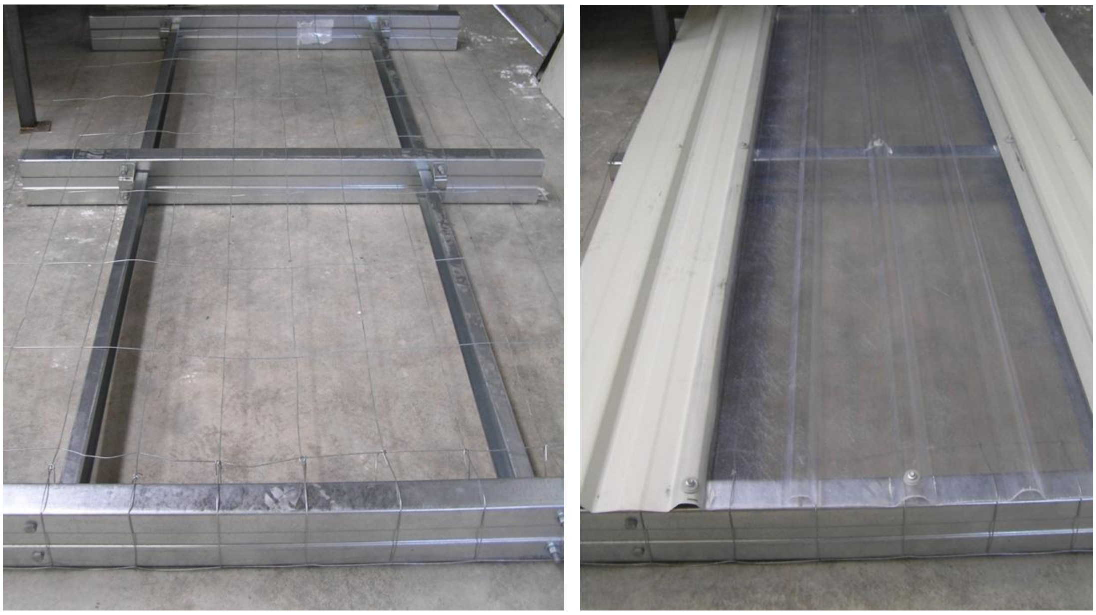
It is intentional that the materials used in the specimens used for testing are not described in this report. The reasons for this include that a single specimen cannot be representative of a general type of polymer (i.e., polymers can be engineered for performance and changing one property may affect the fire and/or fire venting performance characteristics), and material thicknesses and installation combinations would also potentially change the fire venting characteristics of a panel.

The test specimens were constructed similar to their end use configuration, as described in Section 3.1, using purlins, spacers and safety mesh with the roof sheeting attached so that the plastic sheeting is central, as shown in Figure 4.

A summary of the test specimens used as part of this research is presented in Table 2.

Table 2: Summary of the test specimens

Test Specimen	Description
Plasterboard	Used for initial calibration of the apparatus
Specimen A	Used to develop experience of test method characteristics from observations of potential specimen behaviour
Specimen B	



(a) (b)

Figure 4: Example of a test specimen before being placed on the test apparatus, showing (a) before the roof sheeting is attached and (b) after roof sheeting is attached.

3.2.3 Tests Performed

Establishing the test apparatus characteristics without the complications of openings changing the conditions within the test apparatus was of upmost importance. Before example test specimens were trialled, the test apparatus characteristics were investigated. A summary of the tests performed as part of this research is presented in Table 3.

Table 3: Summary of tests performed

Test Number	Test Specimen	Rate of Temperature Increase
1	Plasterboard	Slow
2	Plasterboard	Slow
3	Plasterboard	Slow
4	Plasterboard	Rapid
5	Plasterboard	Rapid
6	Plasterboard	Rapid
7	Plasterboard	Rapid
8	Plasterboard	Rapid
9	Plasterboard	Rapid
10	Plasterboard	Rapid
11	Plasterboard	Rapid
12	Plasterboard	Rapid
13	Specimen A	Slow
14	Specimen B	Slow
15	Specimen B	Slow
16	Specimen B	Slow
17	Plasterboard	Slow
18	Plasterboard	Slow
19	Specimen B	Slow
20	Specimen A	Rapid

4. TEST RESULTS

An example of the test results is presented here. A summary of the test results is included in Appendix B.

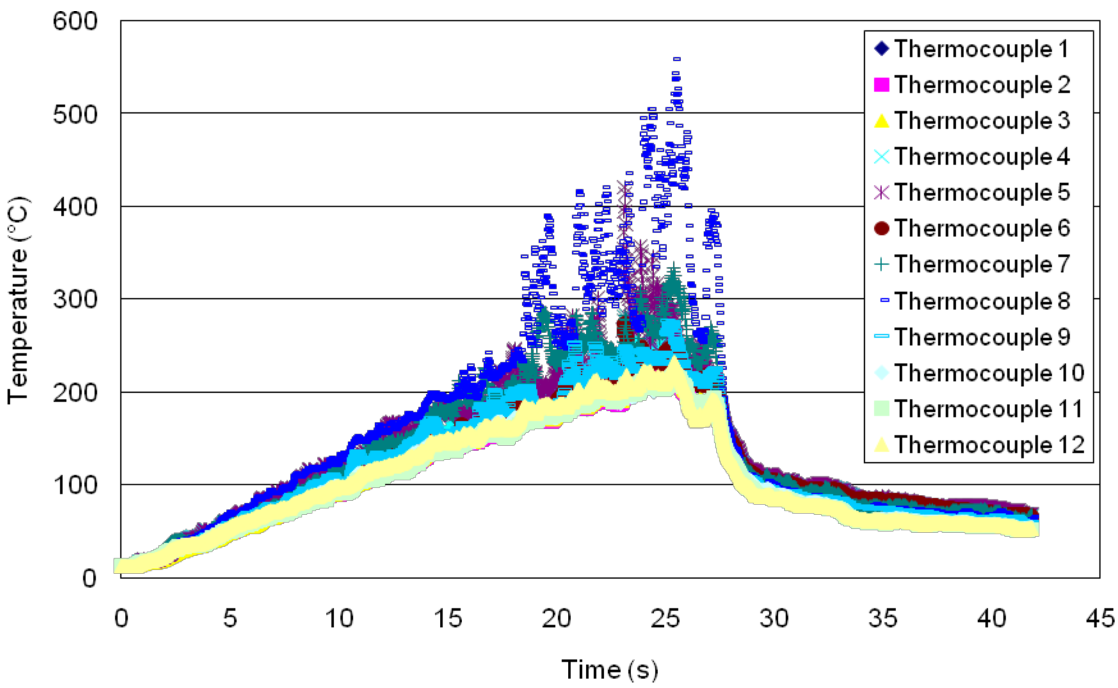


Figure 5: Example of the thermocouple measurements during the test (Test 19).

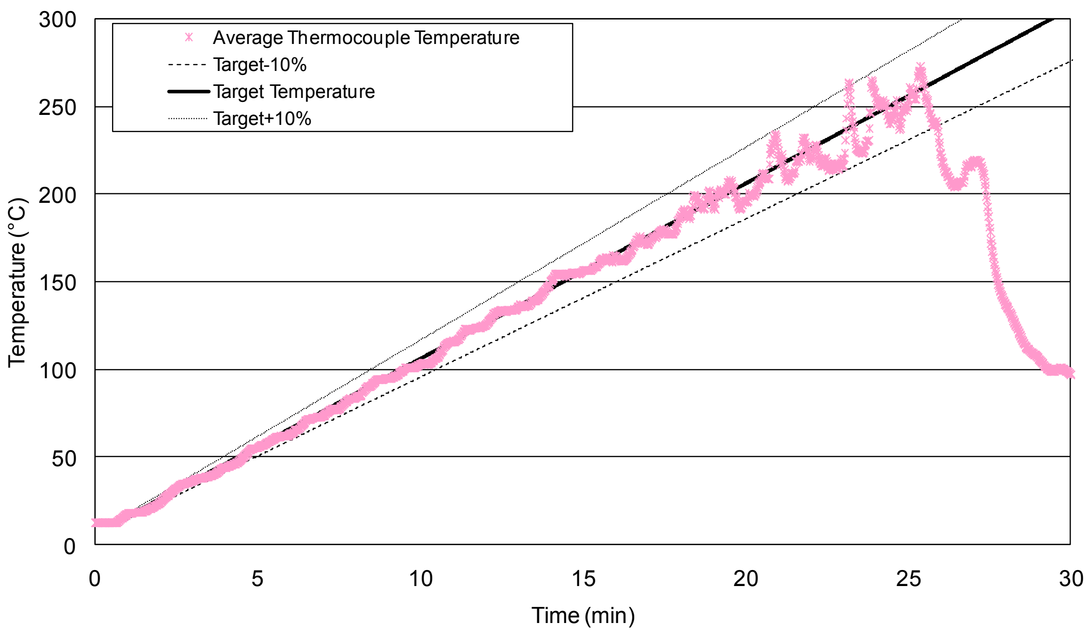


Figure 6: Example of the average temperature versus time compared with target temperature (Test 19).

Table 4: Example of the summary of observations during a test (Test 19).

Time from Burner Ignition (min)	Description of Observation
0	Burner ignited.
9	Deformation of panel in Section A.
10	Smoke rising from around edges of panel.
12	Deformation of panel, both sides of middle purlin. (Figure 104)
18	Sagging of panel both sides of middle purlin.
20	**Opening formed** in panel on Section B side of middle purlin. (Figure 105)
21.5	Glow from burner flames observed between baffles of top layer. No flame impingement on panel. (Figure 106)
27	Burner off. No flaming of panel material.
Post test observations	Panel shown in Figure 107.

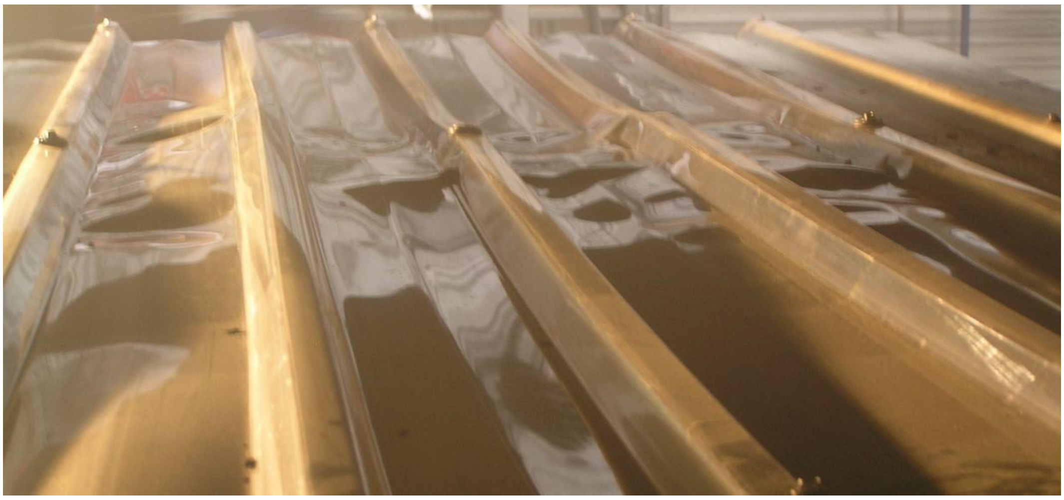


Figure 7: Deformation of panel. (Test 19 at 12 min from ignition of burner.)

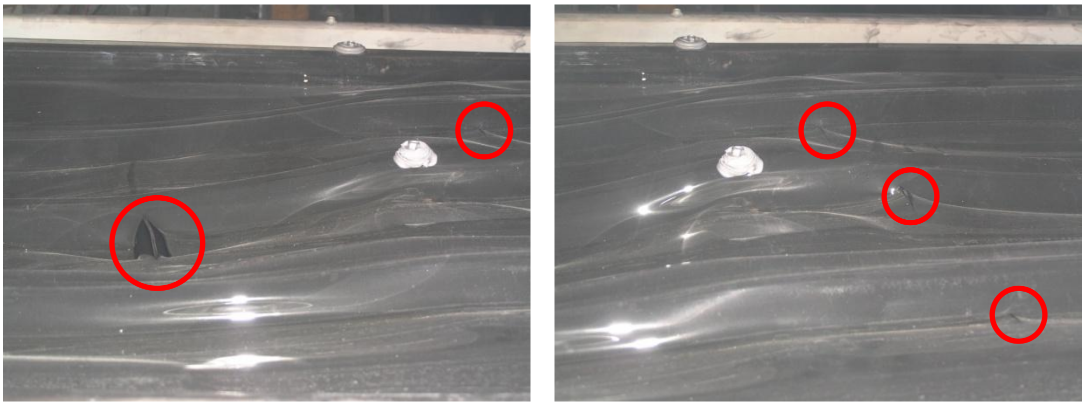


Figure 8: Openings formed in panel. (Test 19 at 20 min from ignition of burner.)

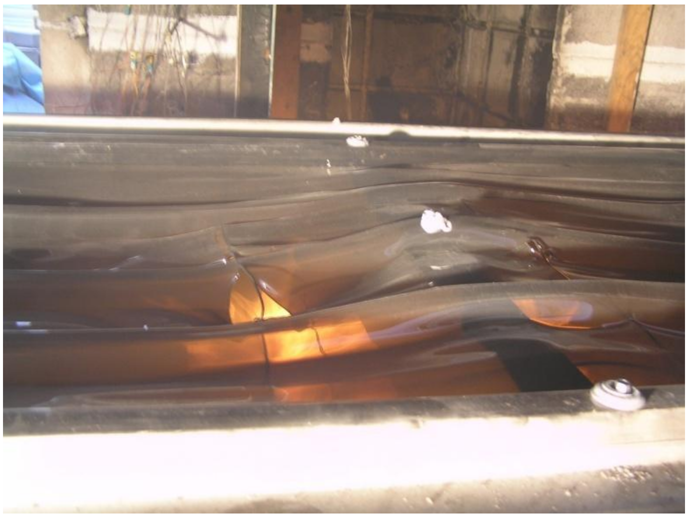


Figure 9: Flames seen around edges of baffles. (Test 19 at 21.5 min from ignition of burner.)

(a) **(b)**
Figure 10: Post-test specimen topside-down from (a) over head and (b) side on. (Test 19)

4.1 Accuracy & Repeatability

The accuracy associated with each of the measurements recorded is summarised in Table 5. The error associated with the K type thermocouple measurements is not displayed on results within this report, since the size of the data points used obscures them. The time of recorded observations had an accuracy of approximately ±15 s. However determining whether or not an opening has formed by observation is a subjective approach, therefore less accuracy is associated with this measurement (i.e. approximately ±30 s).

Table 5: Summary of measurement accuracies.

Parameter	Associated Accuracy
Thermocouple temperature (K type)	±1.5°C
Time of Observations	±15 s

Basing the estimate of the repeatability of the test method on 4 tests on the same specimen type that formed an opening. The observed time to formation of an opening varied from the average by up to 10%.

5. ANALYSIS OF TEST METHOD

The focus of this report is the test method for assessing the fire venting characteristics for roofing panels. One test (Test 19) is presented here as an example of the analysis of the test results. Details of other tests are included in Appendix B.

An example of the target temperature and the measured average thermocouple temperature with the timing of observations superimposed is shown in Figure 11. The matching of the average thermocouple temperature to the target temperature within ±10% of the target temperature was the driver for the test.

In order to gain a better insight into the fluctuations of the average thermocouple temperature, the difference between consecutive data points were considered. An example of the average thermocouple temperature difference between two and then three consecutive data points is shown in Figure 12. The temperature difference between two consecutive data points in excess of the target temperature increase was also considered (e.g. Figure 13 (a)).

Similarly, individual thermocouple temperature measurements with indications of observation timings superimposed are shown in Figure 14. The temperature difference between two consecutive data points during a test for individual thermocouples is shown in Figure 15. Moving averages (using 10 s worth of data) for the individual thermocouples in the vicinity of the resulting observed openings formed during the test are shown in Figure 16.

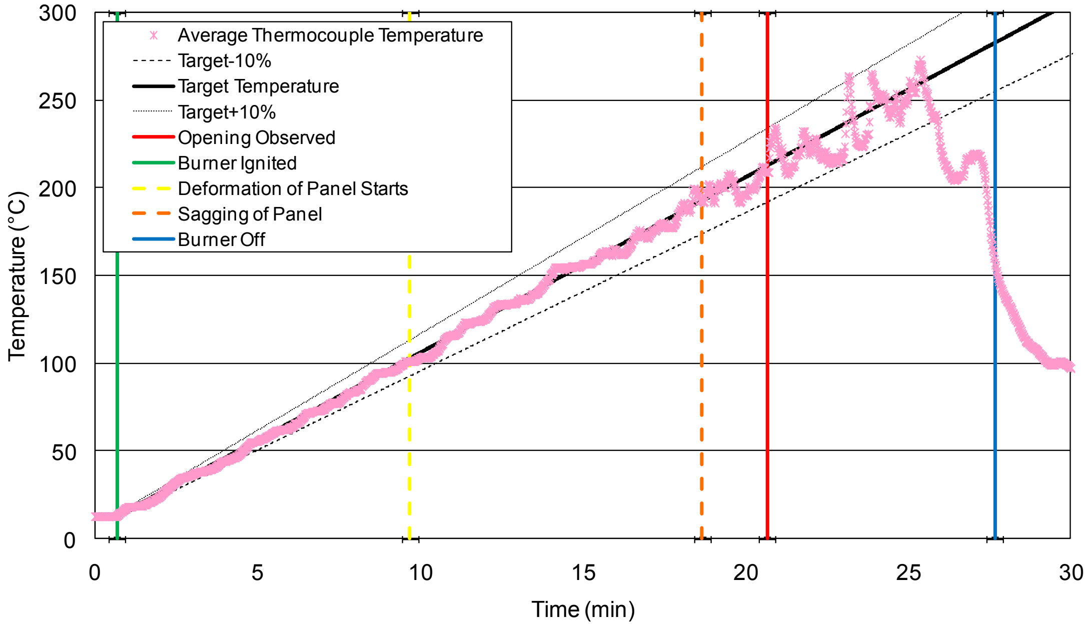
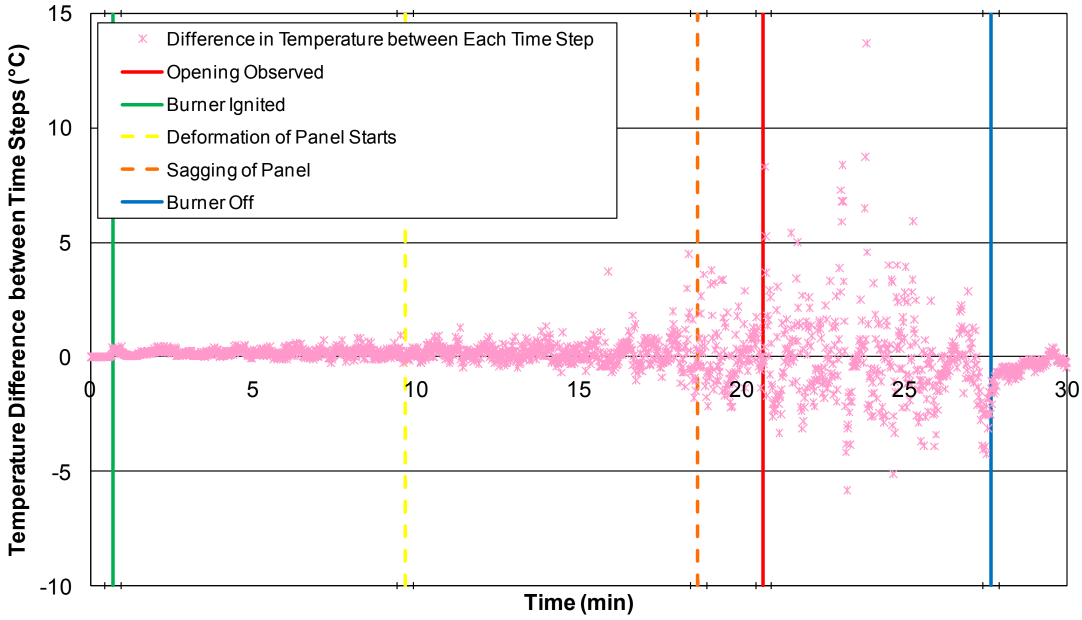
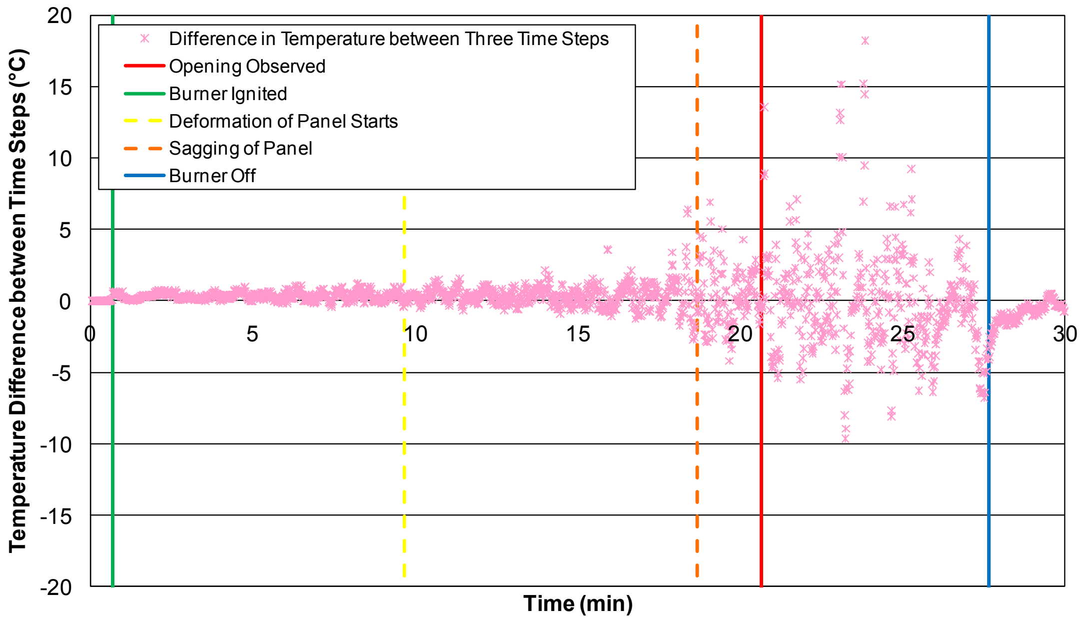


Figure 11: Example of the average thermocouple temperature with observations superimposed (Test 19).

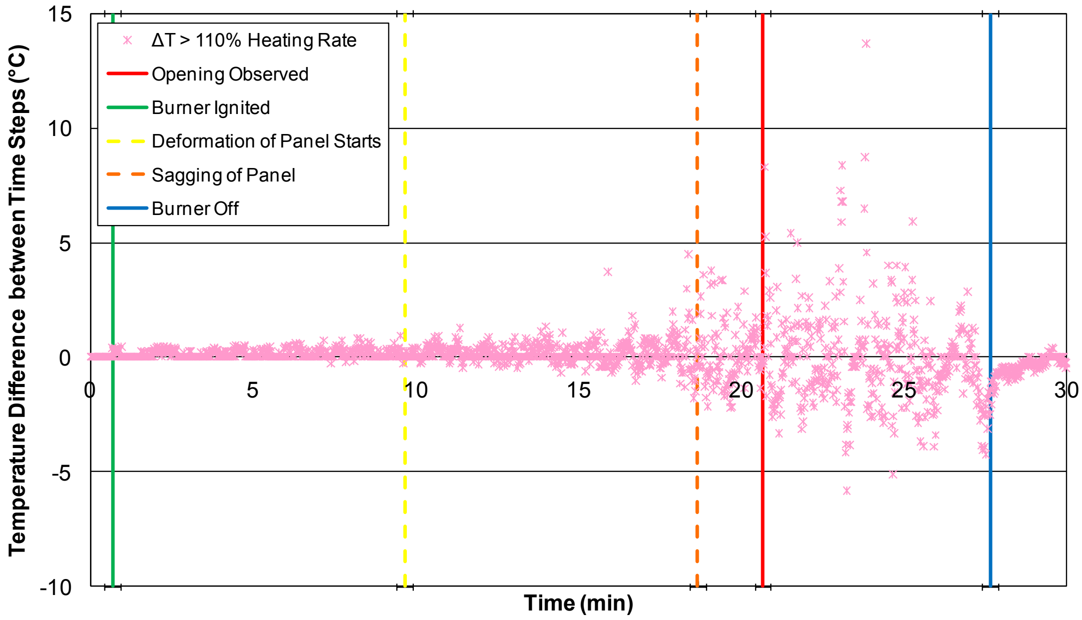


(a)

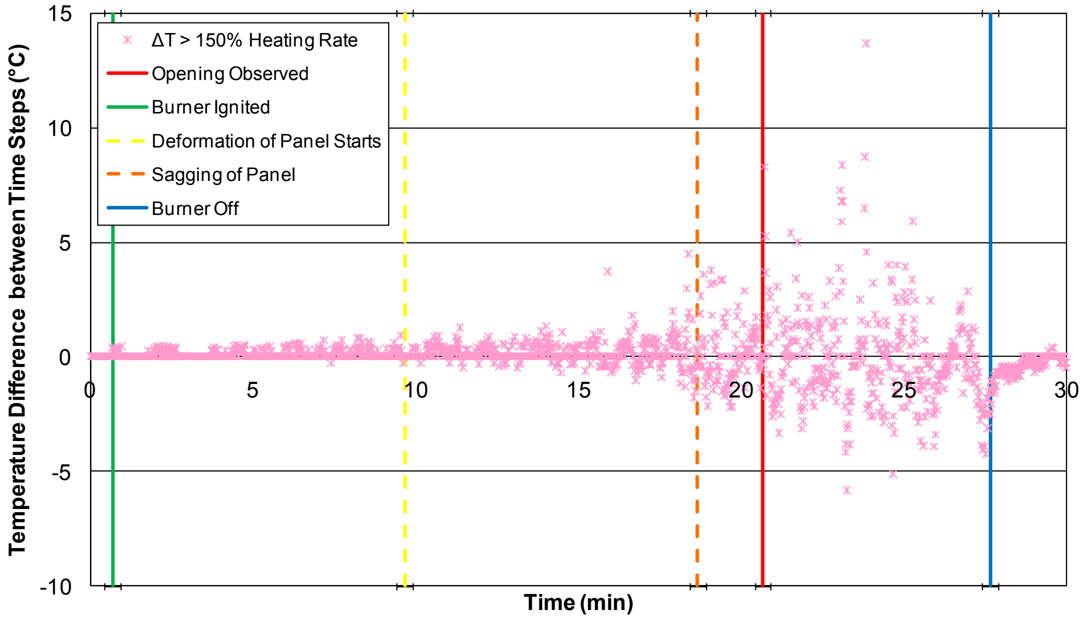


(b)

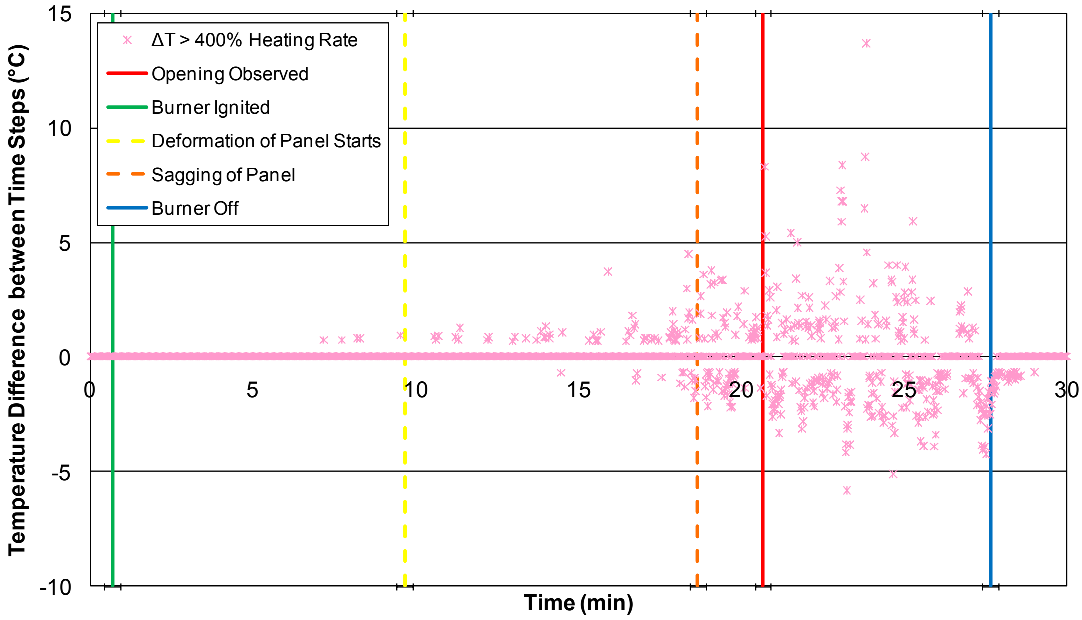
Figure 12: Examples of the temperature difference between (a) two and (b) three consecutive data points during a test (Test 19).


ΔT > 110% Heating Rate
Opening Observed
Burner Ignited
Deformation of Panel Starts
Sagging of Panel
Burner Off
Temperature Difference between Time Steps (°C)
Time (min)
15
10
5
0
-5
-10
0
5
10
15
20
25
30

(a)

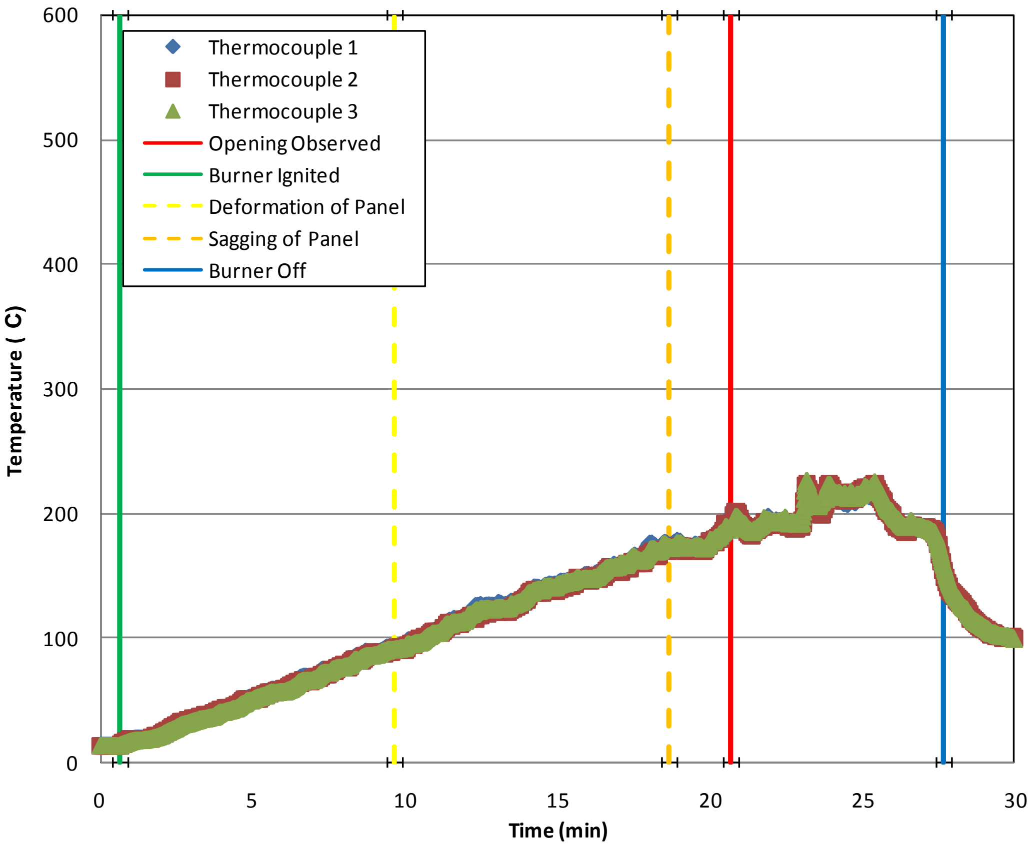

ΔT > 150% Heating Rate
Opening Observed
Burner Ignited
Deformation of Panel Starts
Sagging of Panel
Burner Off
Temperature Difference between Time Steps (°C)
Time (min)
15
10
5
0
-5
-10
0
5
10
15
20
25
30

(b)

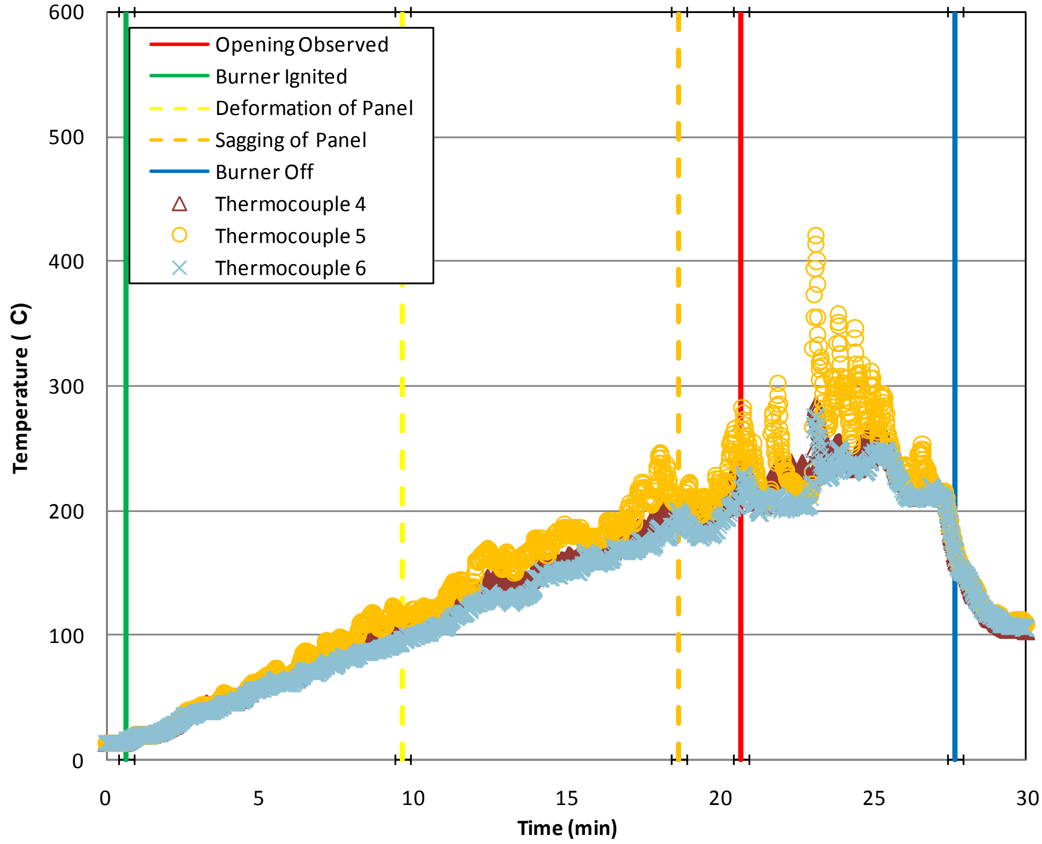


(c)

Figure 13: The temperature difference between two consecutive data points during a test that are in excess of the target temperature increase (Test 19).

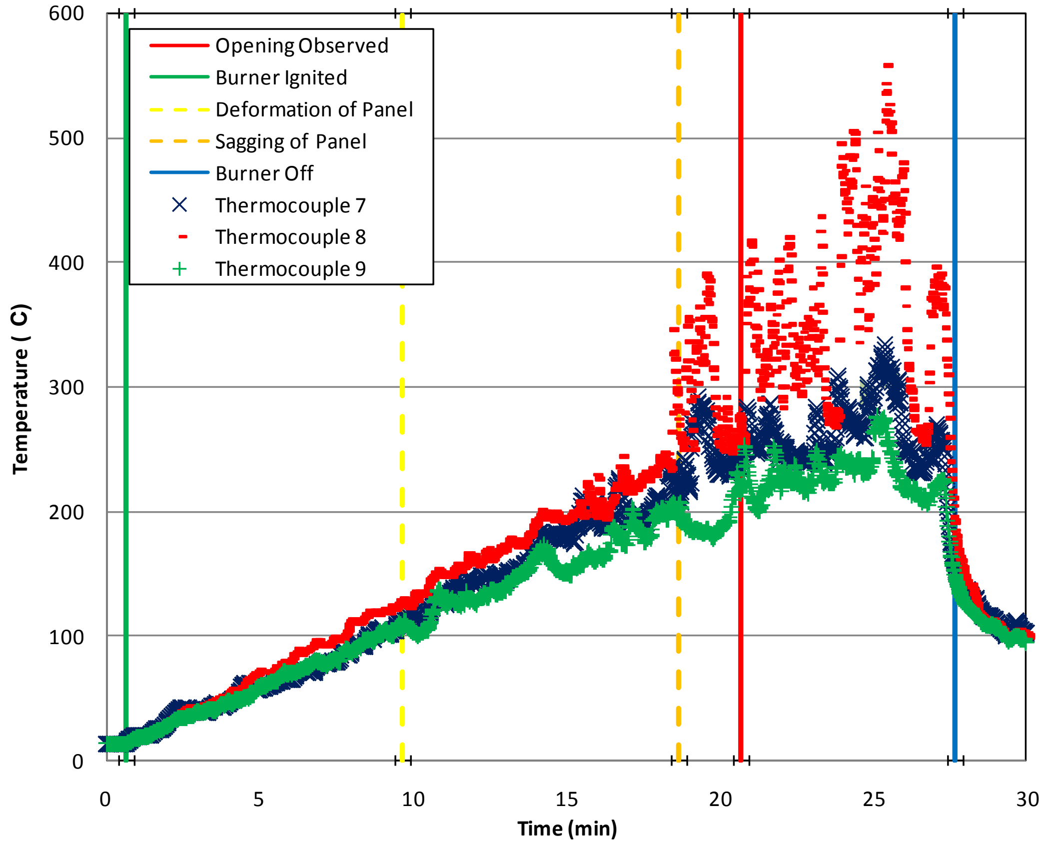


(a)



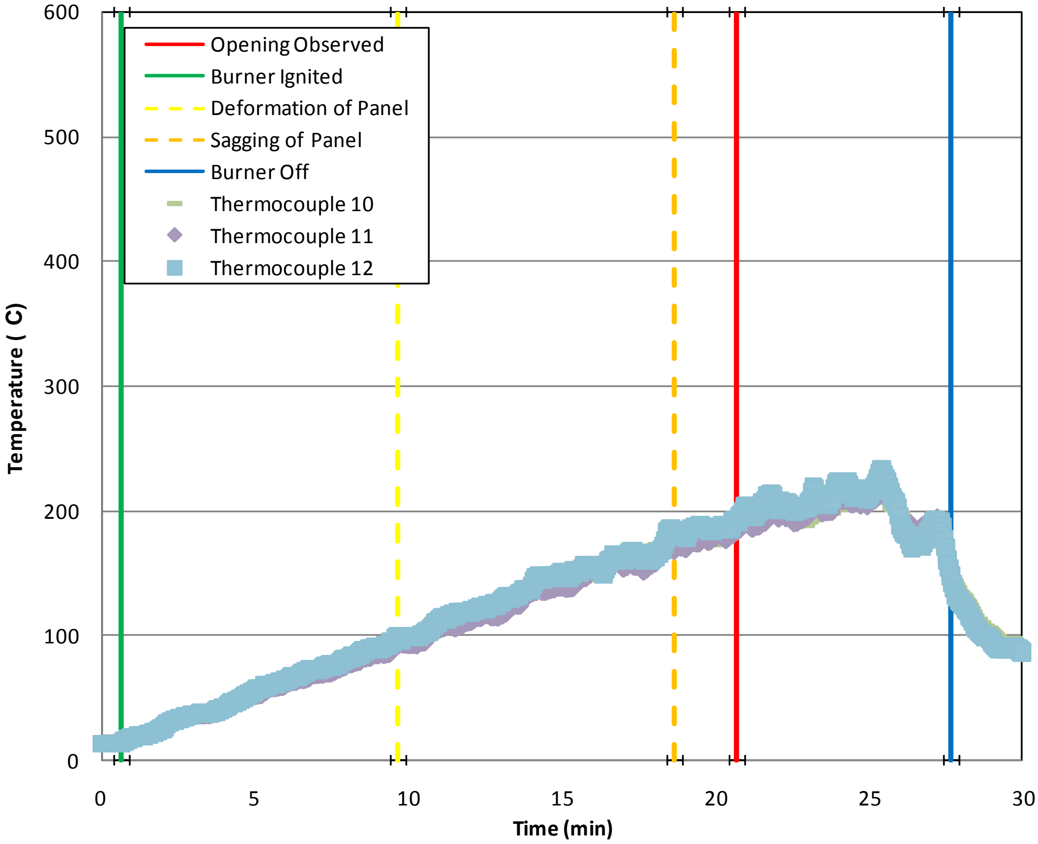
Opening Observed
Burner Ignited
Deformation of Panel
Sagging of Panel
Burner Off
Thermocouple 4
Thermocouple 5
Thermocouple 6
Temperature (C)
Time (min)
0
100
200
300
400
500
600
0
5
10
15
20
25
30

(b)



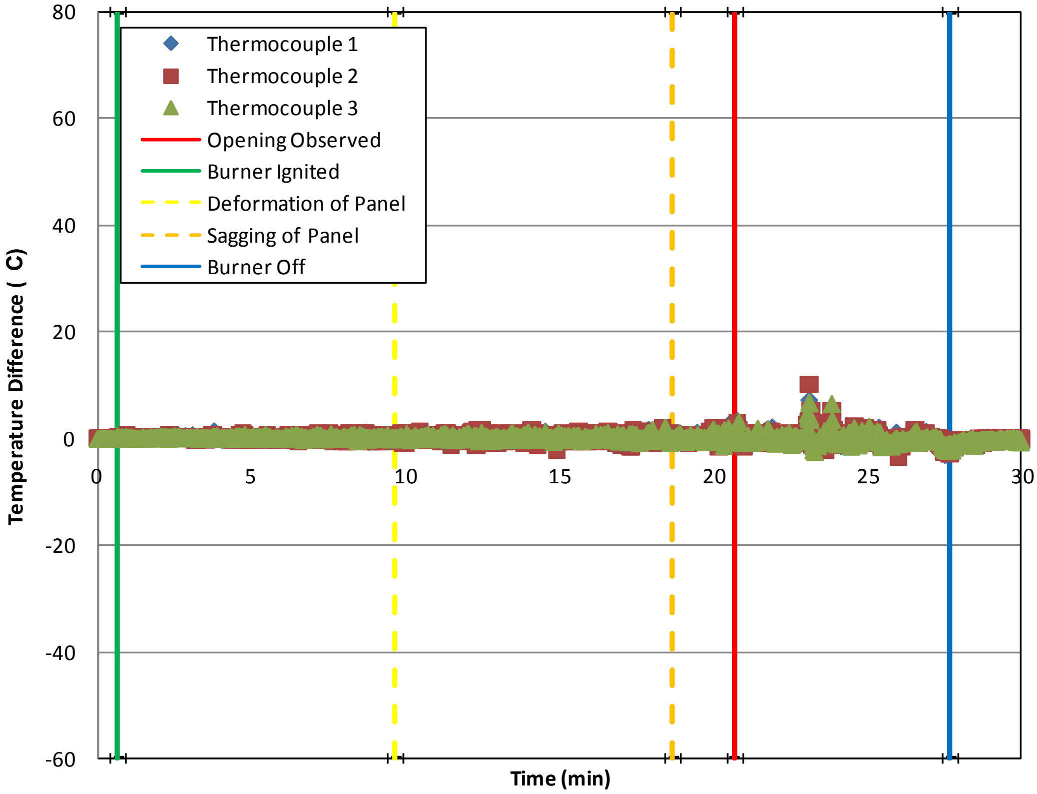
Opening Observed
Burner Ignited
Deformation of Panel
Sagging of Panel
Burner Off
Thermocouple 7
Thermocouple 8
Thermocouple 9
Temperature (C)
Time (min)
0
100
200
300
400
500
600
0
5
10
15
20
25
30

(c)



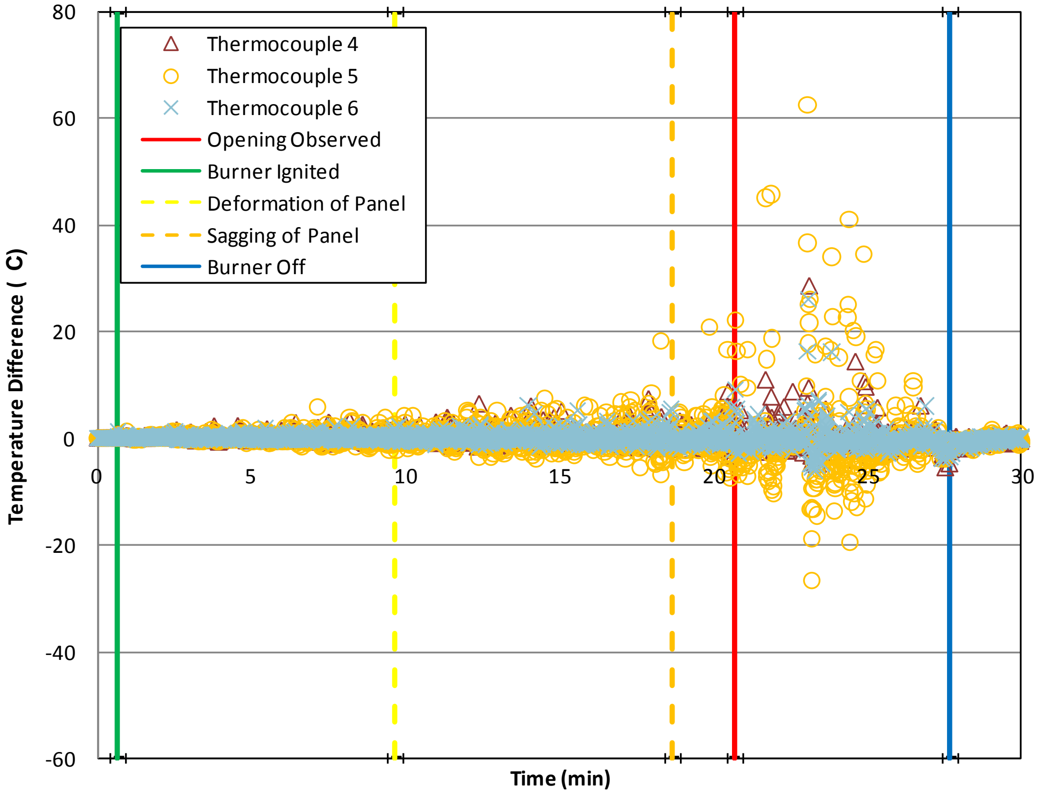
(d)

Figure 14: Example of thermocouple temperature measurements with indications of observation timings superimposed (Test 19).



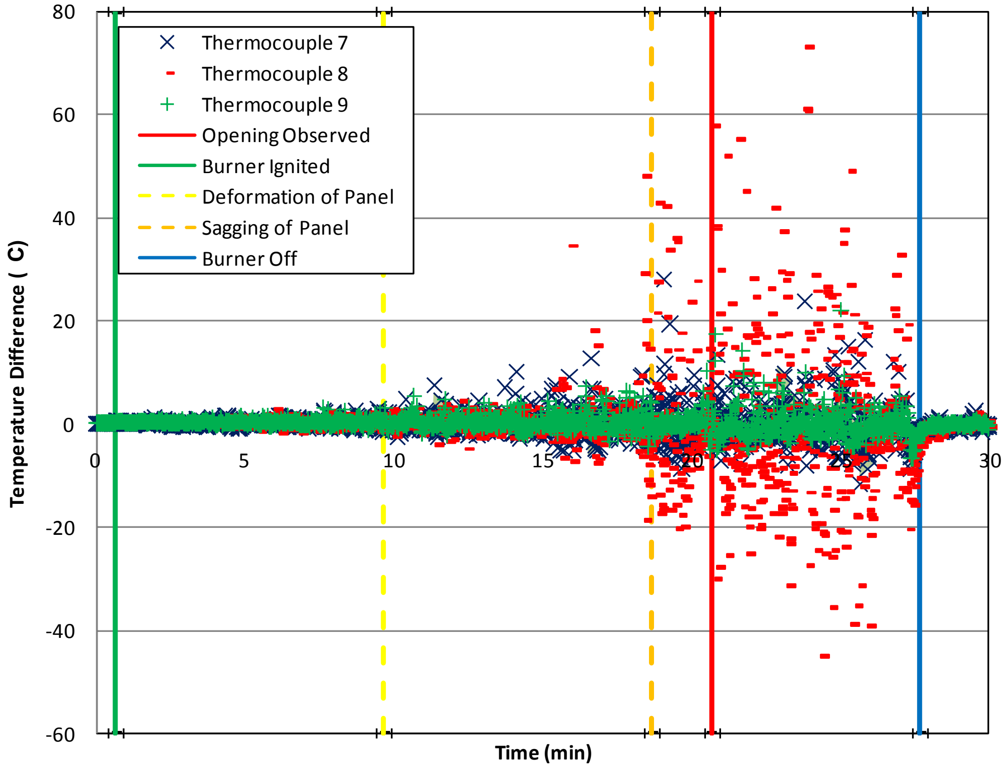
80
60
40
20
0
-20
-40
-60
Temperature Difference (C)
0
5
10
15
20
25
30
Time (min)
Thermocouple 1
Thermocouple 2
Thermocouple 3
Opening Observed
Burner Ignited
Deformation of Panel
Sagging of Panel
Burner Off

(a)

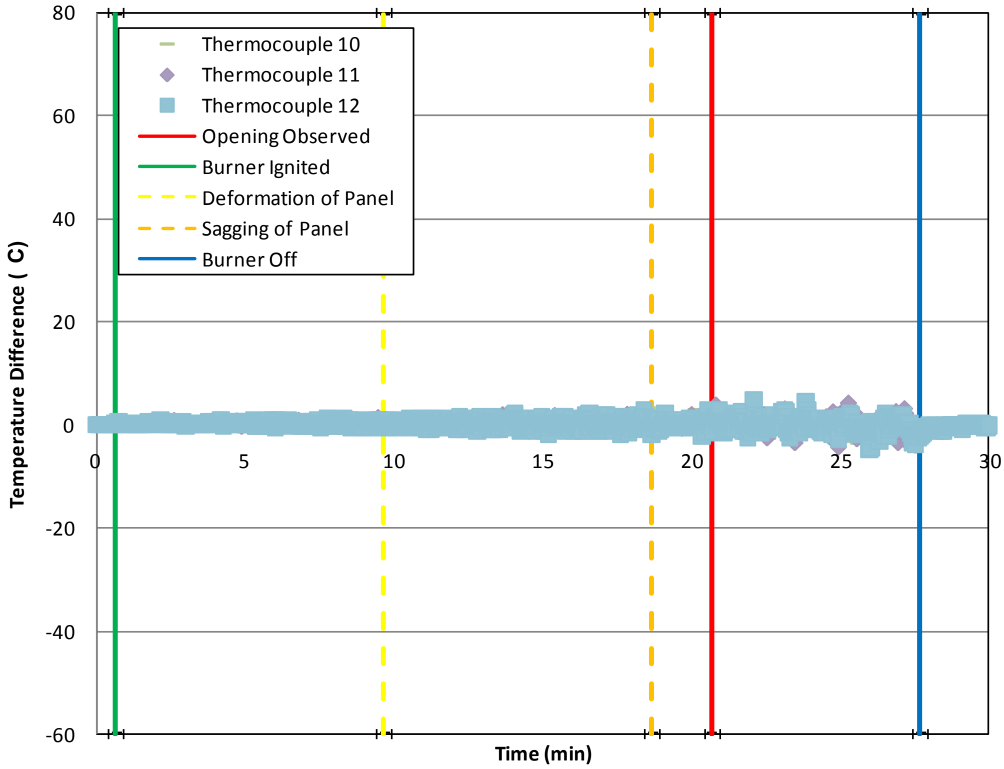


80
60
40
20
0
-20
-40
-60
Temperature Difference (C)
0
5
10
15
20
25
30
Time (min)
Thermocouple 4
Thermocouple 5
Thermocouple 6
Opening Observed
Burner Ignited
Deformation of Panel
Sagging of Panel
Burner Off

(b)

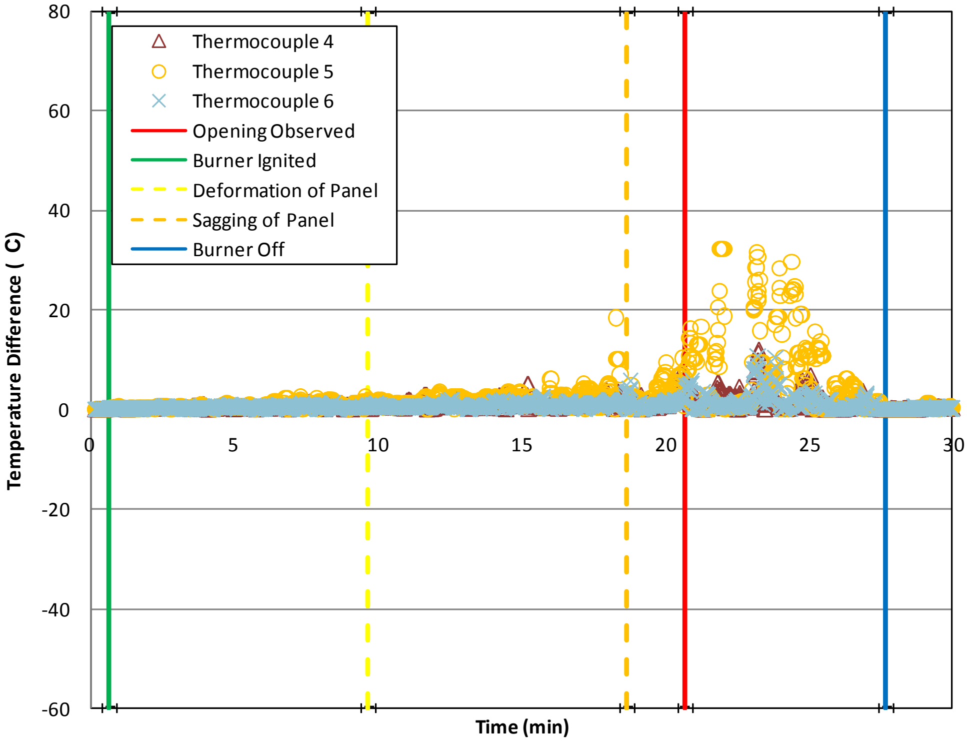


(c)

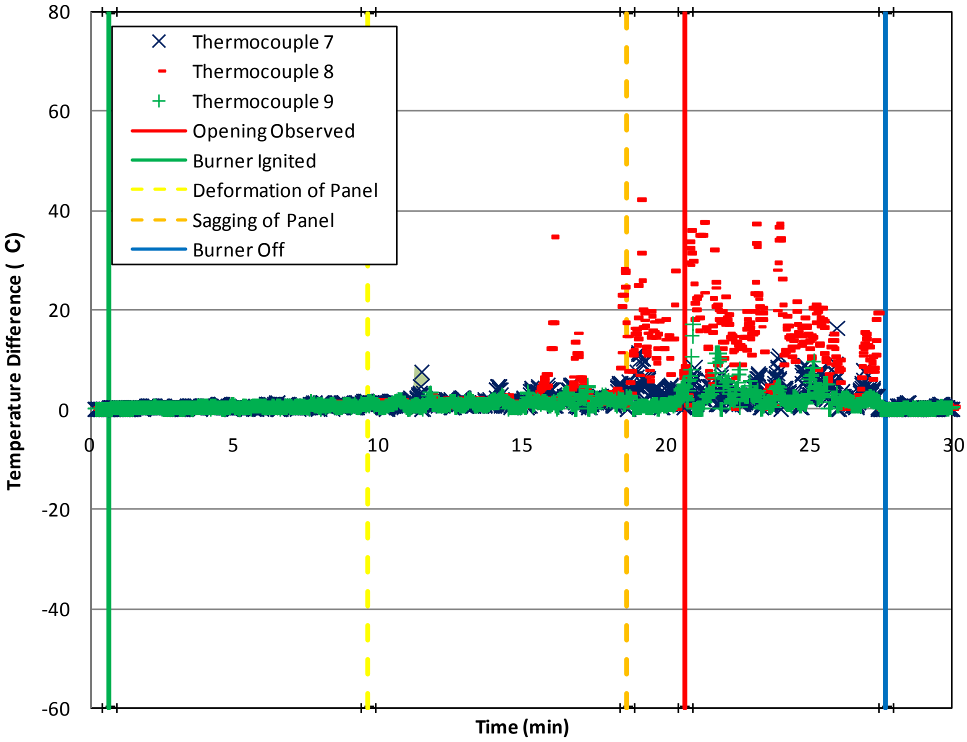


(d)

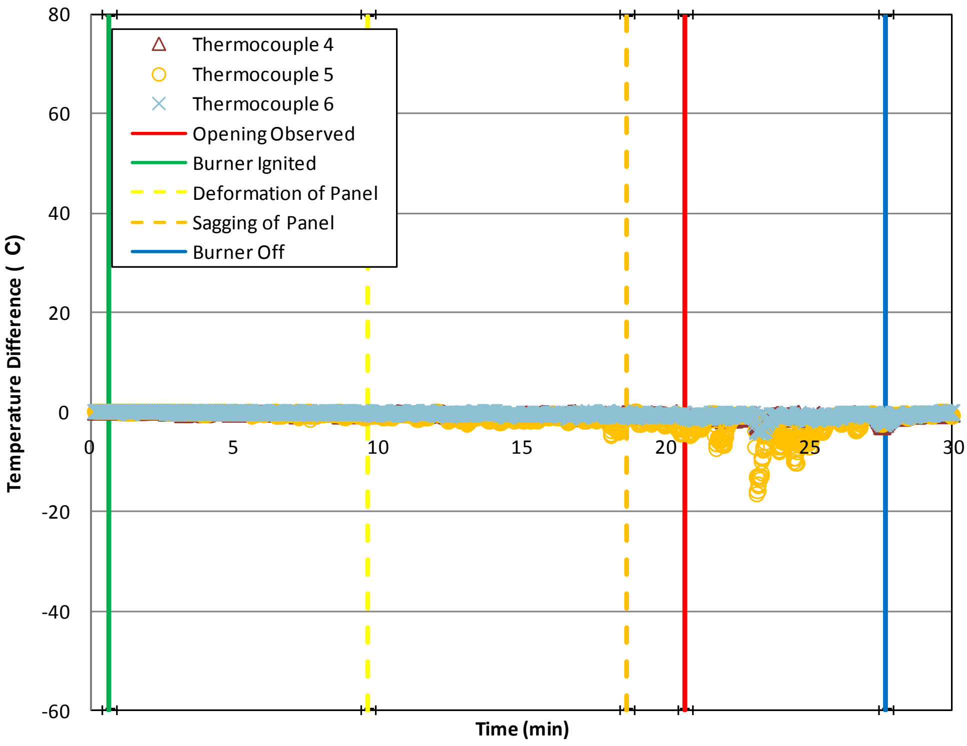
Figure 15: The temperature difference between two consecutive data points during a test for individual thermocouples (Test 19).


Thermocouple 4
Thermocouple 5
Thermocouple 6
Opening Observed
Burner Ignited
Deformation of Panel
Sagging of Panel
Burner Off
Temperature Difference (C)
Time (min)

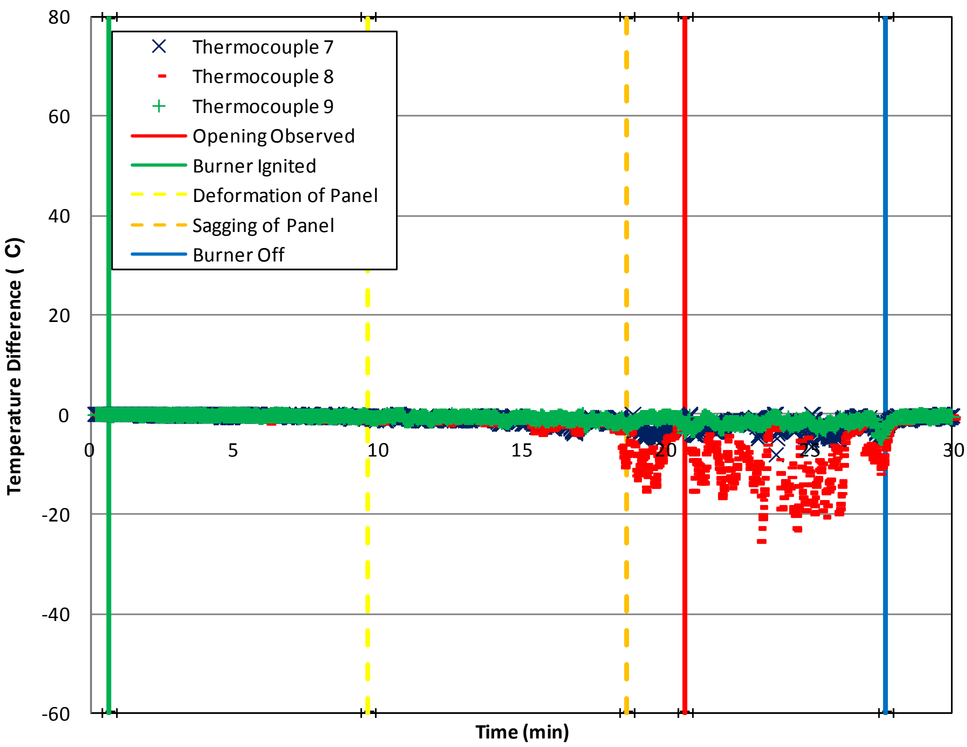
(a)


Thermocouple 7
Thermocouple 8
Thermocouple 9
Opening Observed
Burner Ignited
Deformation of Panel
Sagging of Panel
Burner Off
Temperature Difference (C)
Time (min)

(b)



(c)



(d)

Figure 16: Moving average (using 10 s worth of data) for the thermocouples in the vicinity of the observed openings formed during the test (Test 19). Data sets were divided into positive ((a) & (b)) and negative ((c) & (d)) subsets.

6. DISCUSSION

The following is a discussion of the experiences gained while using the test apparatus and analysing the test results, in terms of the appropriateness of the test to assess a roofing panel for use as fire venting.

6.1 Rate of Temperature Increase

The slower rate of temperature increase was easier to achieve than the rapid increase of temperature. This is attributed to the delay in the feedback loop between the average measured thermocouple temperature and the gas flow control.

The temperature increase was more difficult to control from the time the panel was observed to sag. This coincides with the time that the temperature results start to show large fluctuations (Figure 11 to Figure 16). These fluctuations became more distinct as openings were observed to form, as the feedback of the difference between the average thermocouple temperature and the target temperature was being used to control the mass flow rate of the burner while hot gases were venting.

A problem arises of what to do in terms of driving the temperature increase when the specimen starts to form an opening and vents hot gases. Trying to maintain the linear increase of temperature while the specimen is venting hot gases, leads to increasing the gas flow to try to compensate. Increasing the energy input to try to maintain the regime of measured temperature increase when the specimen is venting is creating an artificial condition, since the desired effect of venting is the release of hot gases.

Another problem was encountered when the panel was burning (e.g. Test 13). During this it was difficult to use the gas flow rate to the burner to control the average thermocouple temperature, since the burning panel was providing additional energy to the system.

An alternative would be to set a gas flow rate, so that the burner flow rate is directly controlled instead of using the temperature measurement(s) as feedback for controlling the gas flow rate. The gas flow rate could be set for the desired temperature increase using an inert covering for the specimen where the potential venting panel would otherwise be located. Then the subsequent specimen would be subject to the same amount of energy from the burner during the test whether or not an opening forms and whether or not the panel burns.

6.2 Measurement of Opening

There are two simple ways of approaching the measurement of the opening for venting:

1. The clear area of the opening, or
2. The temperature profile of the cross-section of the apparatus.

6.2.1 Clear Area

The clear area of the opening is the approach taken for assessing dedicated systems (e.g. AS 2428, BS 7346 Part 1). A value for a clear area of opening would be the simplest way of incorporating a value into a generic building design or modelling. However there is much more variation and potential subjectivity in determining the clear vent area that is formed in a sheet of roofing compared to a dedicated venting system, since the roofing panel material may sag, drip, tear open, burn, char, or a combination of these to form a single opening or multiple openings over the heated area. If this criterion is used to assess a panel for fire venting, then:

1. a definition of clear vent area is required to ensure the minimal subjectivity in terms of sagging, drooping and dripping material, and
2. a minimum acceptable clear vent area must be specified (e.g. 1 m²).

6.2.2 Cross-Sectional Temperature Profile

To use the temperature profile of the cross-section of the apparatus to determine the time of the first opening of a specimen and the effectiveness of the specimen for fire venting, it is necessary to drive the test using a gas flow rate versus time curve instead of the temperature versus time curve. Using the temperature versus time curve as the driver for a test, means that as the panel vents, releasing hot gases, the operator will continue to increase the gas flow to the burner in order to match the temperature time curve. This results in localised hot spots that may unduly influence the results of the test and is counterintuitive to the desired effect of venting, which is the reduction of the thermal load.

Establishing the gas flow rate versus time curve using the specimen with the venting panel replaced by a non-combustible material and matching the temperature versus time curve provides an alternative driver for the test. Using the gas flow rate versus time alternative, once an opening is formed the cross-sectional temperatures of the apparatus compared with the initial temperature time curve will provide a measure of the venting effectiveness.

The panel replacement material must be similar to the shape of the panel and non-combustible so that there is no additional heat from burning of the replacement material. The leakage of the system (that influences the convective heat transfer to the panel) with the replacement panel must also be comparable with the panel for testing.

6.2.3 Pass Criteria

Either or both of the clear area or the cross-sectional temperature profile beneath the roof section may be used to define the pass criteria.

6.3 Construction

The construction of the roof section influences the response of the panel during a test. For instance it was observed that the panel could sag over the mesh below. Depending on the characteristics of the panel the mesh could act as a stressor and assist in formation of openings, or the mesh may assist in holding the panel up and not allowing it to vent.

Similarly the inclusion or exclusion of other materials may influence the outcome of a test. For example, the inclusion of a condensation wrap may provide more heat near to the panel or assist in insulating it for longer.

Therefore individual materials or individual panels cannot be tested in isolation. The construction of the test specimen must be representative of the intended building installation method and materials.

In addition the leakage of hot gases from around the edges of the specimen needs to be limited. Since the test apparatus is designed to limit the radiation and flame impingement on the panel, convective heat transfer is the primary mode of heat flux to the panel. Therefore changes of the leakage between the apparatus and the specimen would change the convective heat flux to the panel.

6.4 Cross-Section Temperature Range

The range of temperatures measured over the cross-section of the apparatus varied relative to the distance from the burner location. The baffles provided reasonable dispersion of the hot gases over the cross-section of the apparatus, without introducing forced convection into the system.

The dimensions of the burner are expected to have a significant influence on the distribution of temperatures over the cross-section of the apparatus. Therefore a burner shape that more closely resembles the shape of the apparatus would provide a more even temperature distribution. A line burner or a pilot furnace may be better options than the standard 200 x 200 mm burner used for this study. However for a pilot furnace to be of practical use for this test method a sensitive control method for the furnace would have to be developed to achieve such relatively low temperatures required for this test and to deal appropriately with the significant variations produced during furnace start-up. For instance the typical significant variations produced during furnace start-up would particularly inhibit the use of a pilot furnace for the rapid temperature increase. However this might be overcome if it were possible to start the furnace and allow the furnace temperatures to stabilise before placing the apparatus on top, then driving the furnace by flow rate instead of matching a target average temperature increase.

6.5 Radiation & Flame Impingement on Specimen

Flames were observed around the edges of the baffles at intermittent intervals that increased in frequency towards the end of a test and coincided with the average thermocouple temperature being harder to control. This coincided with sagging of the panel material, formations of openings in the panel, other observed changes in the panel material, or flaming of the panel material. Driving the test using the matching of the average thermocouple temperature to the target temperature, means that the burner flow rate was increased to compensate with changes in material crystallography or venting through holes. This could have lead to over compensation and thus higher burner flames than necessary that could temporarily be seen around the edges of the baffles.

Observed flame impingement on the specimen was limited. Flame impingement on the specimen was observed where openings were forming and the burner flow rate had been increased to compensate for the venting of hot gases. In these cases it was obvious, since the flame was protruding out of the opening that had formed in the panel. Occasional flame impingement was also observed during periods where parts of the panel were undergoing obvious material changes, such as significant sagging or discolouration of the panel material. In addition, flaming of the underside of one of the products during the testing was observed, which makes it difficult to determine whether the burner flame could also been seen around the edges of the baffles at the same time.

Both radiation and flame impingement on the specimen were related to difficulties in control of the burner flow rate using feedback based on the average thermocouple temperatures.

Radiation and flame impingement on the specimen could be further reduced by using an approach to deliver a set amount of energy from the burner per time to the apparatus, such as has been discussed in earlier sections.

7. CONCLUSIONS & SUMMARY

From the analysis presented here alone a definitive answer cannot be ascertained for the appropriateness of the potential use of plastic panels for passive fire venting. These results are to be considered in conjunction with the results from the theoretical investigation of the plastic panels, before a definitive conclusion can be drawn from the combination of results. This is discussed in Part 3 of this series of reports. However several important aspects highlighted in the results of this study include:

1. It is not recommended to subject roof sheeting for fire venting characteristics to the current test methods or criteria as currently used for dedicated fire vents, such as AS 2428.3 (2004) or BS 7346 Part 1 (1990). The reasons for this include:
    - The entire panel is highly unlikely to open up and openings are not formed at the same time, therefore an arbitrary area would have to be chosen for the minimum acceptable vent area as part of the performance criteria.
    - It is difficult to ascertain the time at which an opening forms in the panel based on how big an opening has to be to be considered effective.
    - There are better ways of assessing the time when openings form based on quantitative recorded parameters rather than subjective observations.
    - Driving the test to fit a pre-determined temperature time curve masks the temperature benefits of any openings that may have formed, since the operator would be inadvertently trying to compensate for them.

- Pass criteria for the reduced-scale test must be carefully selected to incorporate the fundamental processes involved in the formation of an opening in a panel material and the desired overall performance in a building design. One example is the selection of a maximum temperature, such that the gas temperatures below the roof section test specimen must be maintained below this maximum temperature while subjected to a pre-determined gas flow rate over the duration of the test. Another example is a minimum effective open area (e.g. 1 m²) that forms before the end of the test. However if an effective open area was used, then the way in with to determine how "open" the panel is must be clearly defined (i.e. how to interpret the edges of the opening and how much material might be attached to mesh, etc, across the middle of an opening).

2. A reduced-scale test, as described here, using an established burner gas flow rate would be suitable for determining the venting characteristics of a roof sheeting panel for temperature rate increases in the range of the moderate (10 ± 2°C per minute average) and rapid (200 ± 20°C per minute average) temperature increases used here.
3. The test specimen must be constructed in accordance with the intended installation in a building. This is to include rafters, purlins, surrounding roof cladding (e.g. iron sheeting), fasteners, etc, and mesh, condensation wrap, etc, where required.
4. The appropriate portion of the roof area required to be constructed of tested venting roofing panels needs to be assessed.
5. Tested venting panels do not have the same venting characteristics as dedicated venting systems.
6. Appropriate concessions for the inclusion of tested venting roofing panels needs to be assessed.

It is important to note that the experiments performed here were designed to develop a potential test method for roof panels that might be used for fire venting. The materials used in the tests were not assessed as to their appropriateness for fire venting, thus no "pass" or "fail" was recorded or discussed. Testing of individual products could be tested in the future, after discussion and establishment of the appropriateness of this or another test method and the associated pass criteria.

7.1 Recommendations for Future Experimental Work

The recommended areas of further experimental work include:

- Comparison of reduced-scale test results, in accordance with a standard test method such as AS 2428 Part 3, for the performance of passive buoyancy-driven venting utilising roof sheeting (materials and practices that are permitted by C/AS1 and currently used in construction) with thermally-activated buoyancy-driven venting (in accordance with AS 2665).

- Large- and/or full-scale testing is performed for comparison with small-scale experiment results to determine applicability of small-scale test results and appropriate performance criteria for passive buoyancy-driven venting utilising roof sheeting.

8. REFERENCES

8.1 Regulations and Standards

AS 1668 The Use of Ventilation and Airconditioning in Buildings, Part 3: Smoke Control Systems for Large Single Compartments or Smoke Reservoirs. 2001. Standards Association of Australia, North Sydney, Australia.

AS 2428 Methods of Testing Smoke/Heat Release Vents, Method 1: Determination of resistance to leakage during rain. 2004. Standards Association of Australia, North Sydney, Australia.

AS 2428 Methods of Testing Smoke/Heat Release Vents, Method 2: Determination of ability to operate under wind loading. 2004. Standards Association of Australia, North Sydney, Australia.

AS 2428 Methods of Testing Smoke/Heat Release Vents, Method 3: Determination of operating characteristics. 2004. Standards Association of Australia, North Sydney, Australia.

AS 2428 Methods of Testing Smoke/Heat Release Vents, Method 4: Determination of the effect of flame contact. 2004. Standards Association of Australia, North Sydney, Australia.

AS 2428 Methods of Testing Smoke/Heat Release Vents, Method 5: Determination of discharge coefficient and effective aerodynamic area. 2004. Standards Association of Australia, North Sydney, Australia.

AS 2428 Methods of Testing Smoke/Heat Release Vents, Method 6: Determination of ability to operate under snow loading. 2004. Standards Association of Australia, North Sydney, Australia.

BS 7346 Components for smoke and heat control systems. Part 1: Specification for natural smoke and heat exhaust ventilators. 1990. British Standards Institute, London, UK.

Compliance Document for New Zealand Building Code Clauses C1, C2, C3, C4 Fire Safety. (Including Amendments to October 2005). 2001. Victoria University Book Centre, Wellington, New Zealand.

8.2 General References

Edwards APR, Soja E and Wade CA. 2007. *Effective Passive Roof Venting in the Event of Fire – Literature Review*. BRANZ Study Report SR 165. BRANZ Ltd, Judgeford, New Zealand.

Morgan HP and Gardner JP. 1990. *Design Principles for Smoke Ventilation in Enclosed Shopping Centres, BR 186*. Fire Research Station, Building Research Establishment, Borehamwood, UK.

Thomas PH, Hinkley PL, Theobald CR and Simms, DL. 1963. *Investigations into the Flow of Hot Gases in Roof Venting*. Department of Scientific and Industrial Research and Fire Offices' Committee, Joint Fire Research Organisation, Her Majesty's Stationery Office, London, UK.

Robbins AP and Wade CA. 2008a. *Effective Passive Roof Venting using Roof Panels in the Event of Fire. Part 1: Preliminary Modelling Results*. BRANZ *Study Report SR 197*. BRANZ Ltd, Judgeford, New Zealand.

Robbins AP and Wade CA. 2008b. *Effective Passive Roof Venting using Roof Panels in the Event of Fire. Part 3: Summary*. BRANZ *Study Report SR 199*. BRANZ Ltd, Judgeford, New Zealand.

APPENDIX.A TEST APPARATUS

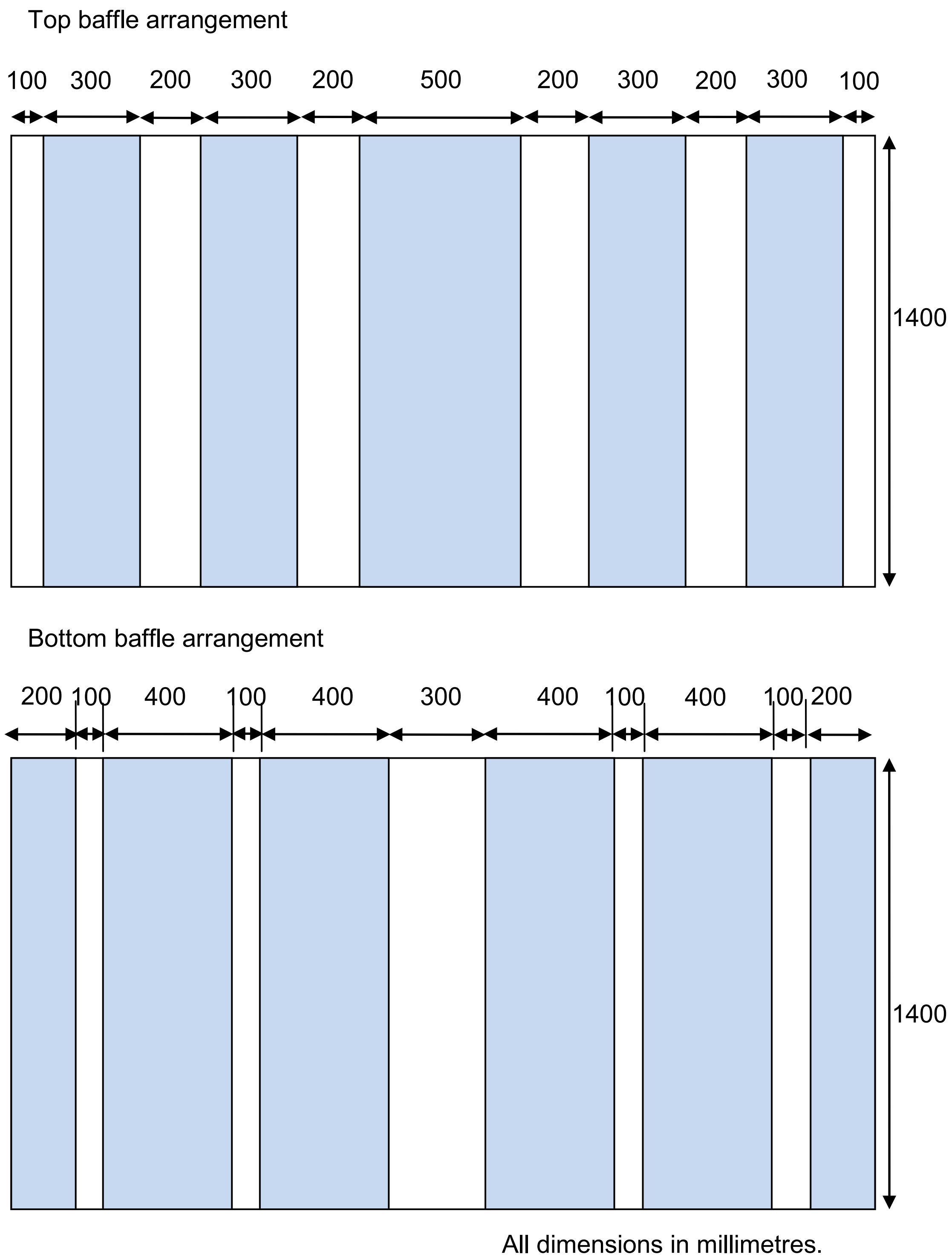


Figure 17: Schematic of the baffle arrangement shielding the test specimen from flame impingement and radiation from the burner.

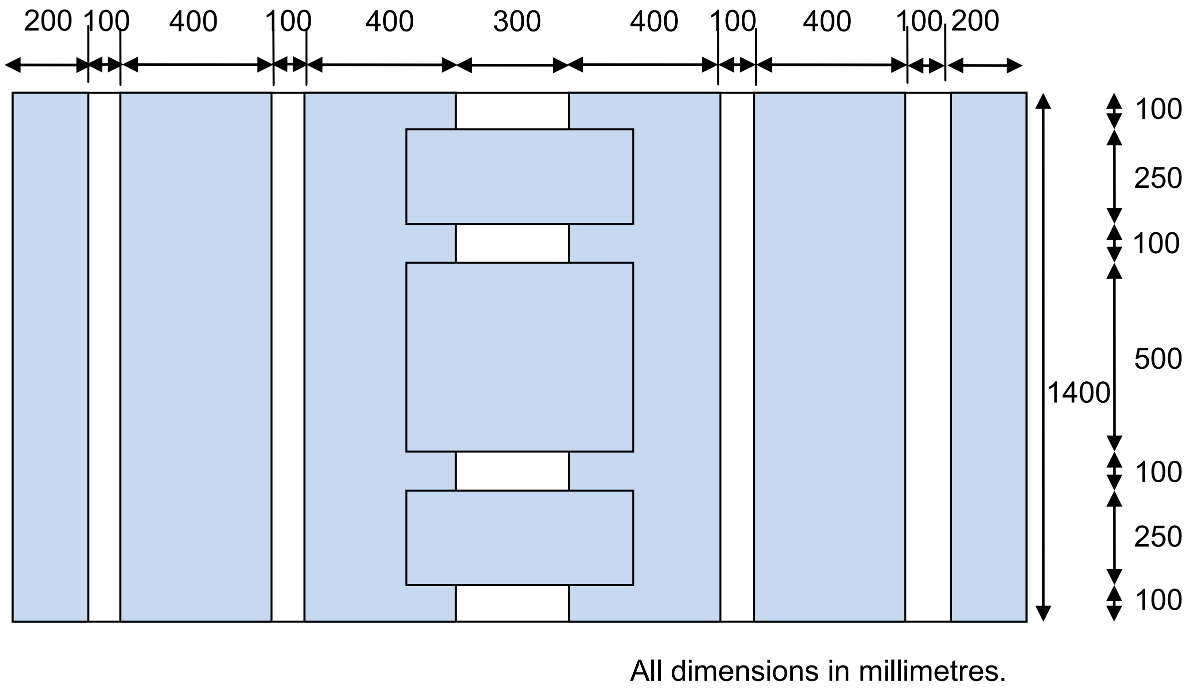


Figure 18: Schematic of the modified bottom baffle.

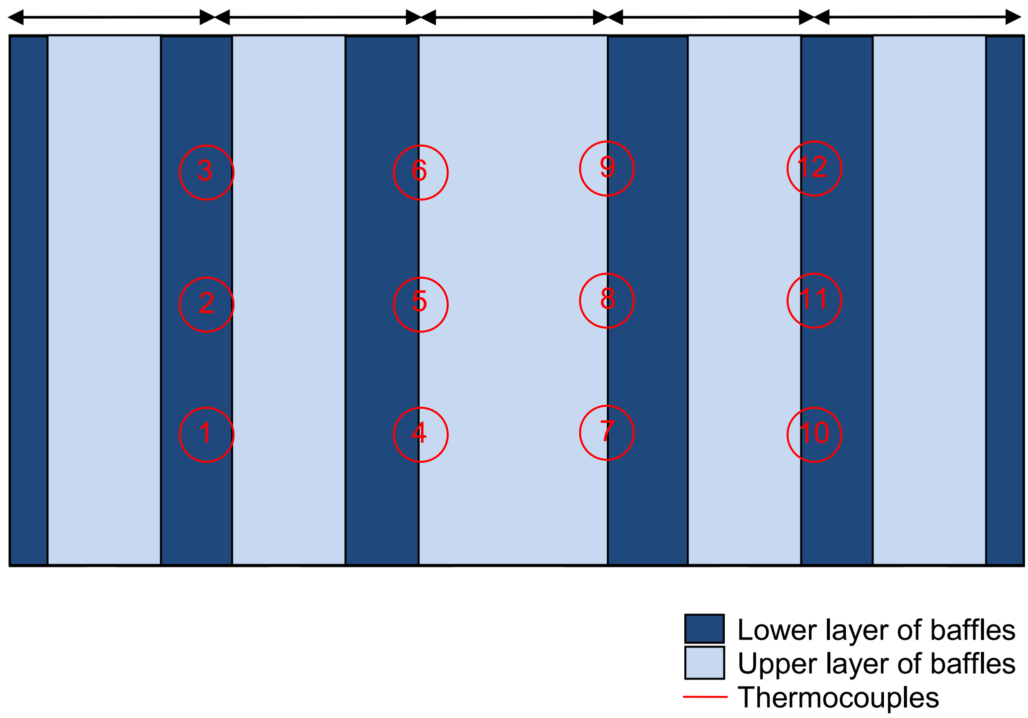


Figure 19: Schematic of overlap of upper and lower layer of baffles and thermocouples.

(a) (b)

Figure 20: Example of a test specimen on the test apparatus, before testing.

(a) (b)

(c) (d)

Figure 21: Photographs of a calibration run (Test 1).

APPENDIX.B TEST RESULTS

B.1 Test 1

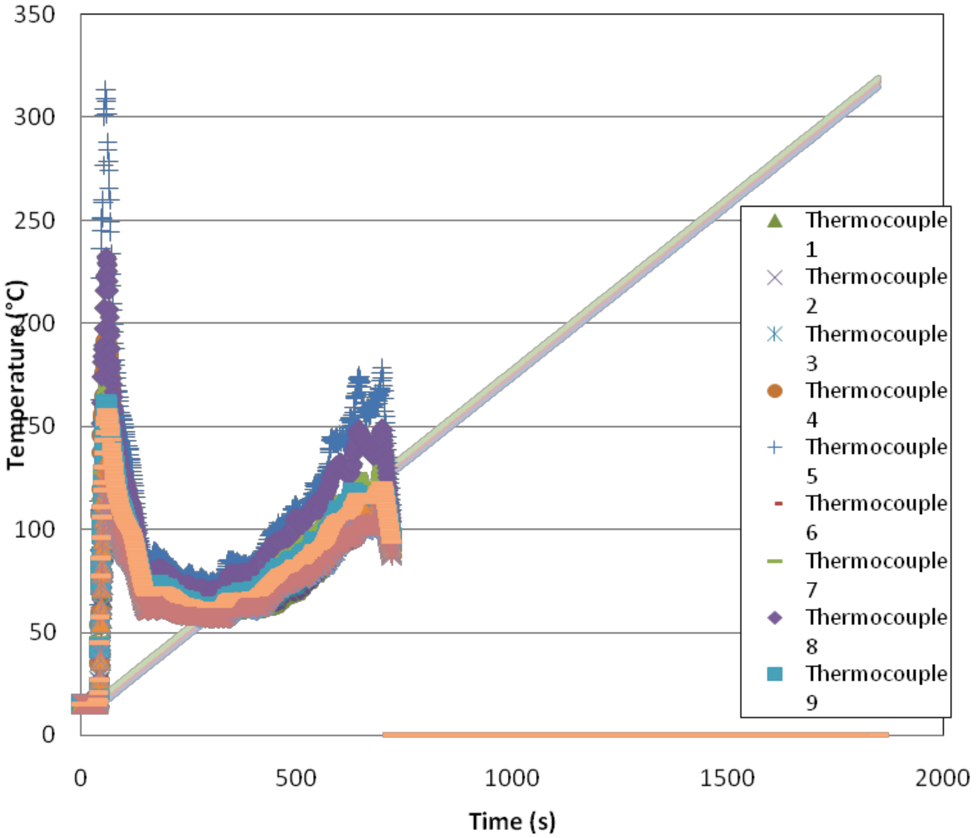


Figure 22: Thermocouple measurements, average of all 12 thermocouple measurements and target temperature for Test 1.

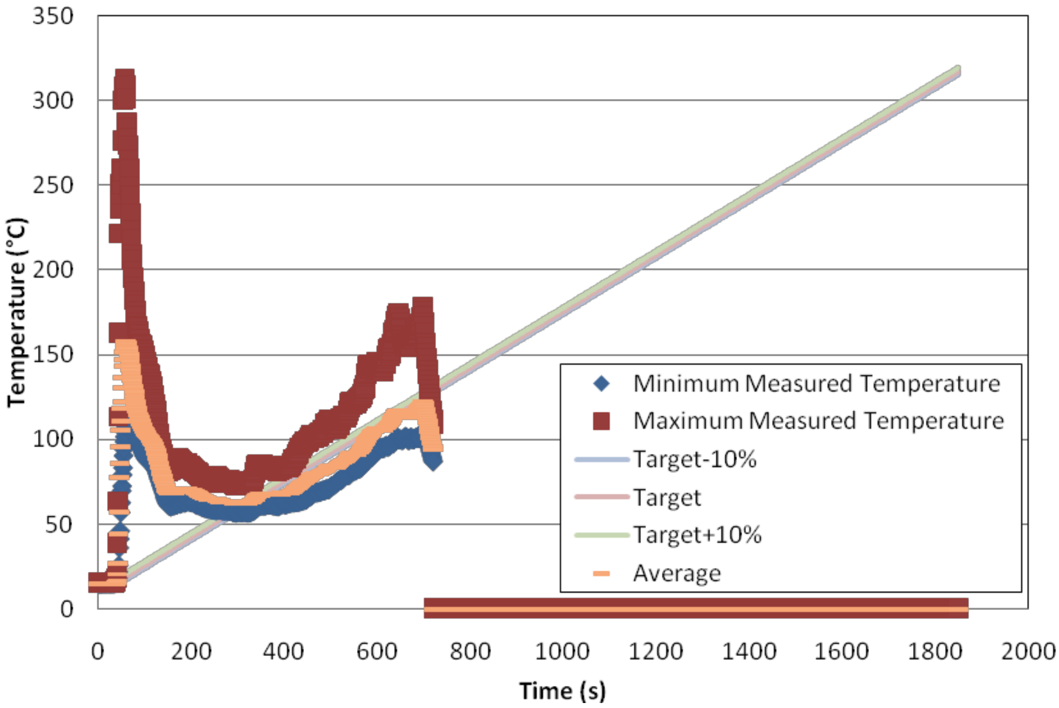


Figure 23: Maximum and minimum thermocouple measurements, average measured temperature and target temperature for Test 1.

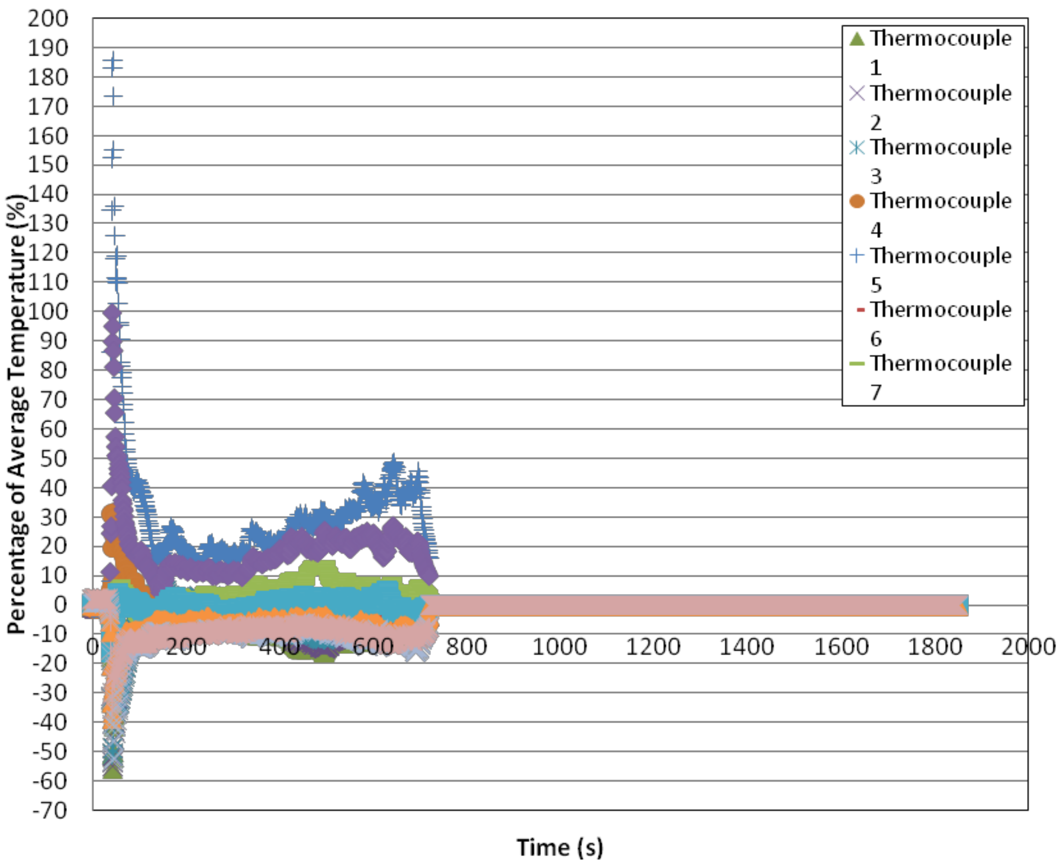


Figure 24: Temperature difference between each thermocouple measurement and the average measured temperature as a percentage of the average temperature for Test 1.

B.2 Test 2

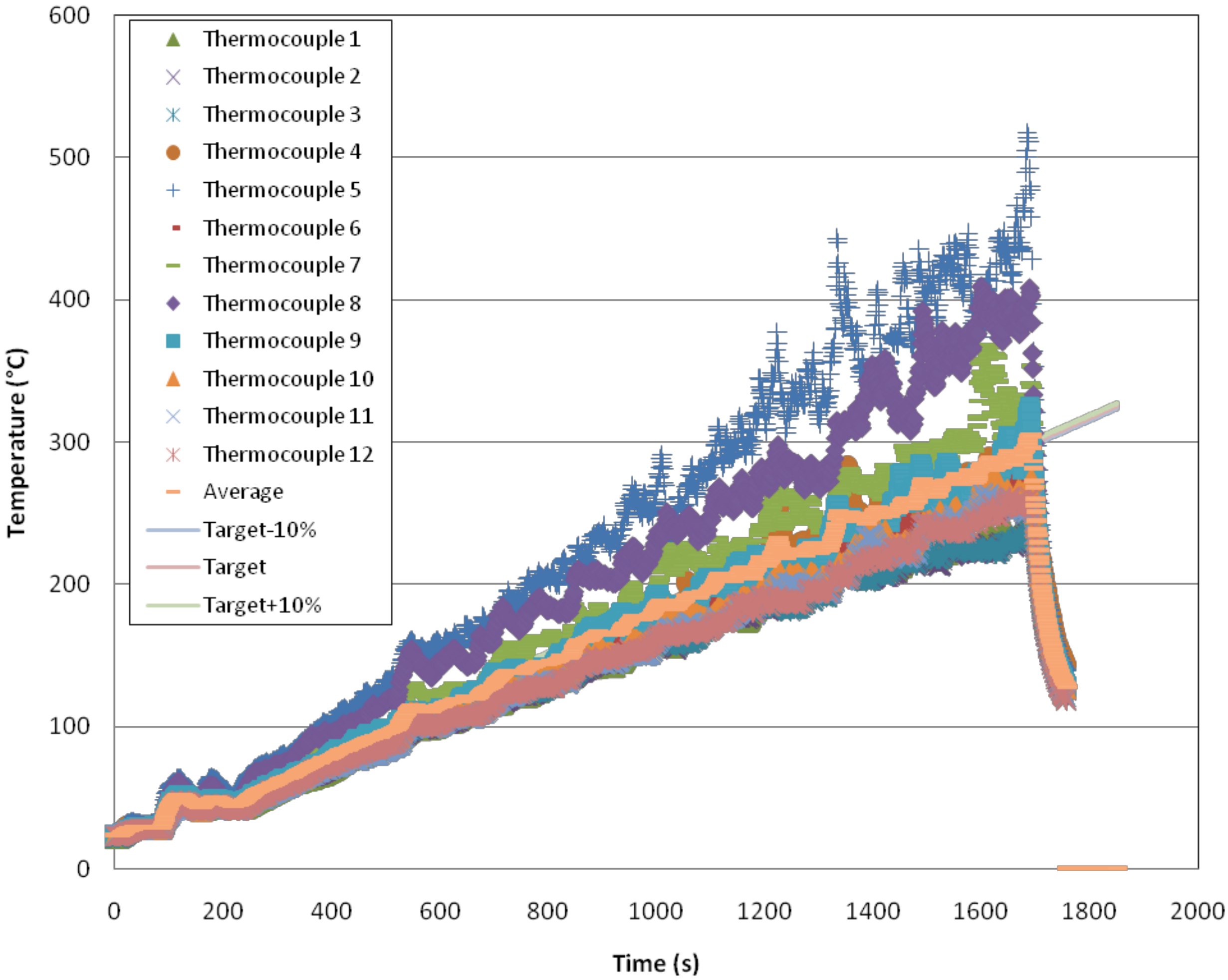


Figure 25: Thermocouple measurements, average of all 12 thermocouple measurements and target temperature for Test 2.

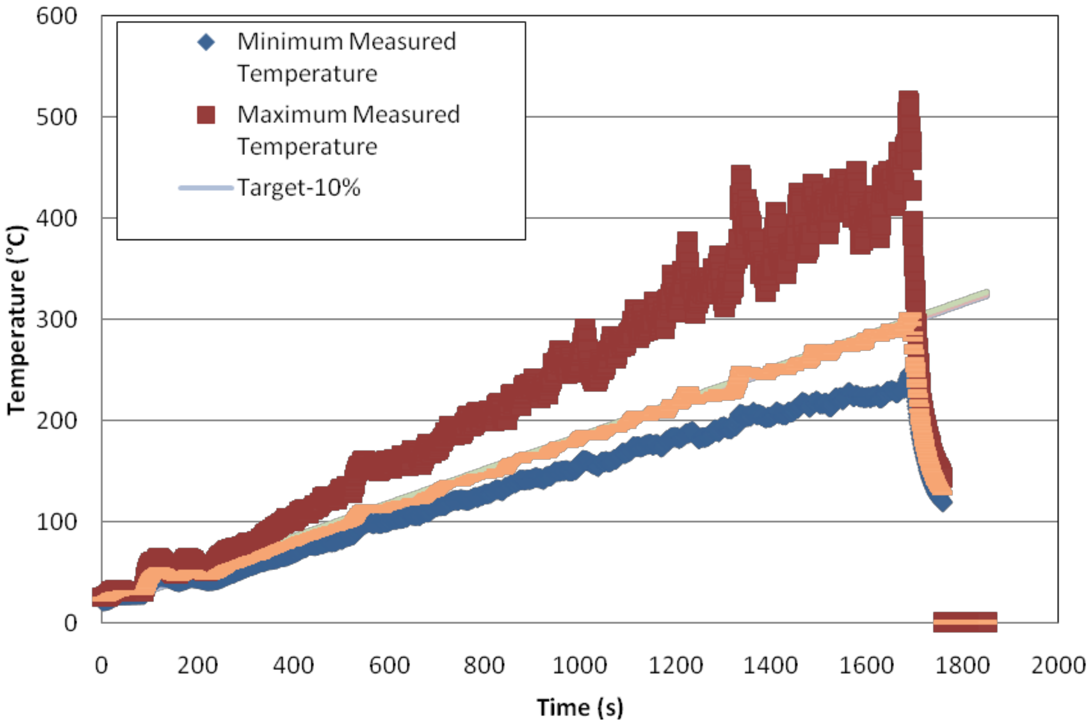


Figure 26: Maximum and minimum thermocouple measurements, average measured temperature and target temperature for Test 2.

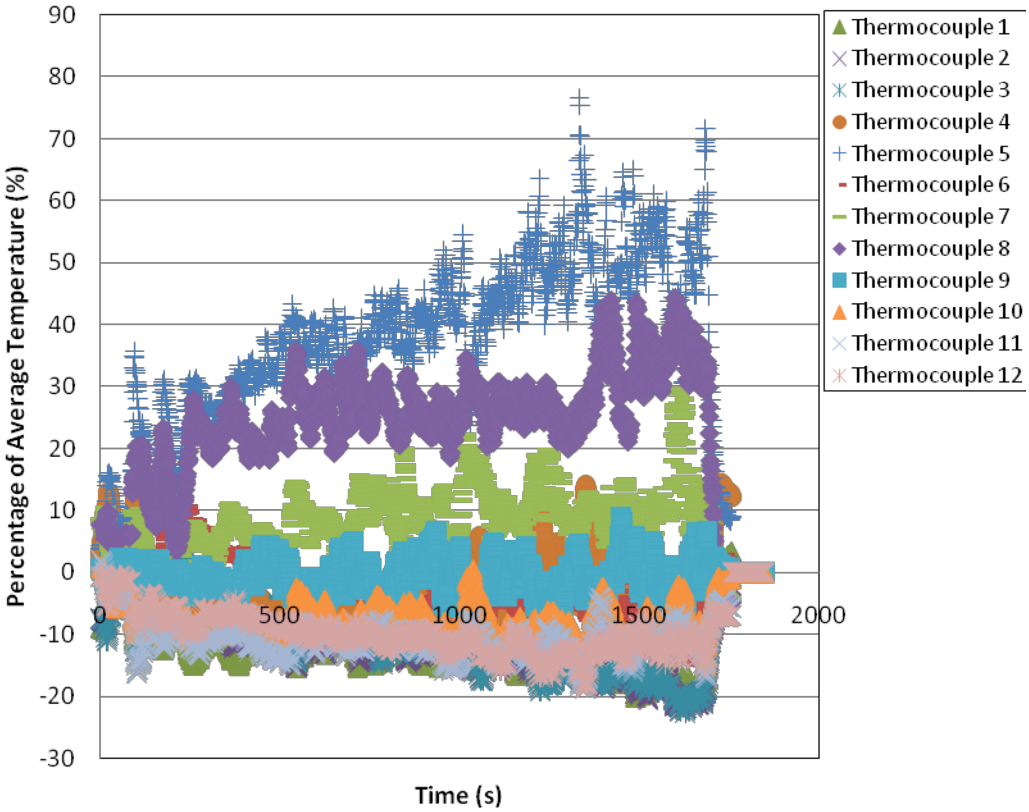


Figure 27: Temperature difference between each thermocouple measurement and the average measured temperature as a percentage of the average temperature for Test 2.

B.3 Test 3

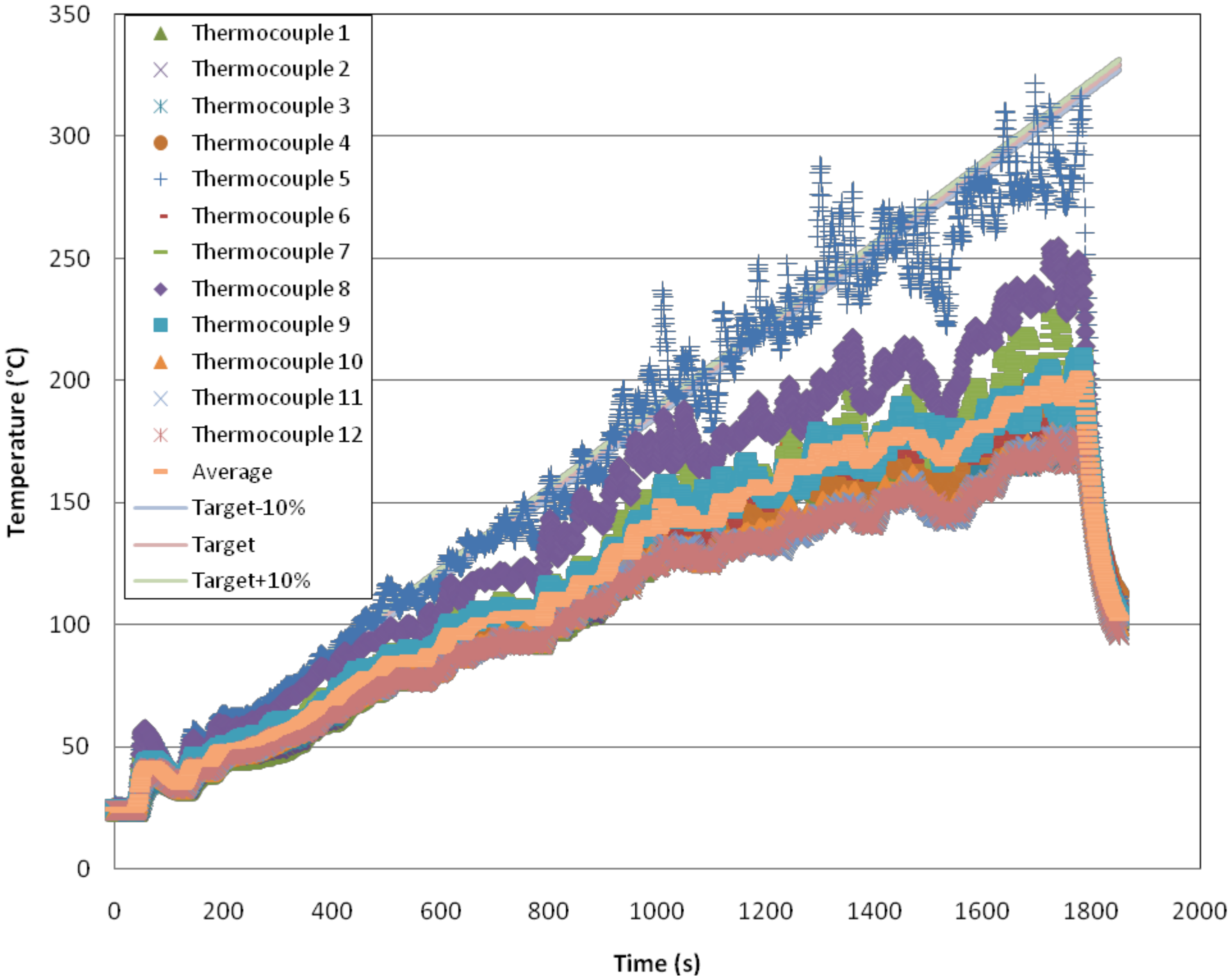


Figure 28: Thermocouple measurements, average of all 12 thermocouple measurements and target temperature for Test 3.

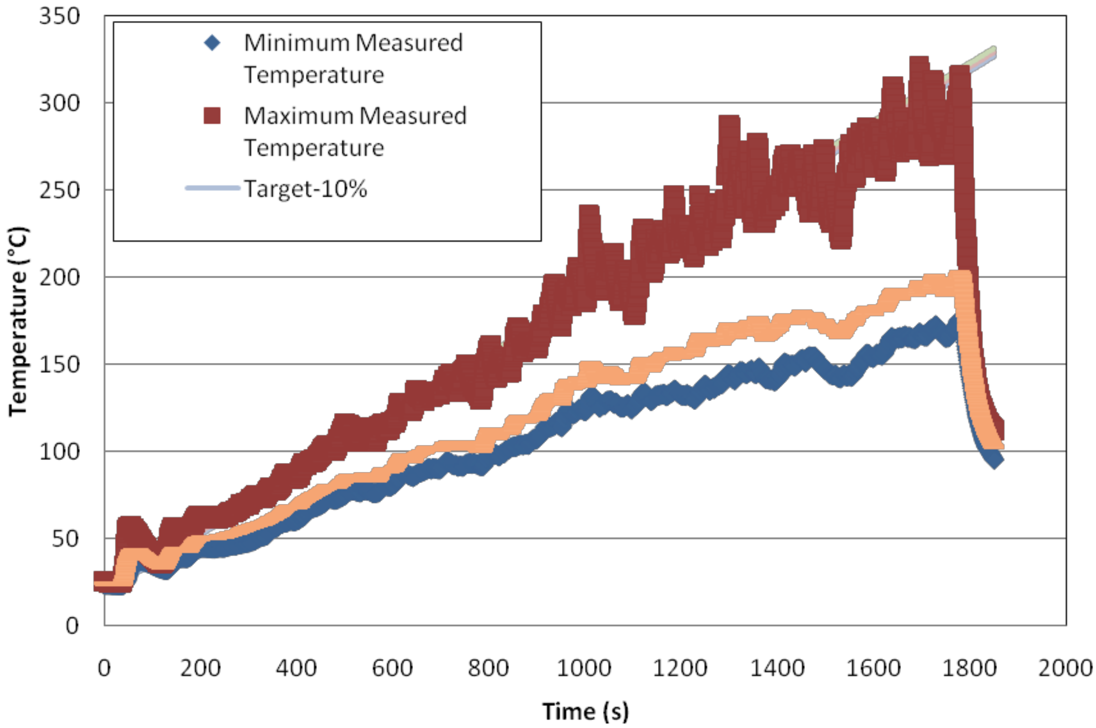


Figure 29: Maximum and minimum thermocouple measurements, average measured temperature and target temperature for Test 3.

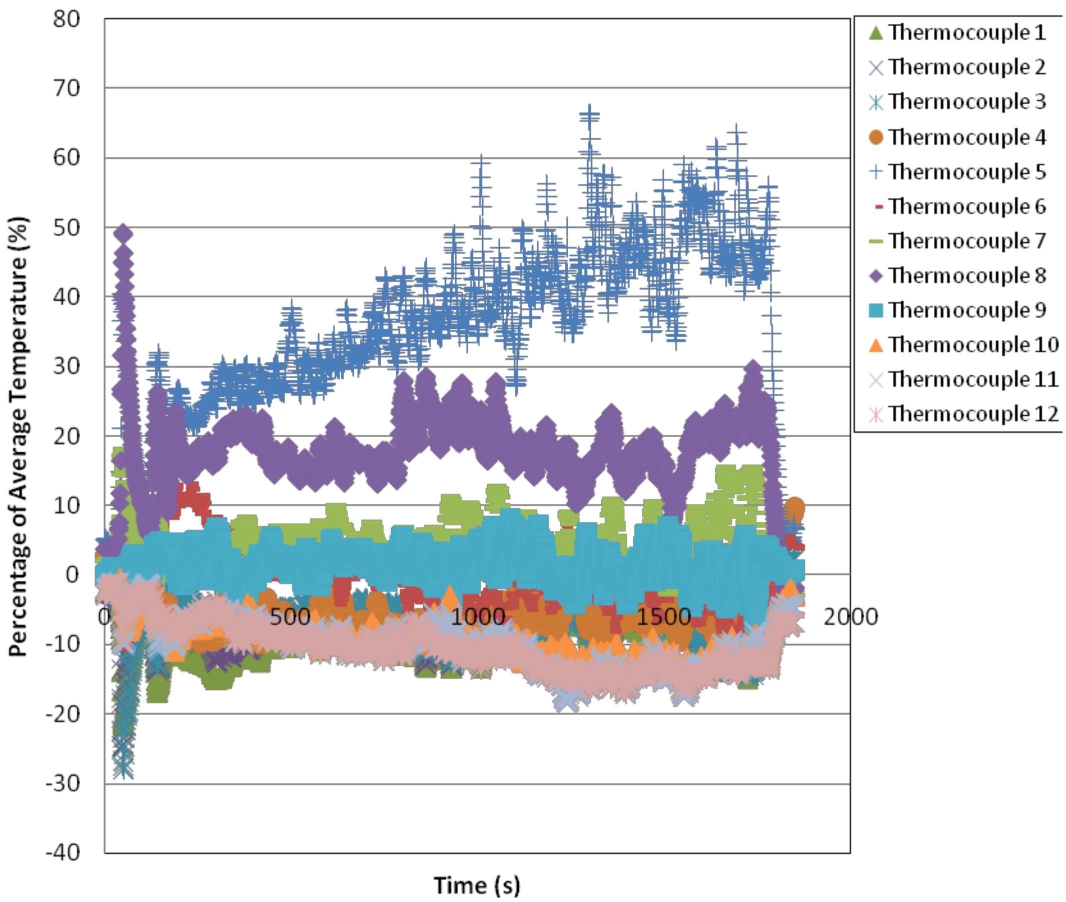


Figure 30: Temperature difference between each thermocouple measurement and the average measured temperature as a percentage of the average temperature for Test 3.

B.4 Test 4

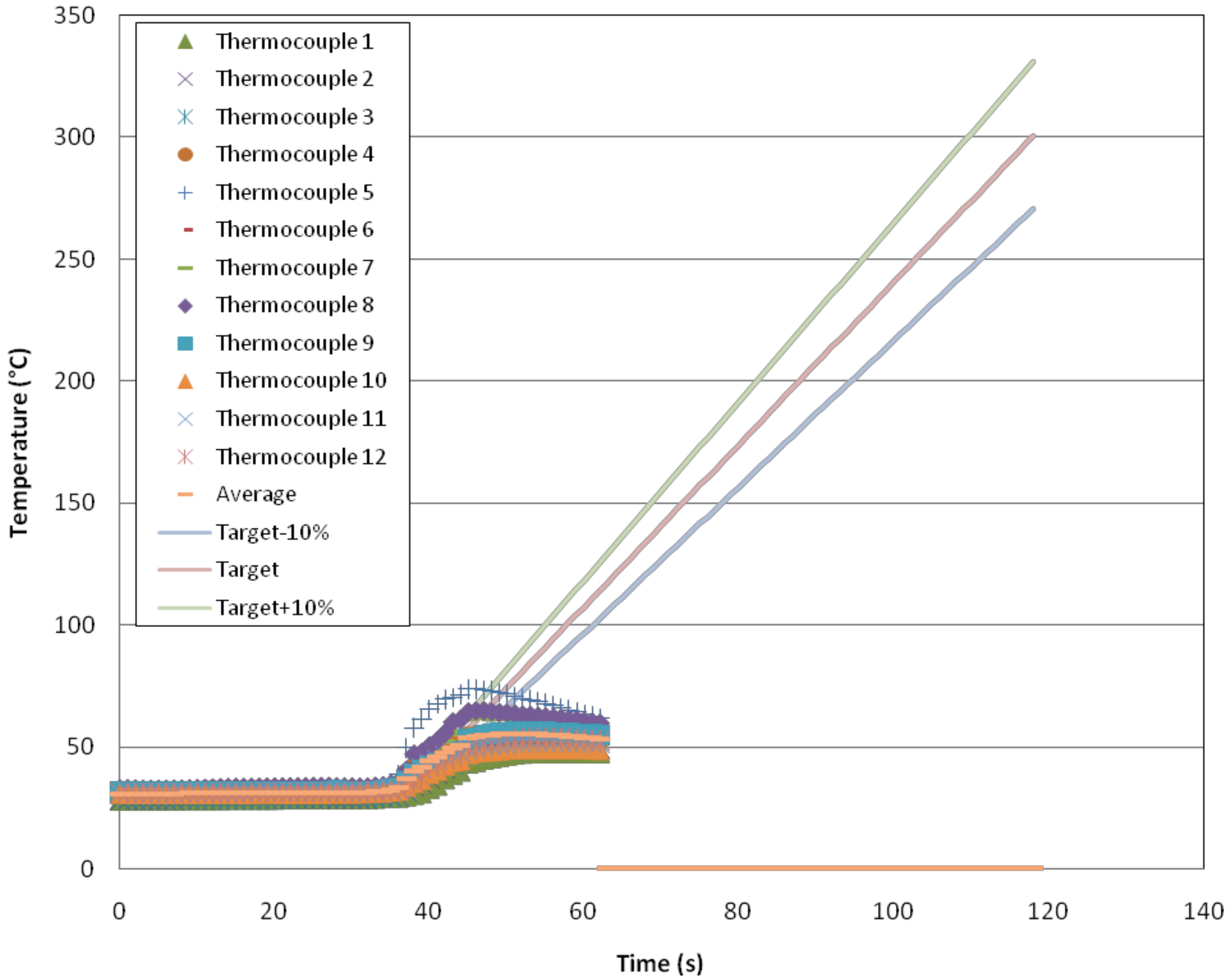


Figure 31: Thermocouple measurements, average of all 12 thermocouple measurements and target temperature for Test 4.

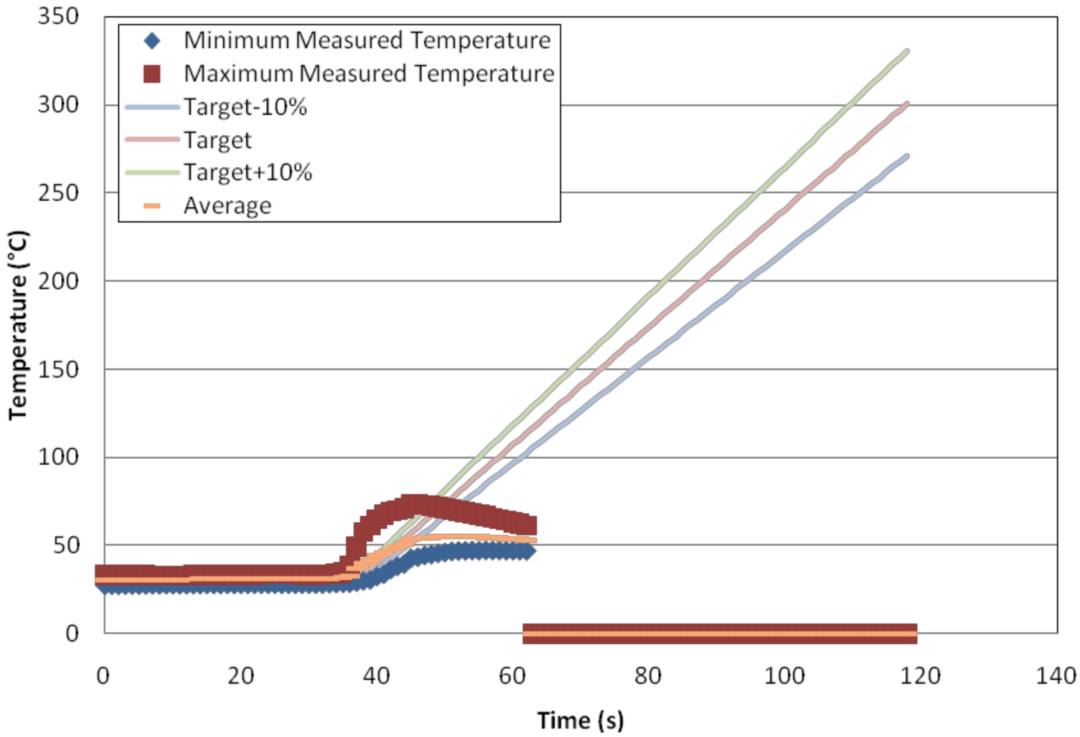


Figure 32: Maximum and minimum thermocouple measurements, average measured temperature and target temperature for Test 4.

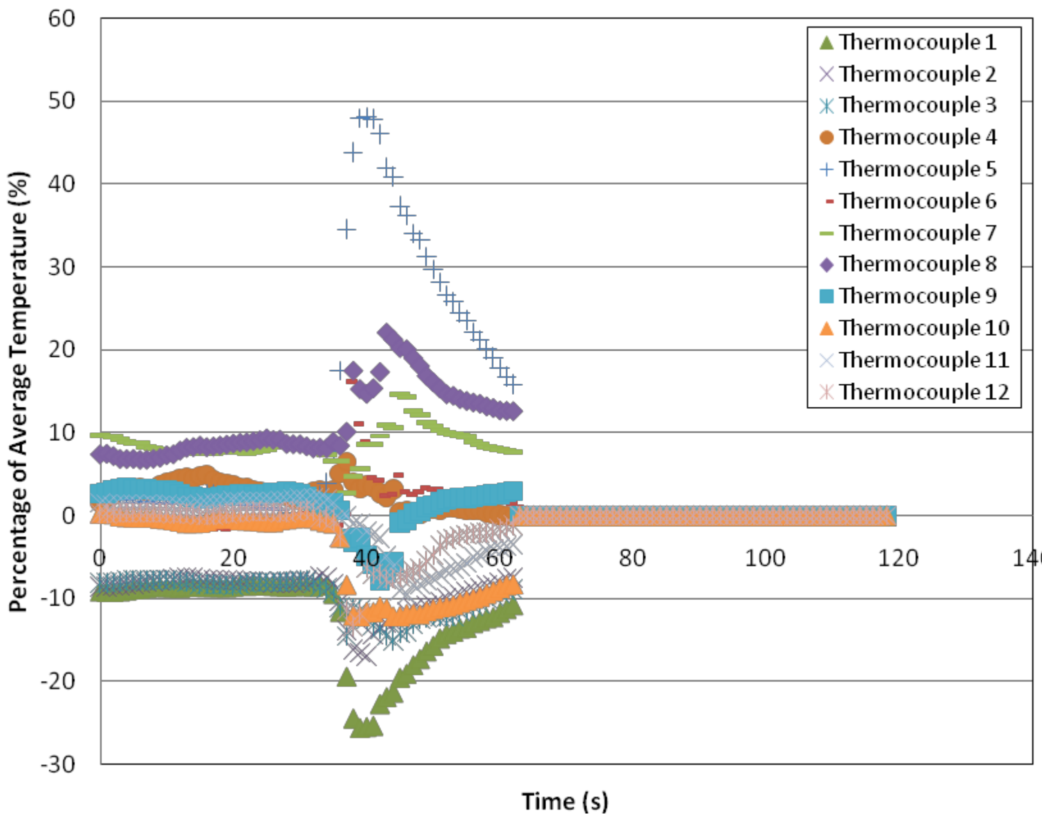


Figure 33: Temperature difference between each thermocouple measurement and the average measured temperature as a percentage of the average temperature for Test 4.

B.5 Test 5

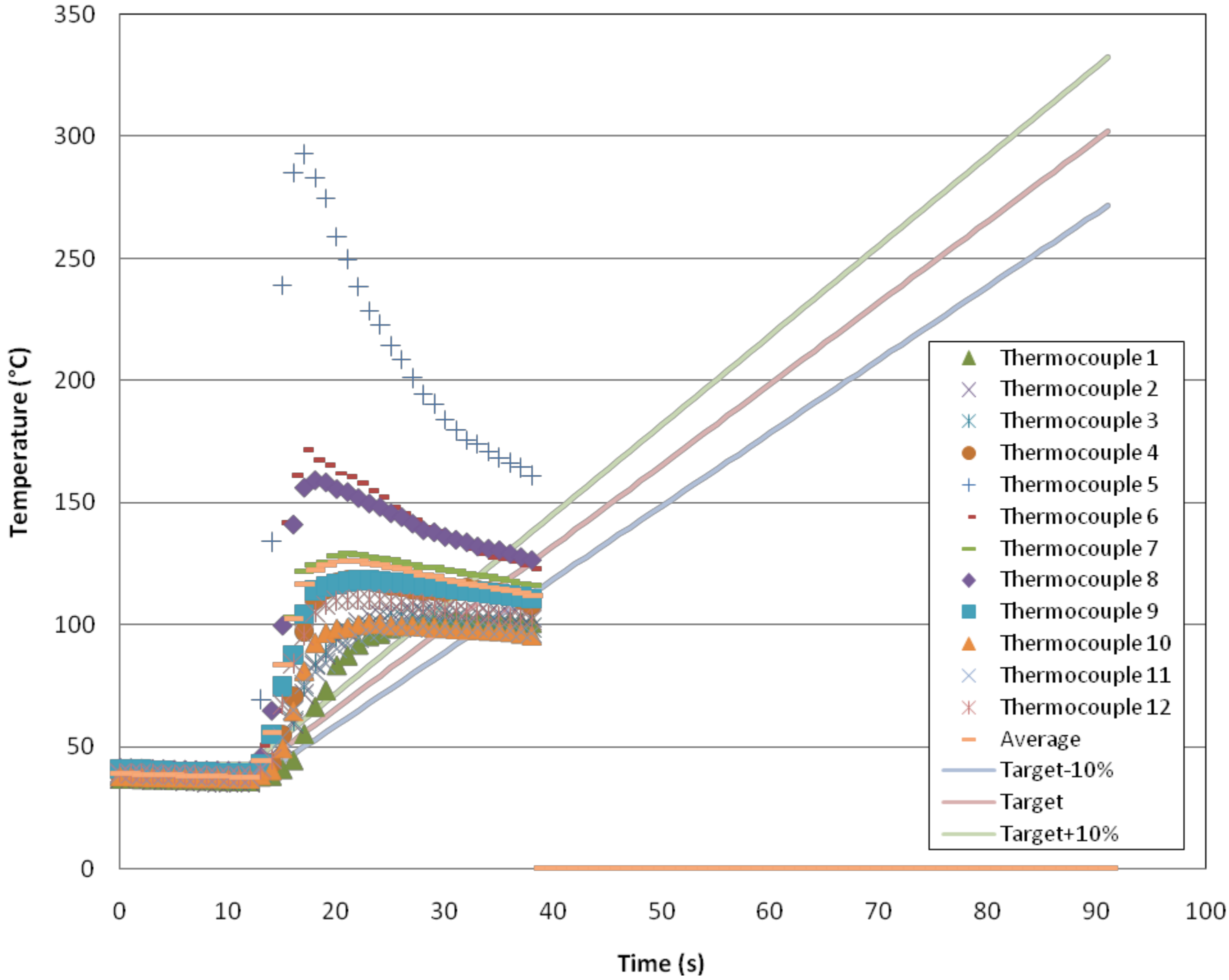


Figure 34: Thermocouple measurements, average of all 12 thermocouple measurements and target temperature for Test 5.

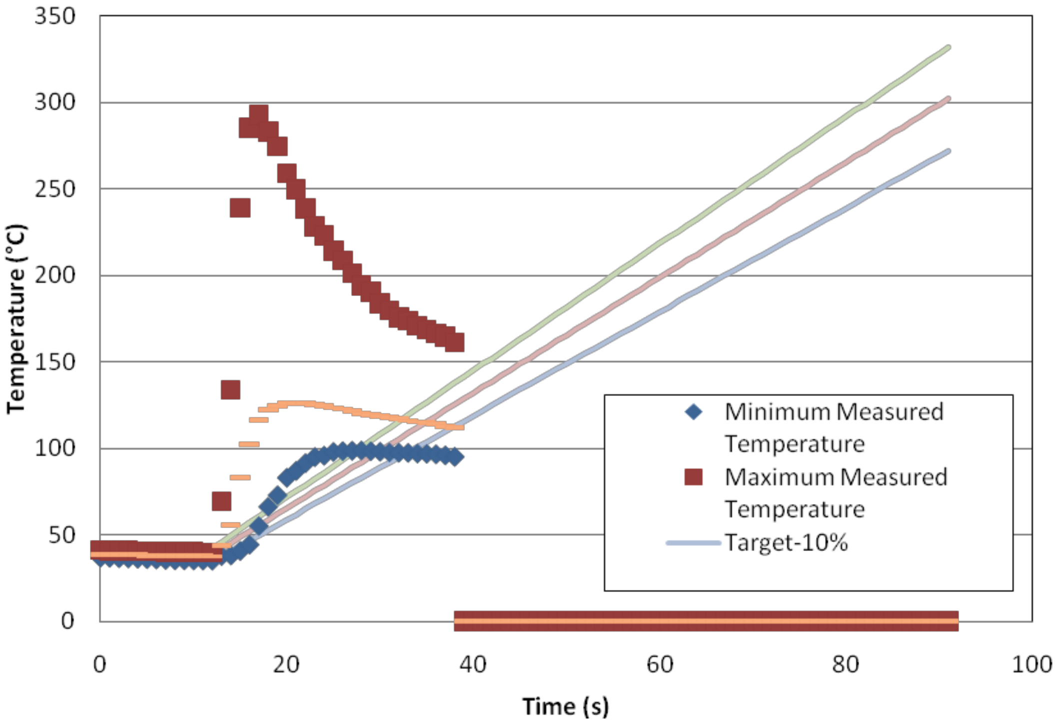


Figure 35: Maximum and minimum thermocouple measurements, average measured temperature and target temperature for Test 5.

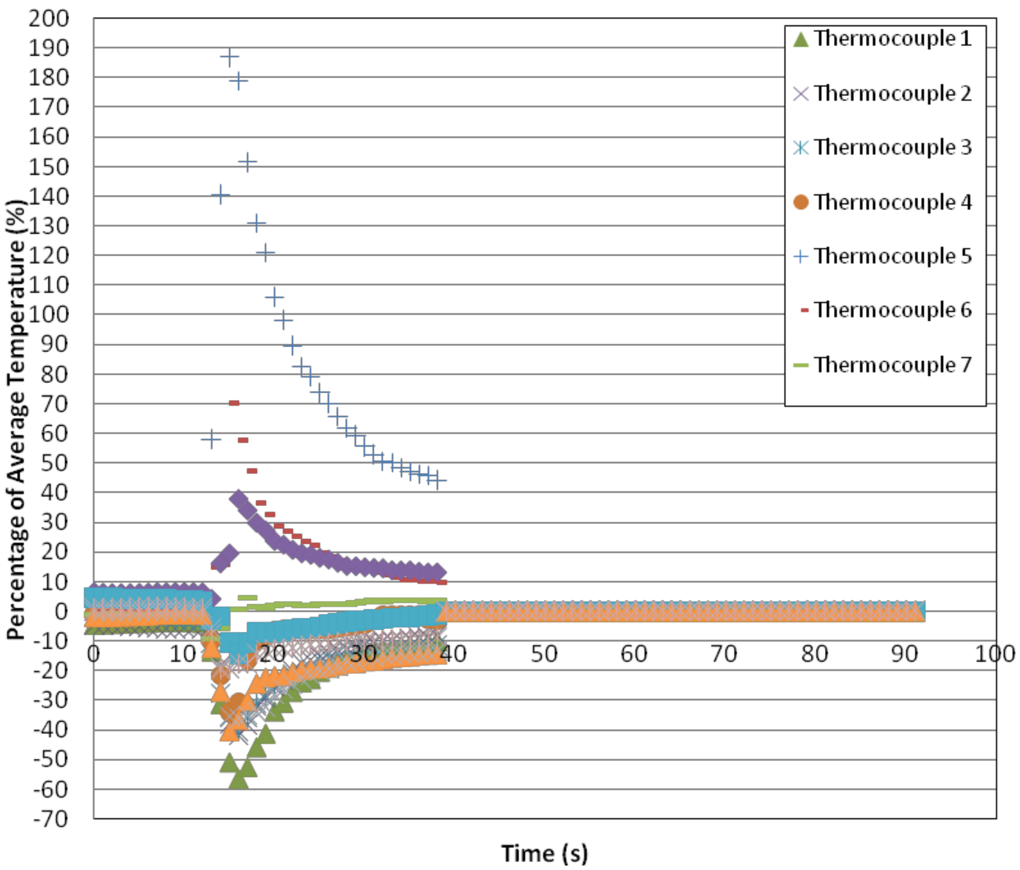


Figure 36: Temperature difference between each thermocouple measurement and the average measured temperature as a percentage of the average temperature for Test 5.

B.6 Test 6

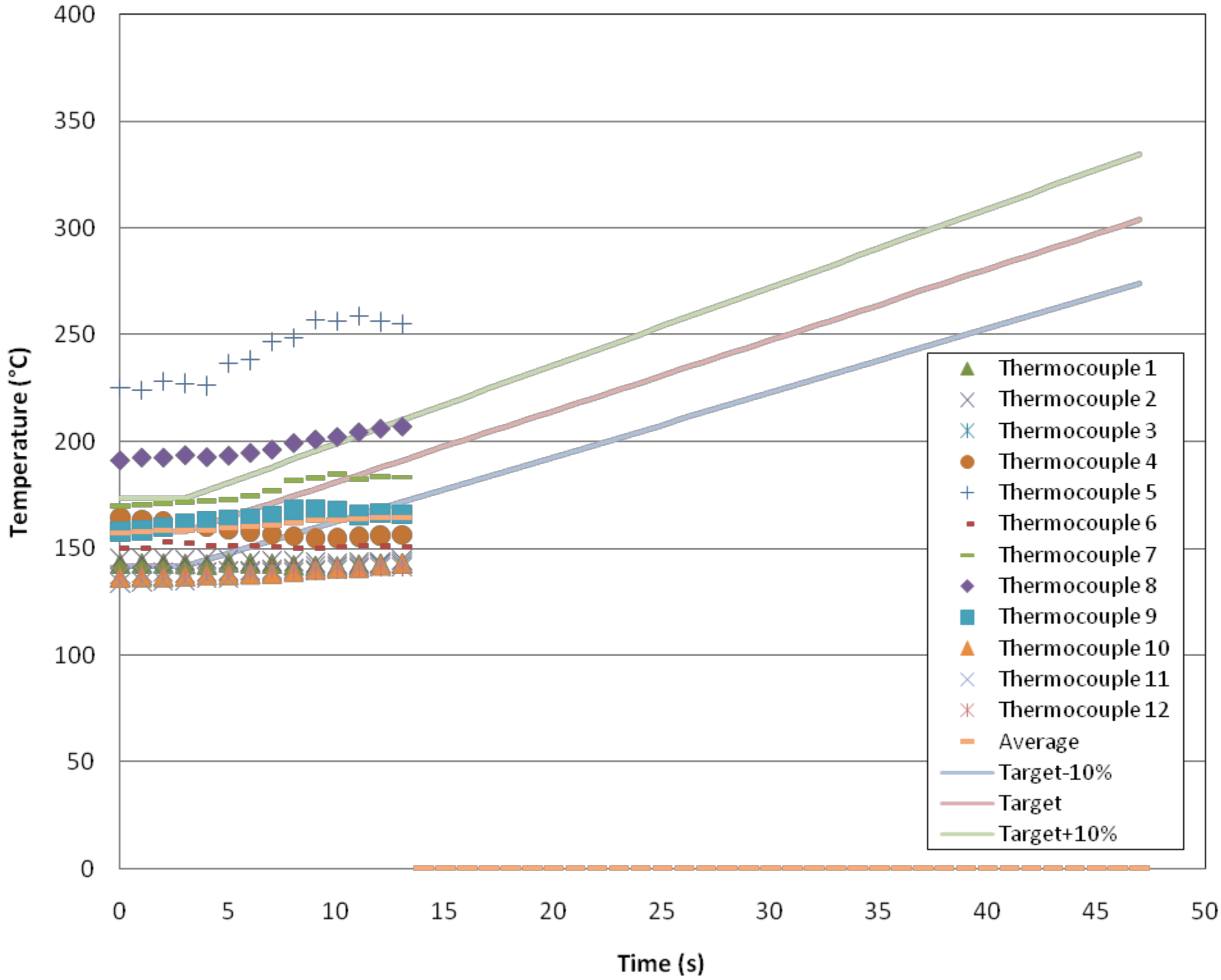


Figure 37: Thermocouple measurements, average of all 12 thermocouple measurements and target temperature for Test 6.

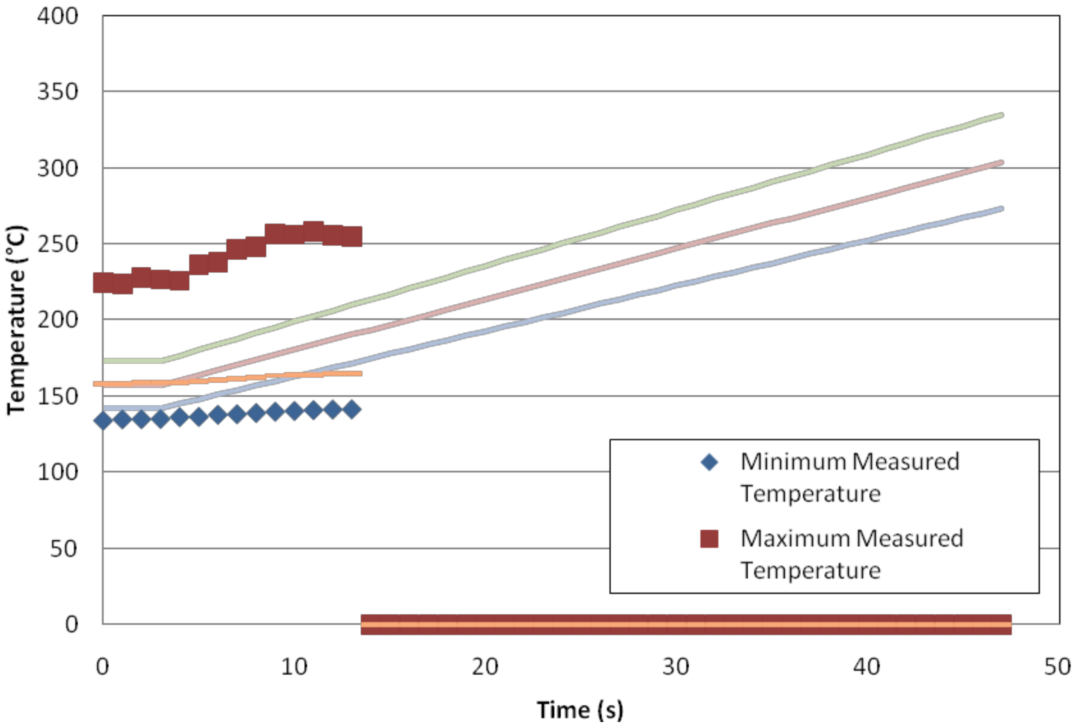


Figure 38: Maximum and minimum thermocouple measurements, average measured temperature and target temperature for Test 6.

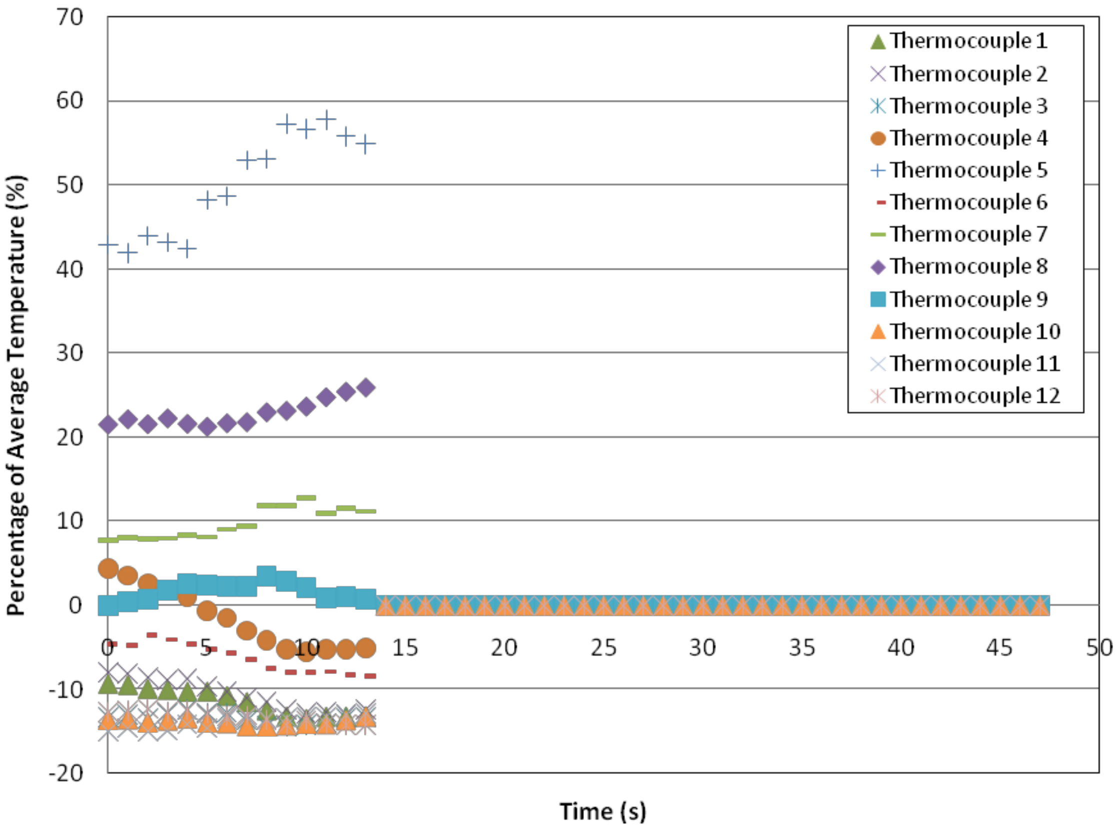


Figure 39: Temperature difference between each thermocouple measurement and the average measured temperature as a percentage of the average temperature for Test 6.

B.7 Test 7

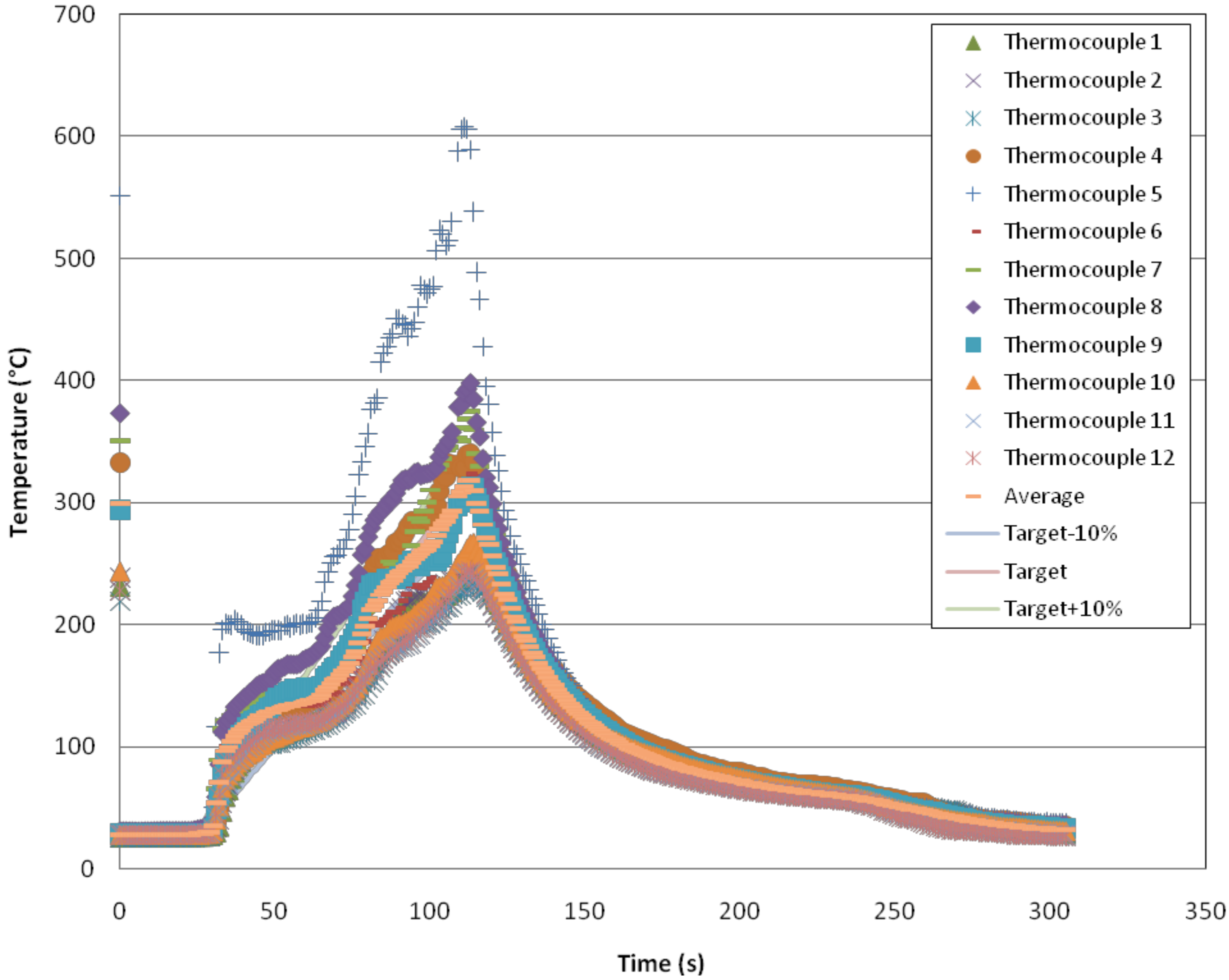


Figure 40: Thermocouple measurements, average of all 12 thermocouple measurements and target temperature for Test 7.

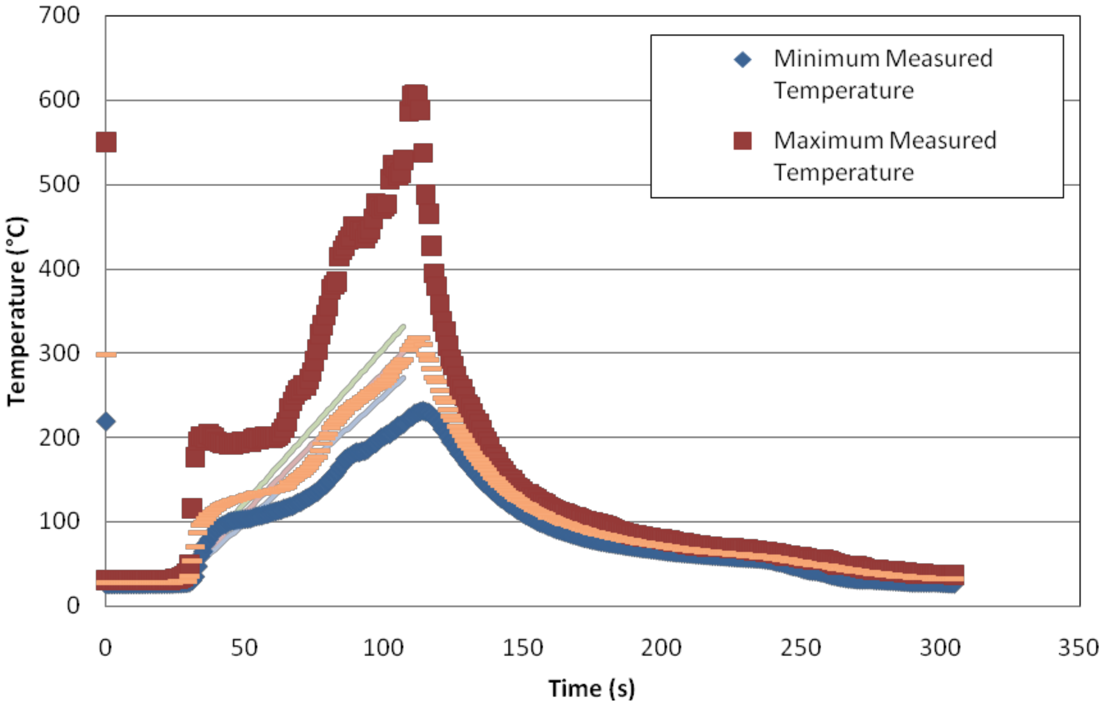


Figure 41: Maximum and minimum thermocouple measurements, average measured temperature and target temperature for Test 7.

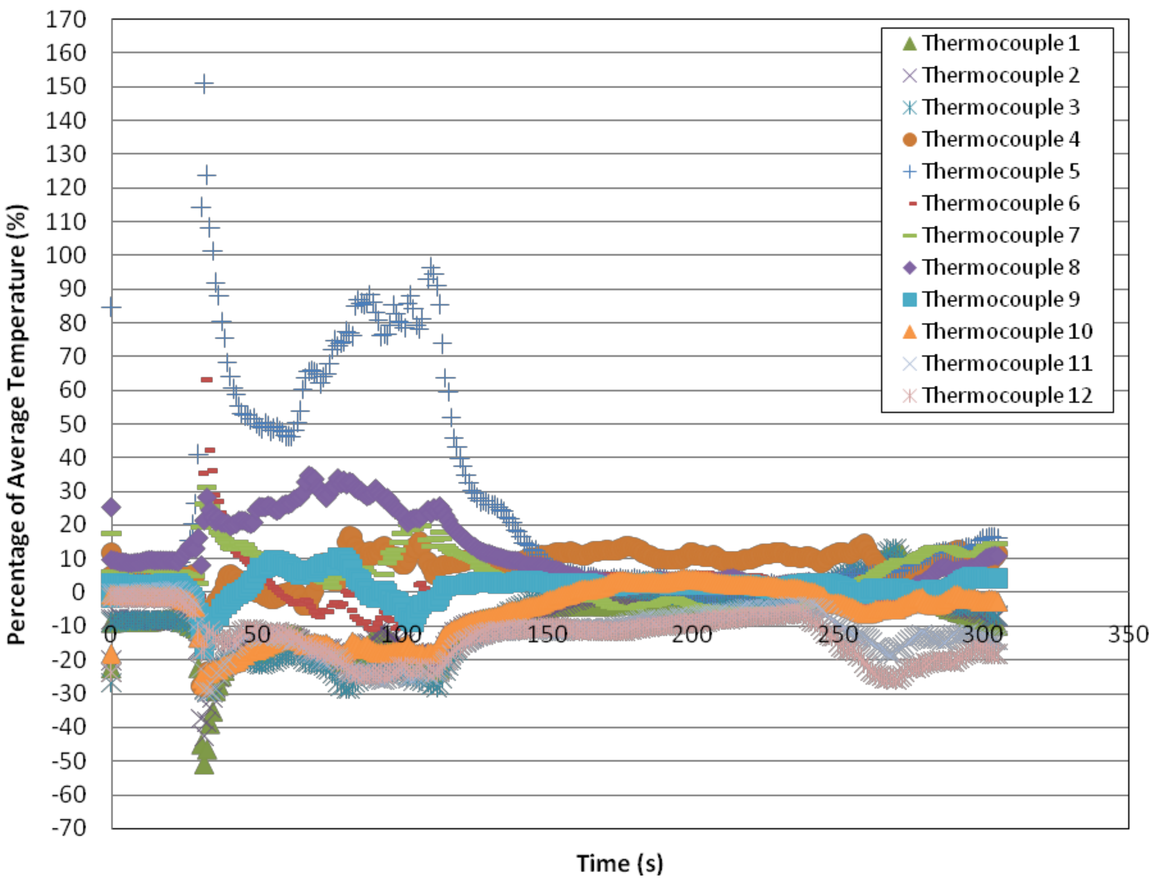


Figure 42: Temperature difference between each thermocouple measurement and the average measured temperature as a percentage of the average temperature for Test 7.

B.8 Test 8

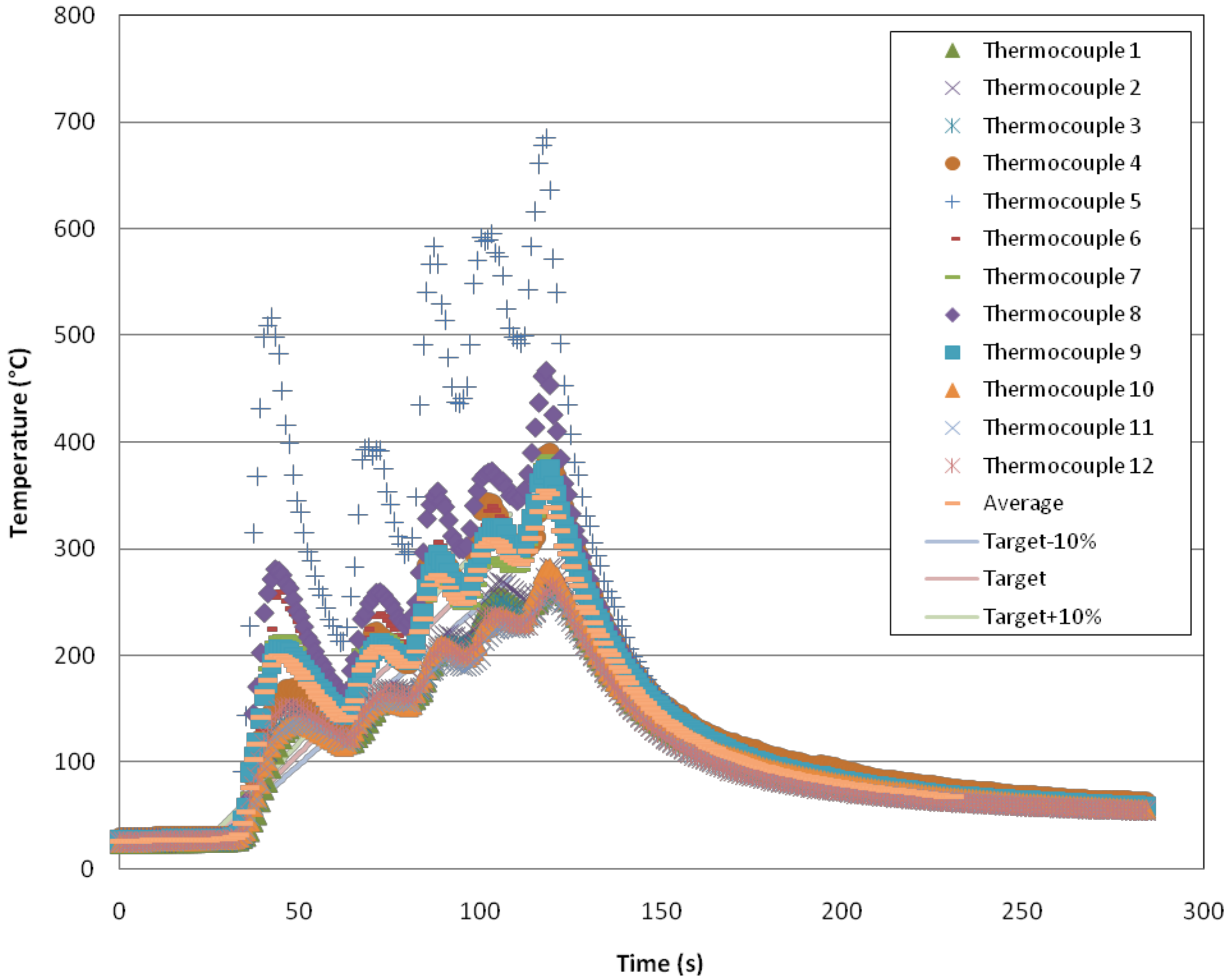


Figure 43: Thermocouple measurements, average of all 12 thermocouple measurements and target temperature for Test 8.

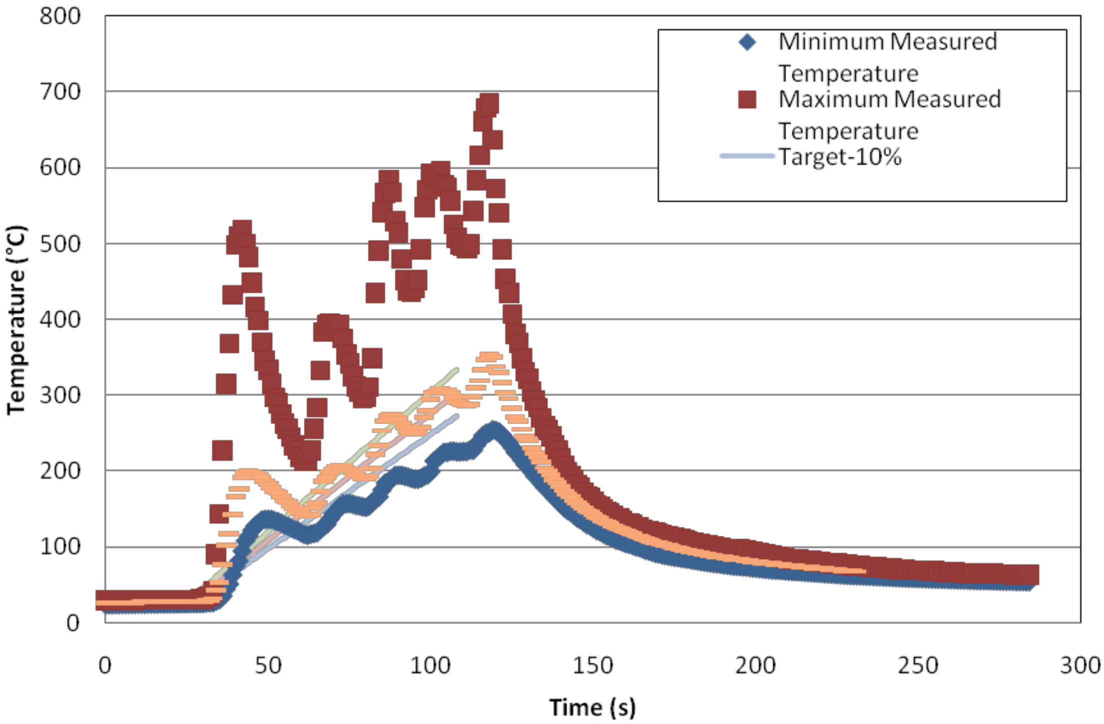


Figure 44: Maximum and minimum thermocouple measurements, average measured temperature and target temperature for Test 8.

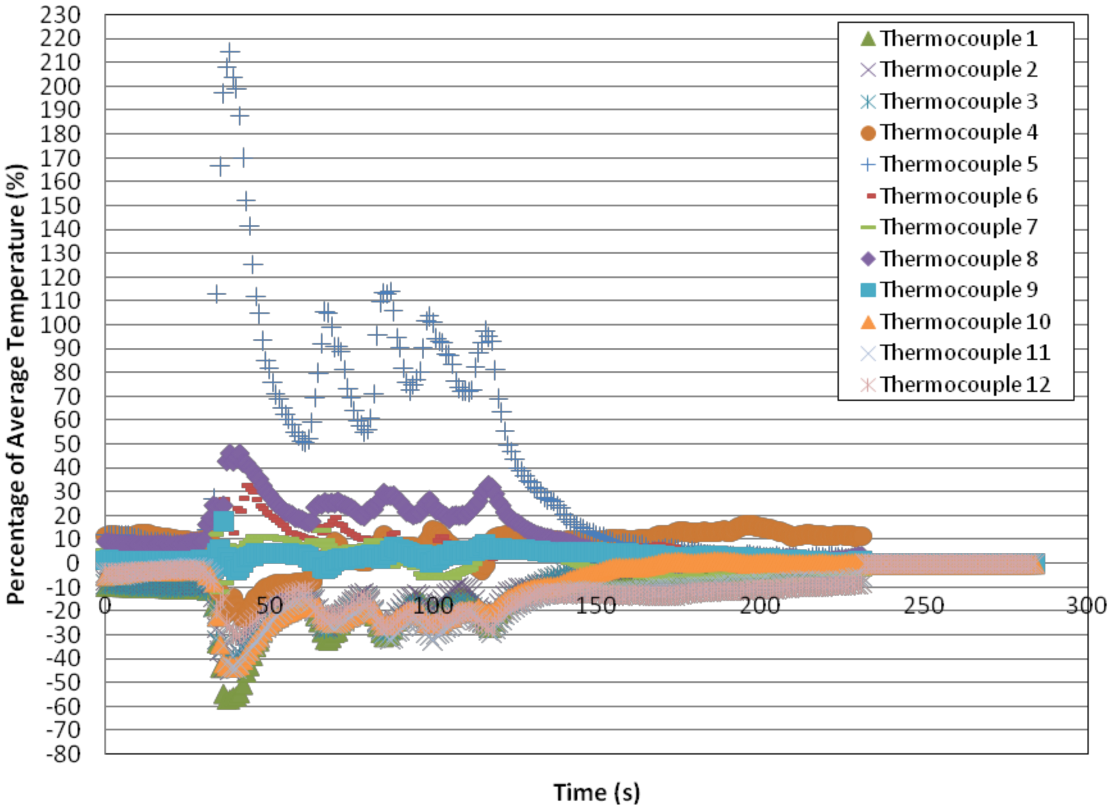


Figure 45: Temperature difference between each thermocouple measurement and the average measured temperature as a percentage of the average temperature for Test 8.

B.9 Test 9

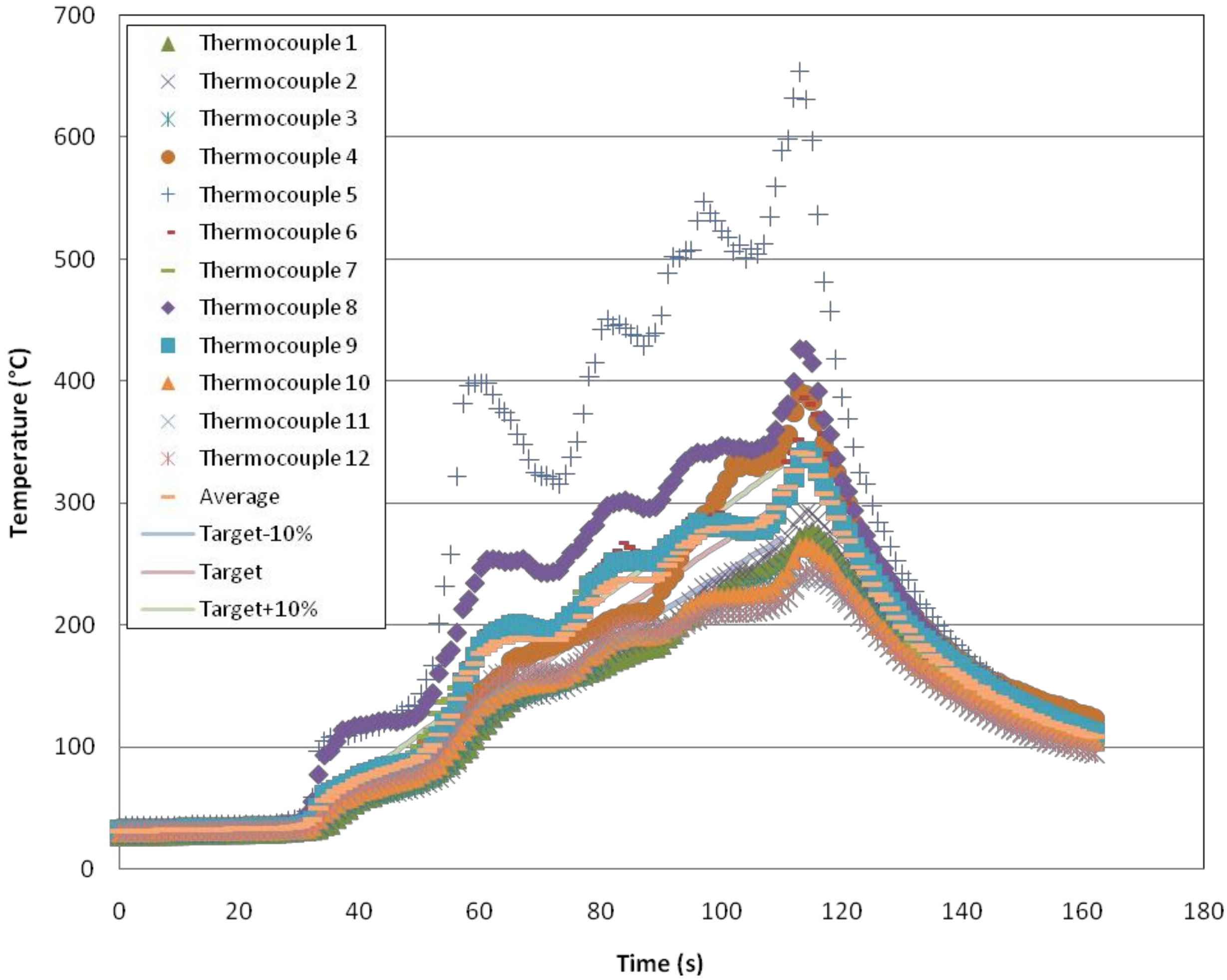


Figure 46: Thermocouple measurements, average of all 12 thermocouple measurements and target temperature for Test 9.

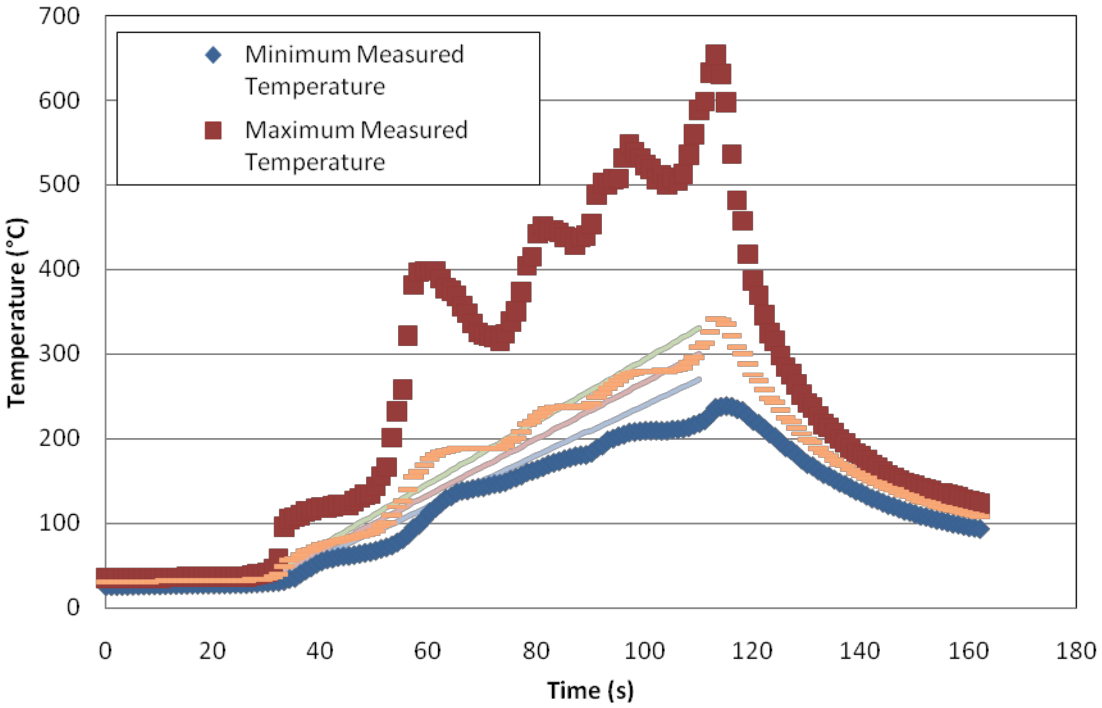


Figure 47: Maximum and minimum thermocouple measurements, average measured temperature and target temperature for Test 9.

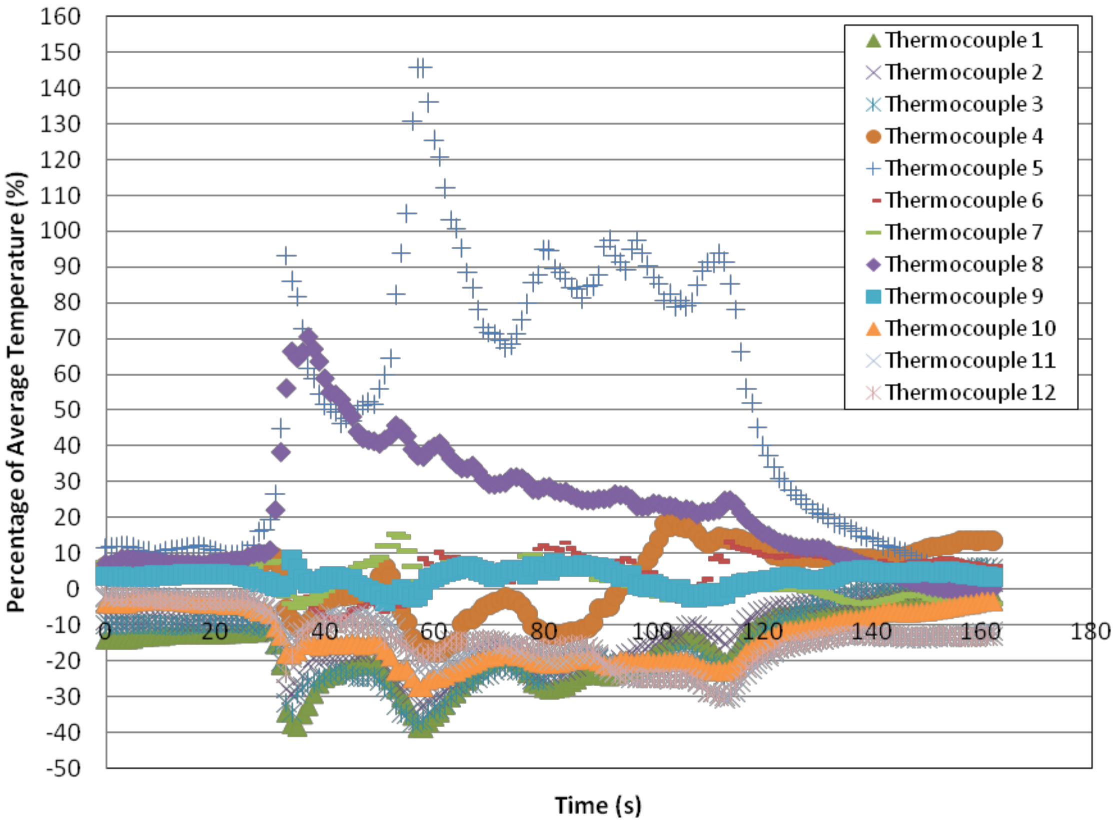


Figure 48: Temperature difference between each thermocouple measurement and the average measured temperature as a percentage of the average temperature for Test 9.

B.10 Test 10

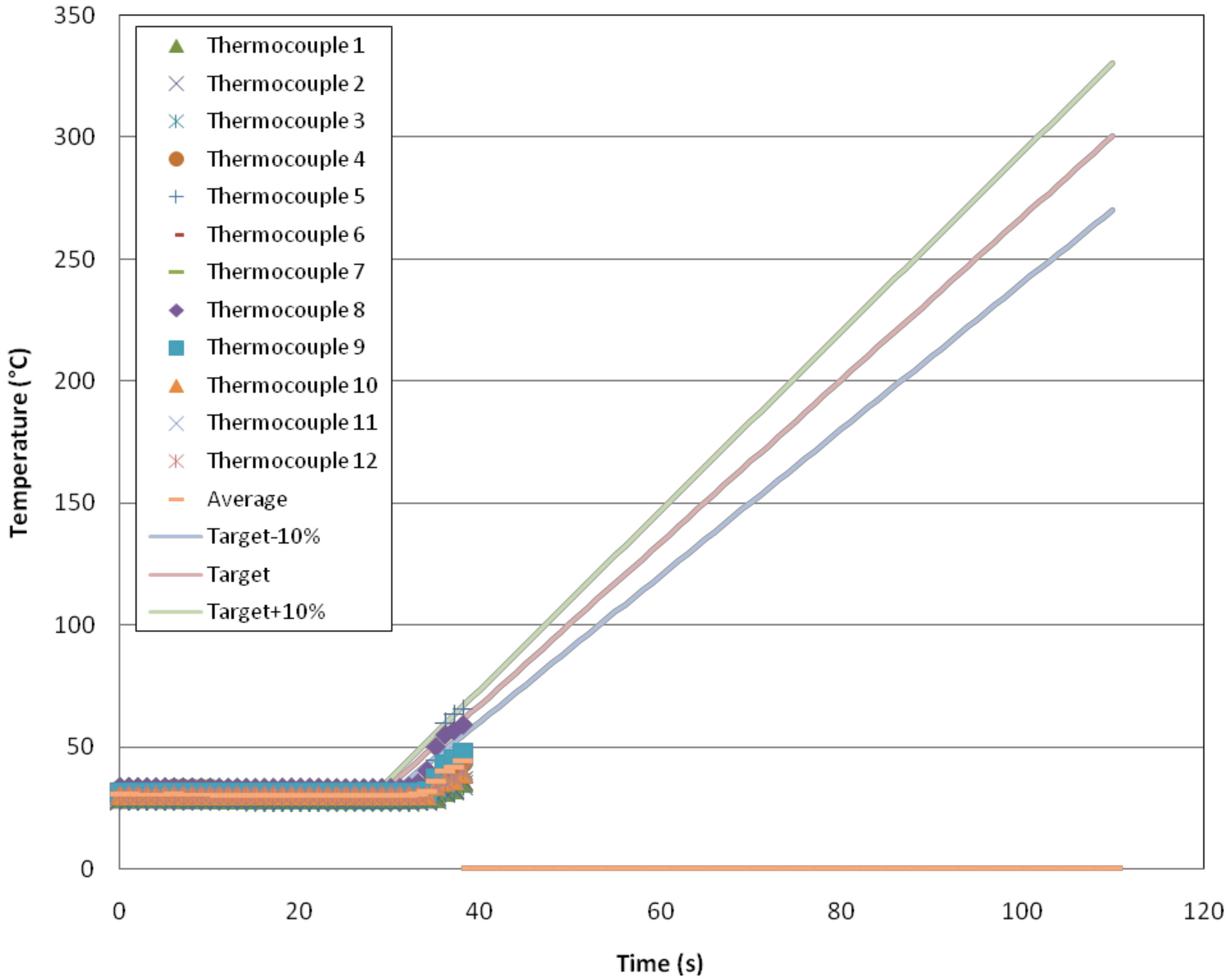


Figure 49: Thermocouple measurements, average of all 12 thermocouple measurements and target temperature for Test 10.

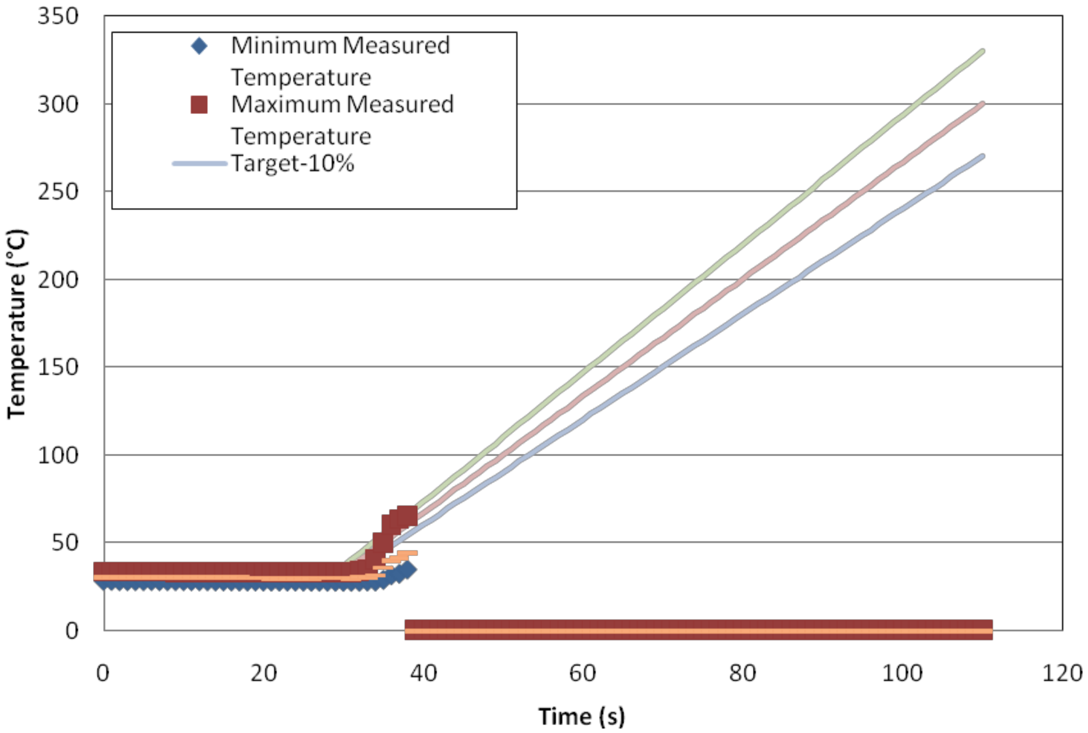


Figure 50: Maximum and minimum thermocouple measurements, average measured temperature and target temperature for Test 10.

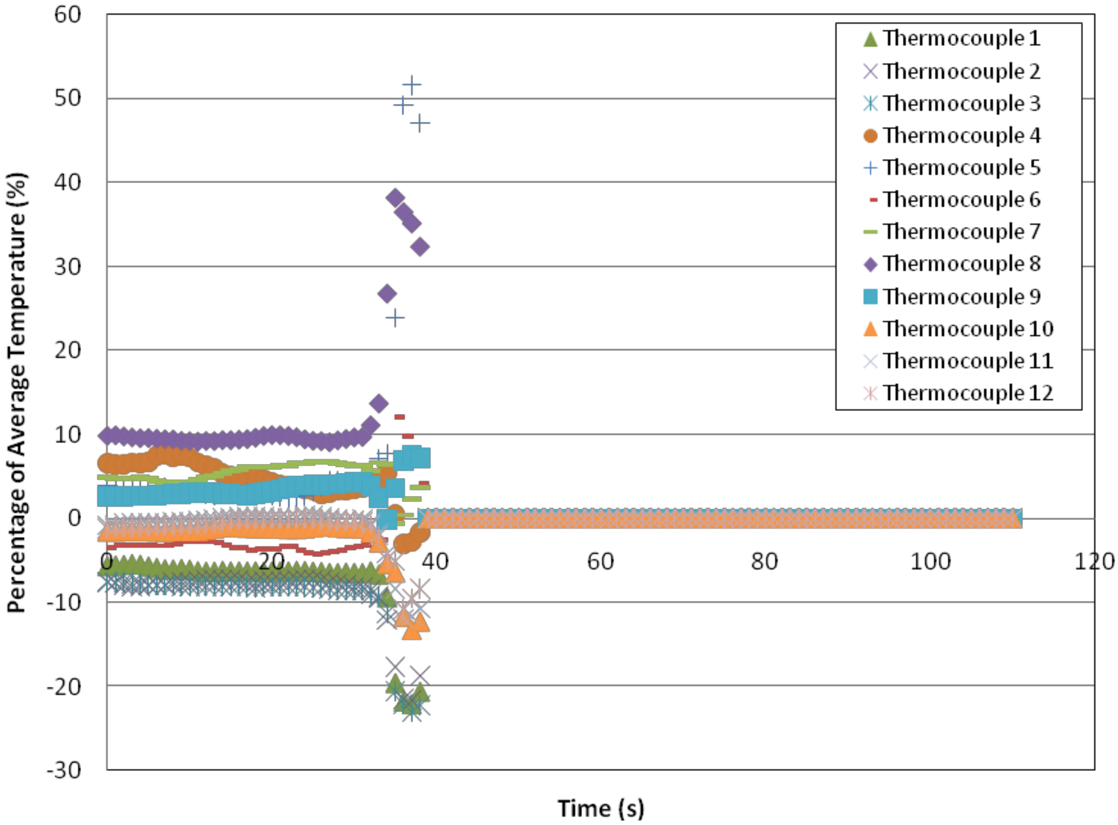


Figure 51: Temperature difference between each thermocouple measurement and the average measured temperature as a percentage of the average temperature for Test 10.

B.11 Test 11

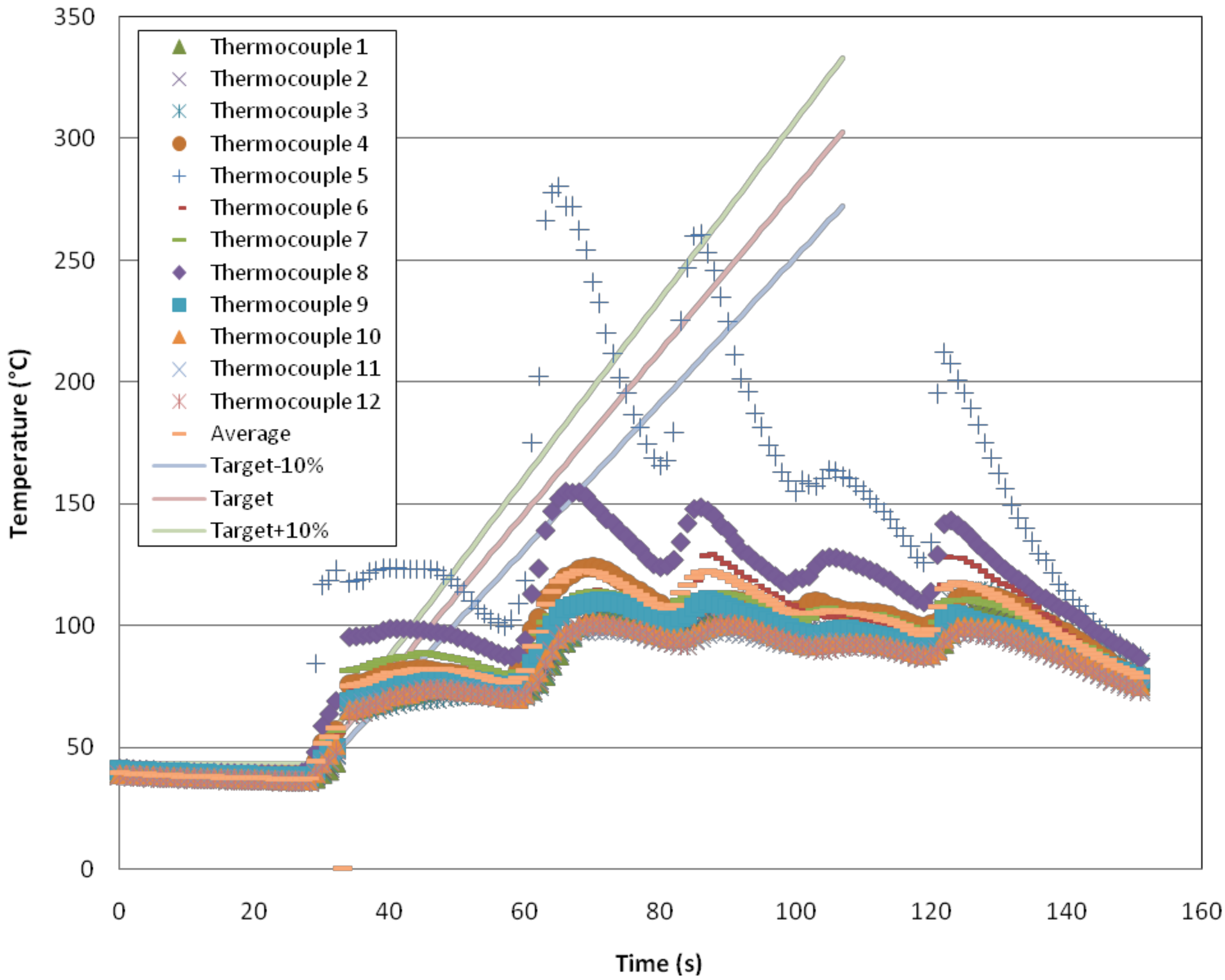


Figure 52: Thermocouple measurements, average of all 12 thermocouple measurements and target temperature for Test 11.

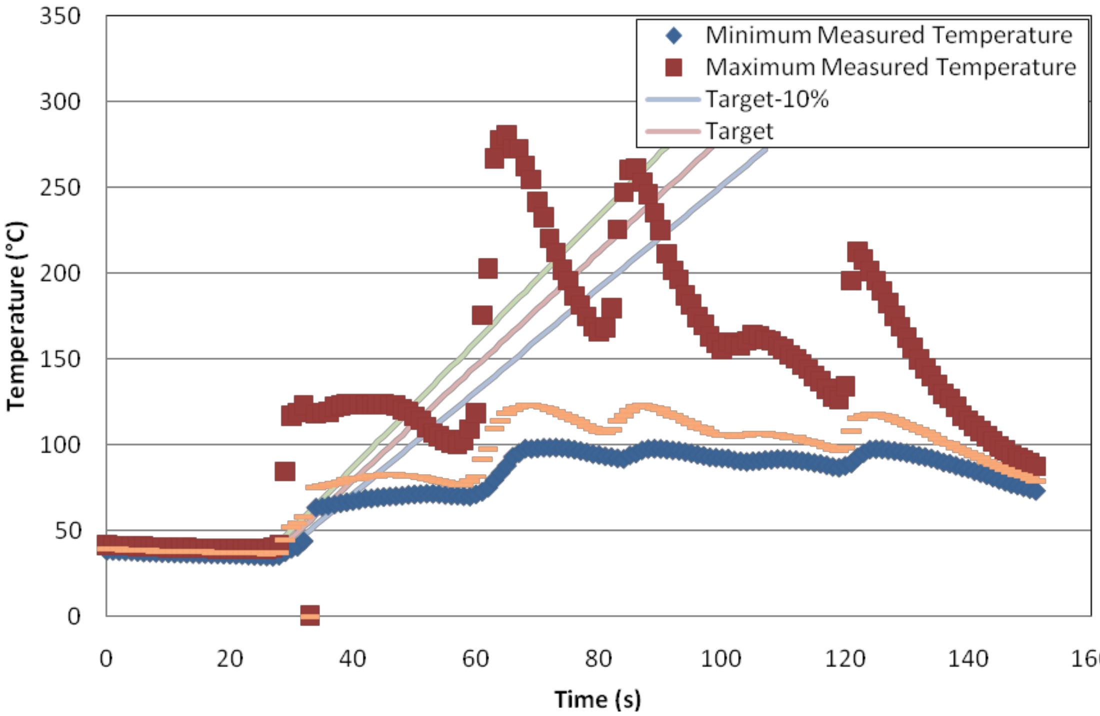


Figure 53: Maximum and minimum thermocouple measurements, average measured temperature and target temperature for Test 11.

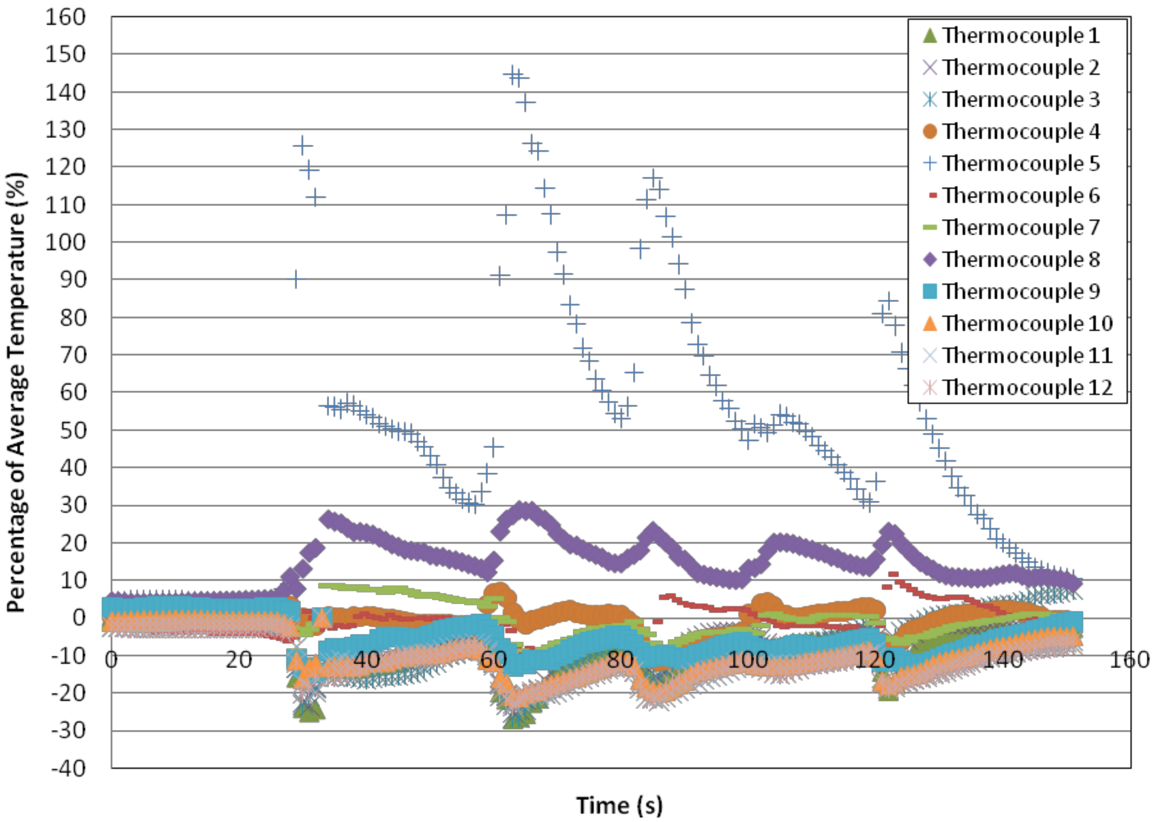


Figure 54: Temperature difference between each thermocouple measurement and the average measured temperature as a percentage of the average temperature for Test 11.

B.12 Test 12

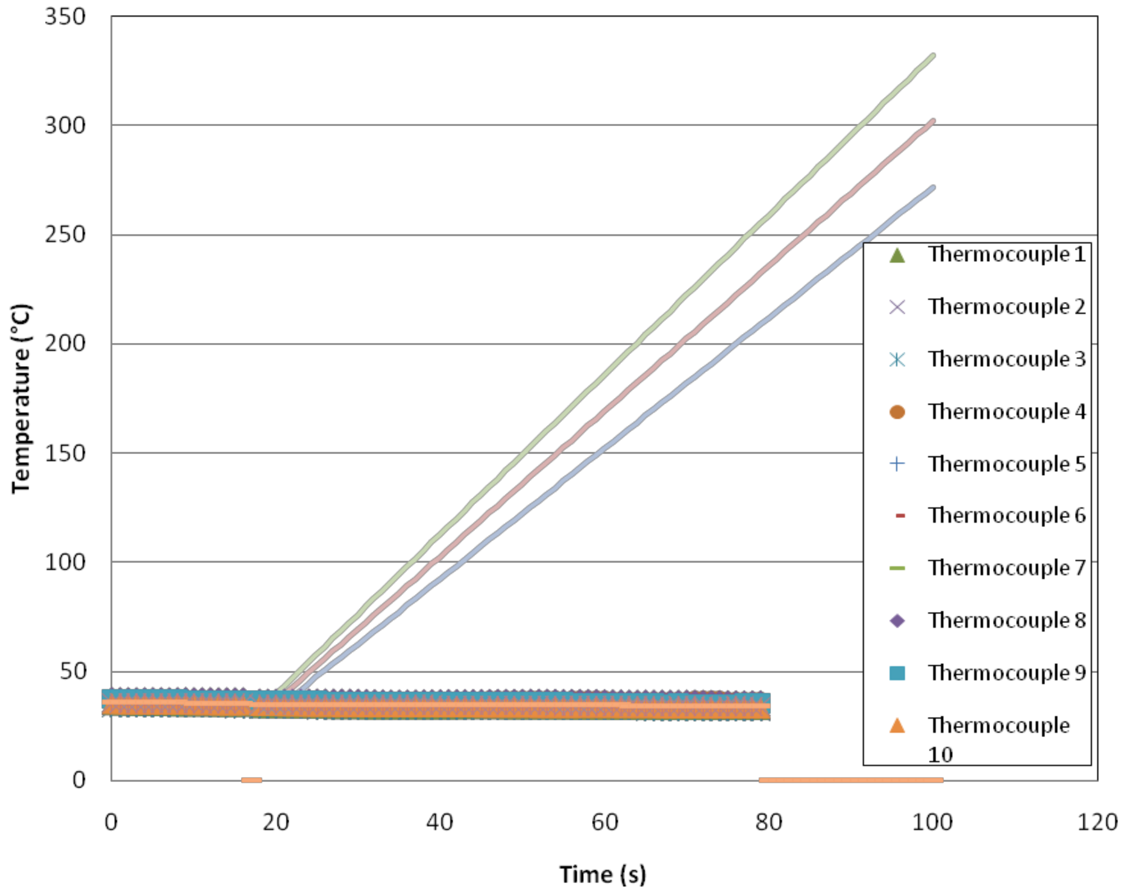


Figure 55: Thermocouple measurements, average of all 12 thermocouple measurements and target temperature for Test 12.

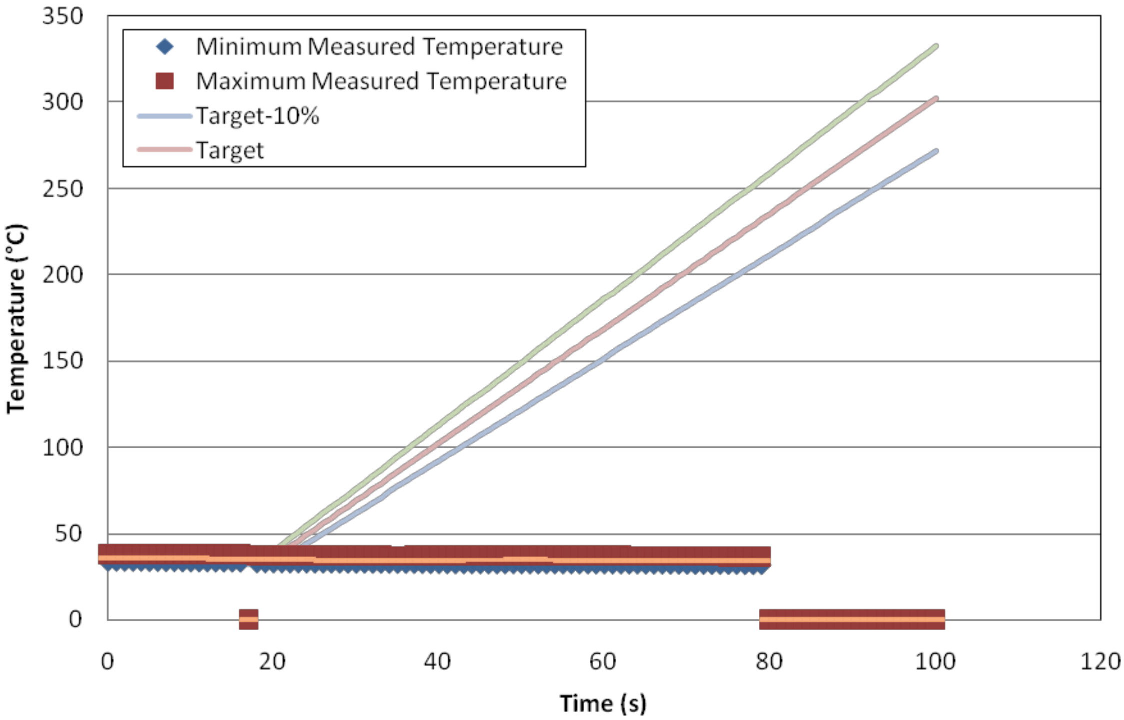


Figure 56: Maximum and minimum thermocouple measurements, average measured temperature and target temperature for Test 12.

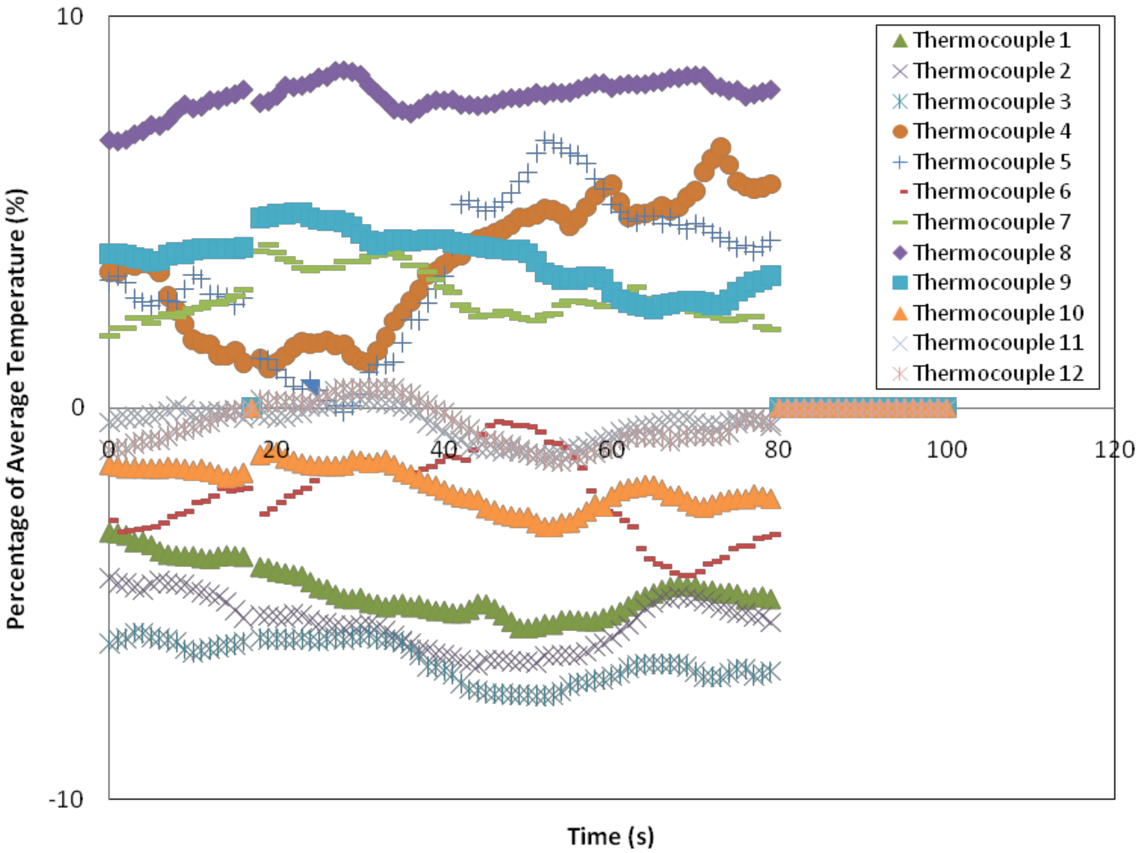


Figure 57: Temperature difference between each thermocouple measurement and the average measured temperature as a percentage of the average temperature for Test 12.

B.13 Test 13

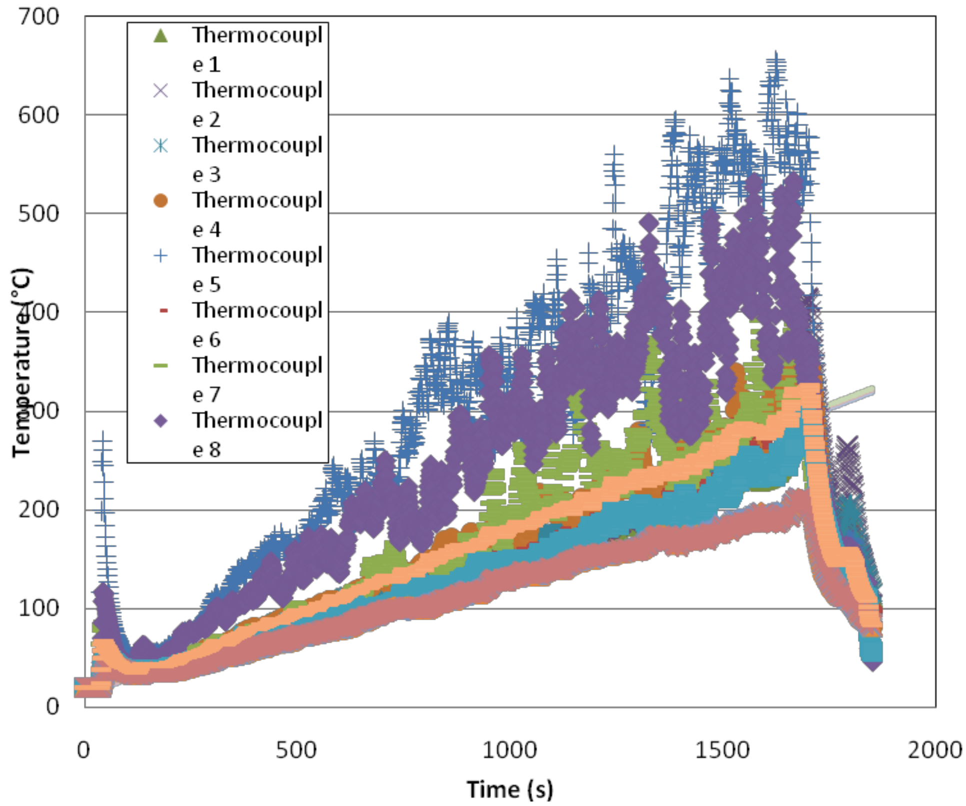


Figure 58: Thermocouple measurements, average of all 12 thermocouple measurements and target temperature for Test 13.

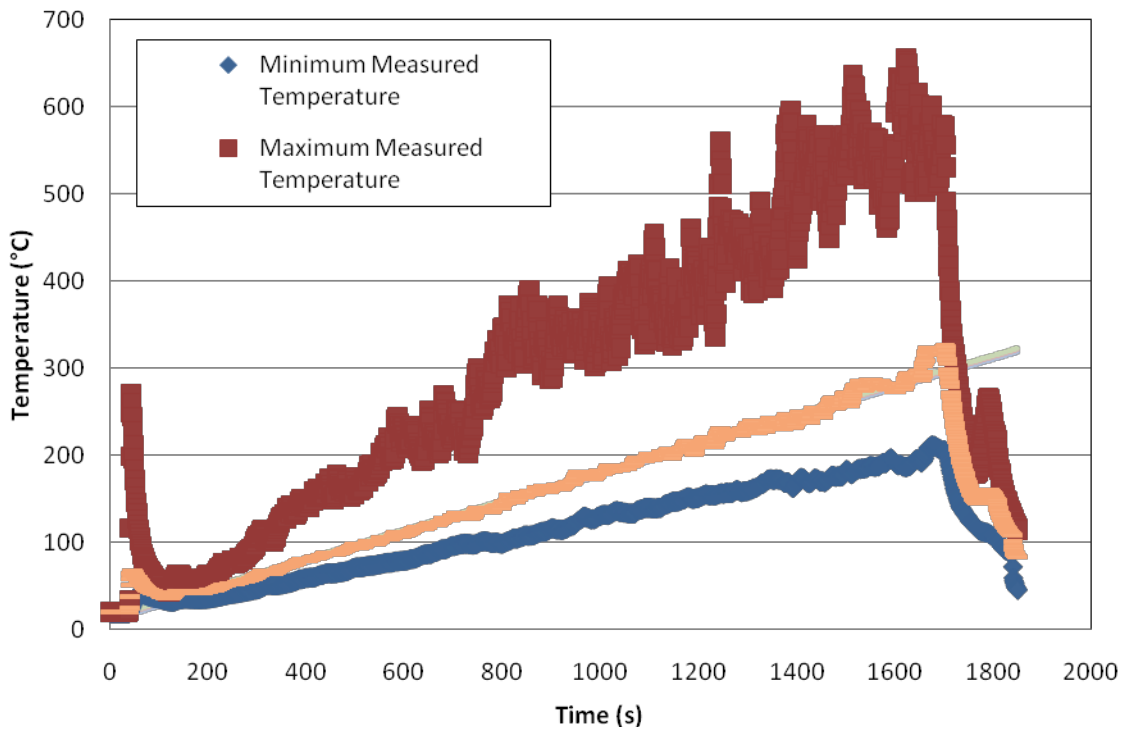


Figure 59: Maximum and minimum thermocouple measurements, average measured temperature and target temperature for Test 13.

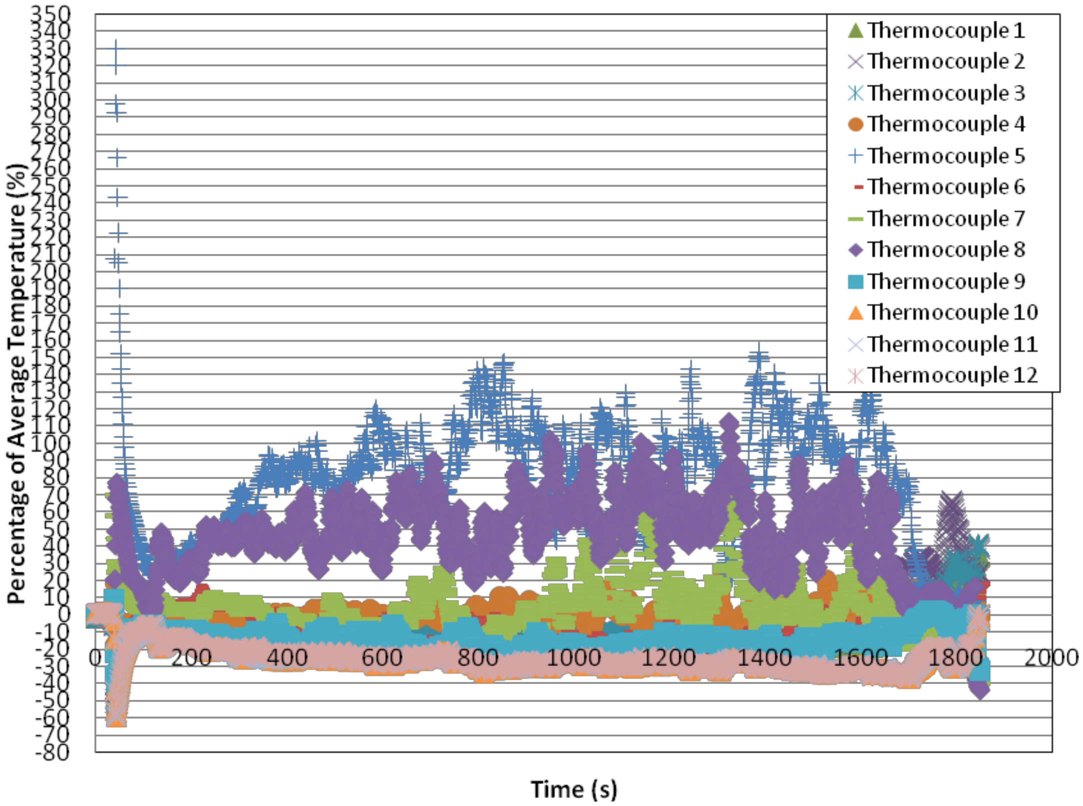


Figure 60: Temperature difference between each thermocouple measurement and the average measured temperature as a percentage of the average temperature for Test 13.

Table 6: Summary of observations during Test 13

Time from Burner Ignition (min)	Description of Observation
0	Burner ignited
0 - 0.30	Intermittent flame impingement on underside of panel at start up of burner.
13	Occasional flame glow seen through panel
15	More frequent flame glow seen through panel
17.5	Short-lived flame impingement on underside of panel. Slight blackening attributed to soot deposits on underside of panel, particularly on parts of panel with space over the top of purlins.
20	Light patches on underside of the panel. Light smoke rising from panel (see Figure 61).
23	More consistent flame impingement on underside of panel and more light smoke from top of panel.
25	Panel starting to burn
27	A short-lived flame on the topside of the panel. Lots of smoke (Figure 62).
28	Flaming on underside of panel.
28.5	Flames coming out from edge of panel, where attached to iron sheeting and cut end of panel (see Figure 63).
28.5	Burner off.
Post test observations	Panel continues to flame (see Figure 64) until water is applied.
	No opening in panel had formed during test (see Figure 65).

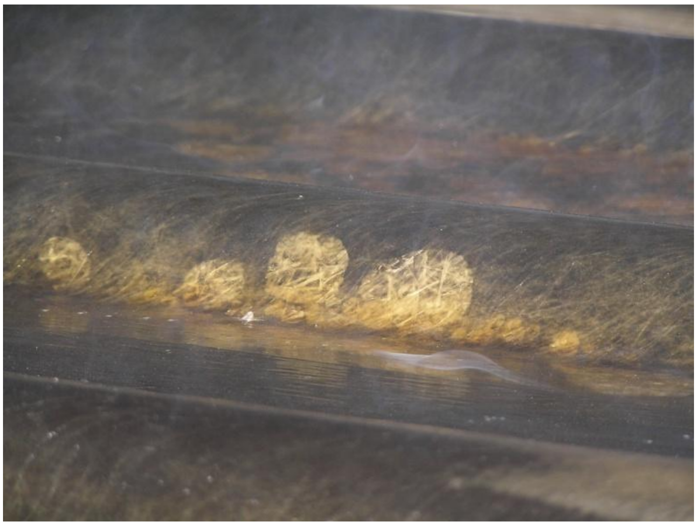


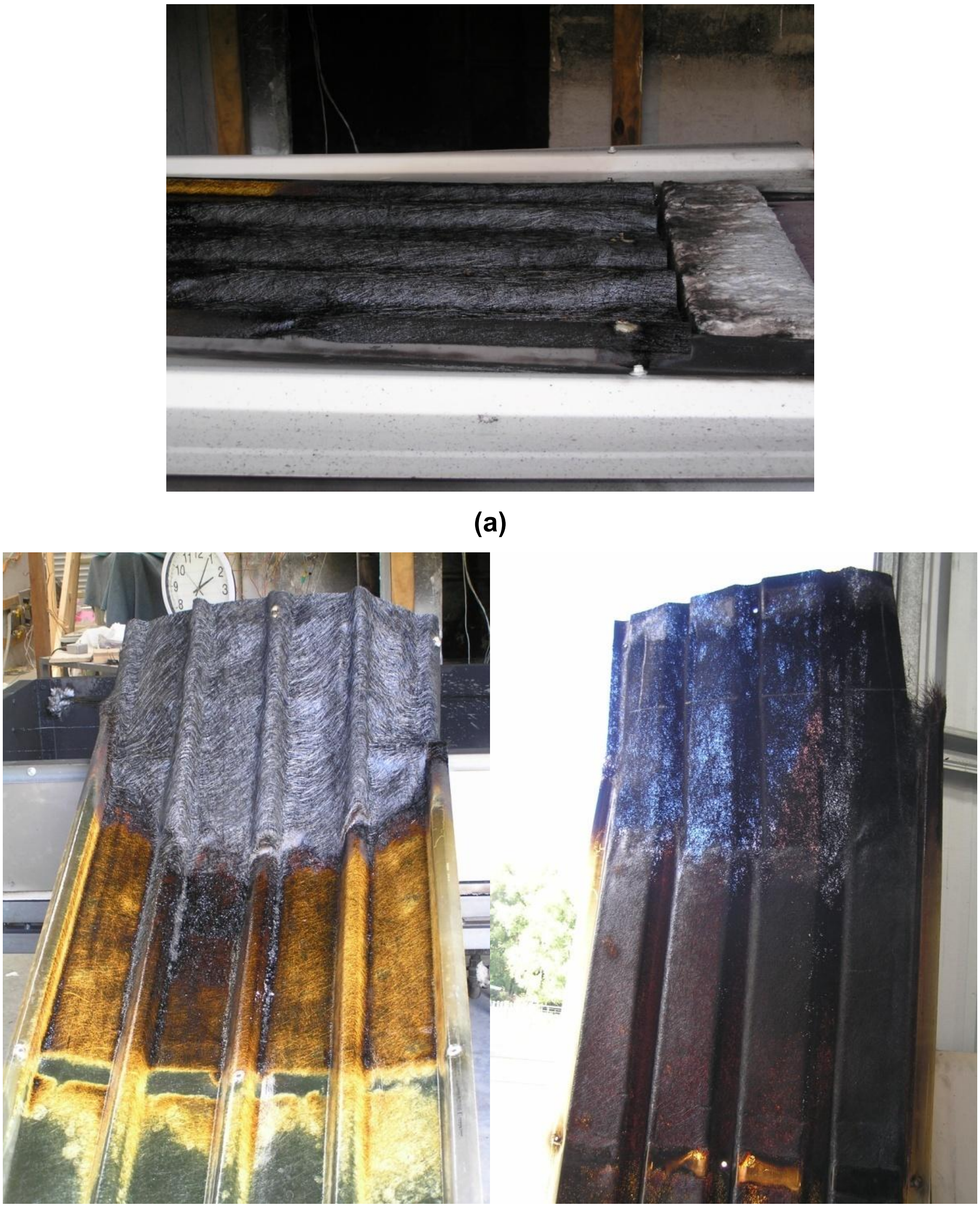
Figure 61: Topside of panel, showing light smoke rising from surface. (Test 13 at 20 min from ignition of burner.)

Figure 62: Topside of panel, showing smoke rising from surface. (Test 13 at 27 min from ignition of burner.)

Figure 63: Heavy smoke and flames from burning panel. Burner is off. (Test 13 at 20 s after burner was switched off).

(a) **(b)**

Figure 64: After burner was switched off and underside of panel had stopped flaming, (a) edges of panel were flaming and (b) then the flames moved across the topside of the panel.



(a)

(b) (c)

Figure 65: Photographs of the post-test specimen (a) still in the test apparatus, (b) topside of panel outside of test apparatus, and (c) underside of panel outside of test apparatus.

B.14 Test 14

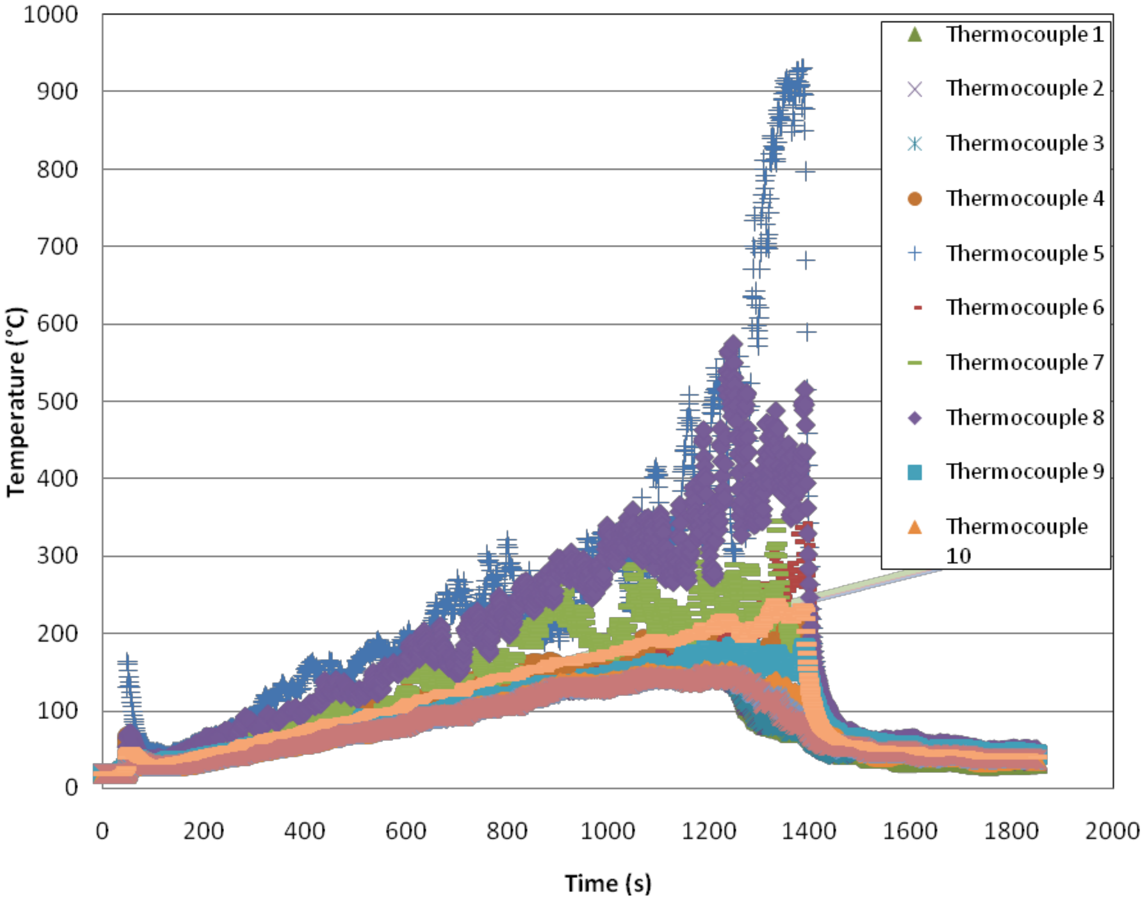


Figure 66: Thermocouple measurements, average of all 12 thermocouple measurements and target temperature for Test 14.

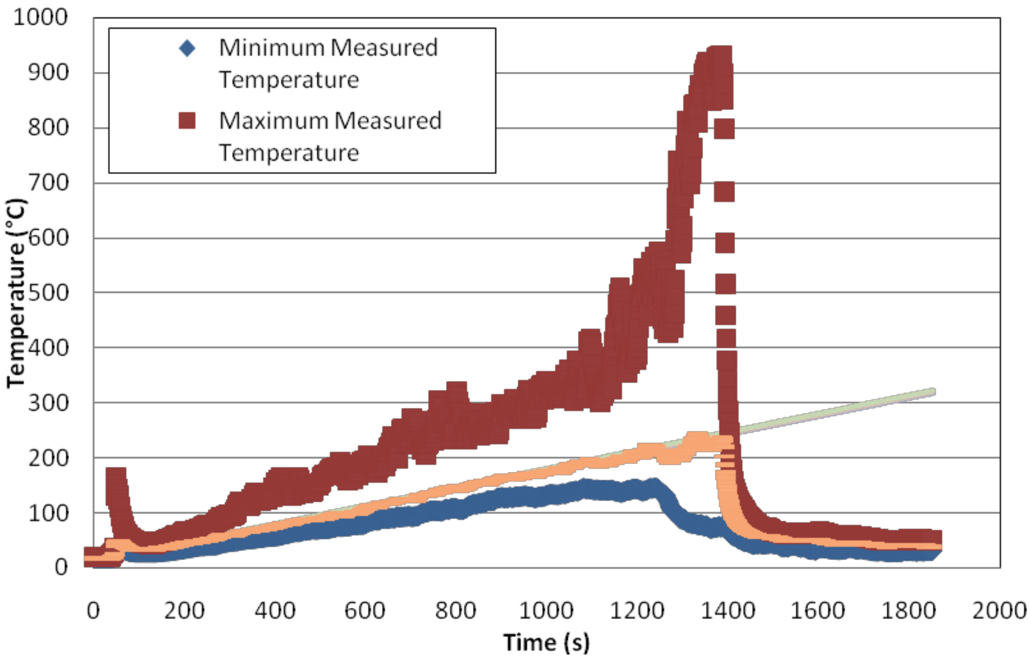


Figure 67: Maximum and minimum thermocouple measurements, average measured temperature and target temperature for Test 14.

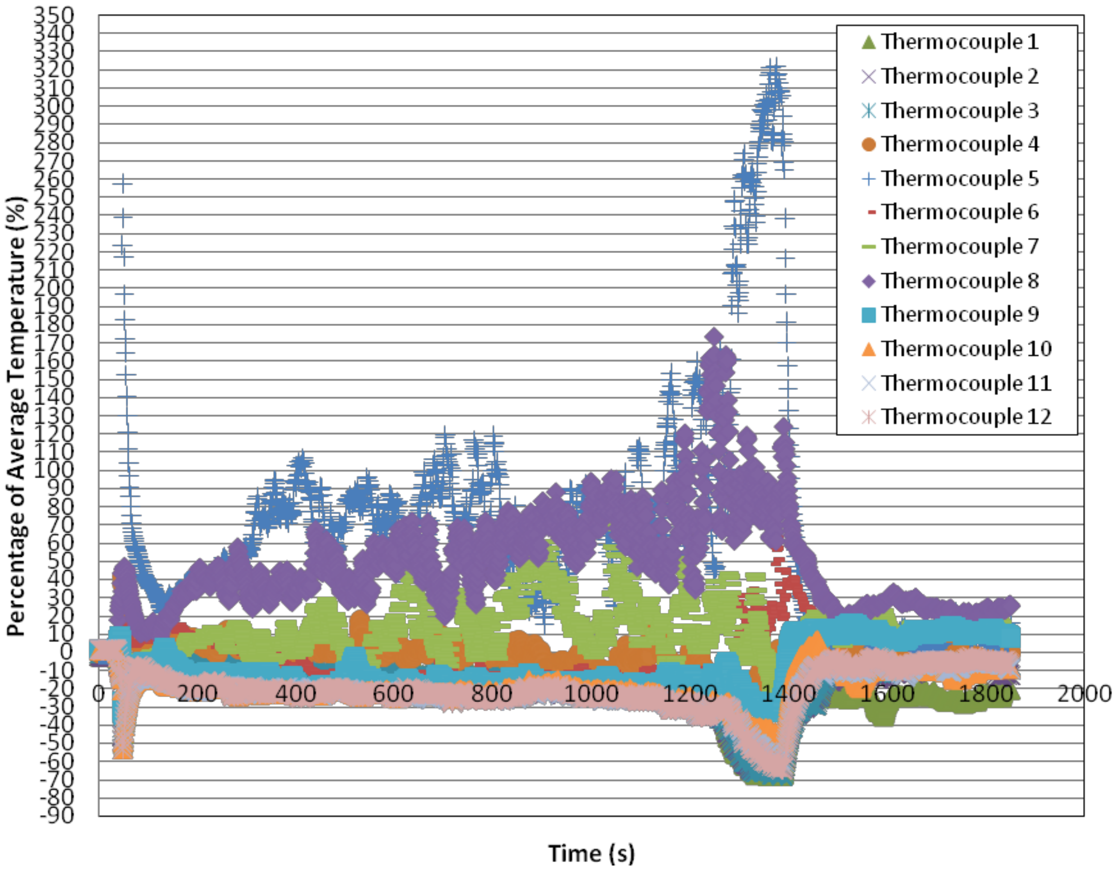


Figure 68: Temperature difference between each thermocouple measurement and the average measured temperature as a percentage of the average temperature for Test 14.

Table 7: Summary of observations during Test 14

Time from Burner Ignition (min)	Description of Observation
0	Burner ignited
0 - 0.15	Intermittent flame impingement on underside of panel at start up of burner.
5	Intermittent flames observed around edges of the baffle. (Figure 69)
11	Clear panel slowly turning milky, attributed to soot deposition. Slight sagging of panel (Section A-B).
12	Glow seen through panel. Occasional flame impingement on underside of panel (near to edges of panel in Section C).
14	Slight sagging and wrinkling of panel (near section C) (Figure 70)
15	Panel sagging either side of the middle purlin.
15.5	Occasional flame impingement on panel getting more frequent, mostly nearer to Section C than to Section A.
16	Topside of panel starts to smoke near to Section B.
16.5	A 3 second burst of flames visible through panel coming around edges of baffle, but not impinging on the panel surface. (near Section C)
17	Flames seen around edges of baffle continuously. No flame impingement on panel.
18	**Opening formed** in panel on Section B side of middle purlin.
18.5	Burner flames intermittently issuing from opening in panel.
19	Burner flames regularly issuing from opening in panel.
20.5	High burner flames regularly issuing from opening in panel.
23	Burner off. No flaming of panel material.
Test Method Improvements from Test Results and Observations	1. Reduce initial gas flow rates for ignition of burner. 2. Increase apparatus stand height by approximately 300 mm to reduce flames getting through the two layers of baffles. 3. Use an additional 3 baffles over the centre gap of the lower layer of baffles – 1x 500 mm wide, 2x 250 mm wide.

Figure 69: Small intermittent flames around the edges of the centre-most baffles, as observed through the transparent panel. (Test 14 at 5 min from ignition of burner.)

Figure 70: Slight sagging and wrinkling of panel. (Test 14 at 14 min from ignition of burner.)

Figure 71: Slight sagging and wrinkling of panel. (Test 14 at 15 min from ignition of burner.)

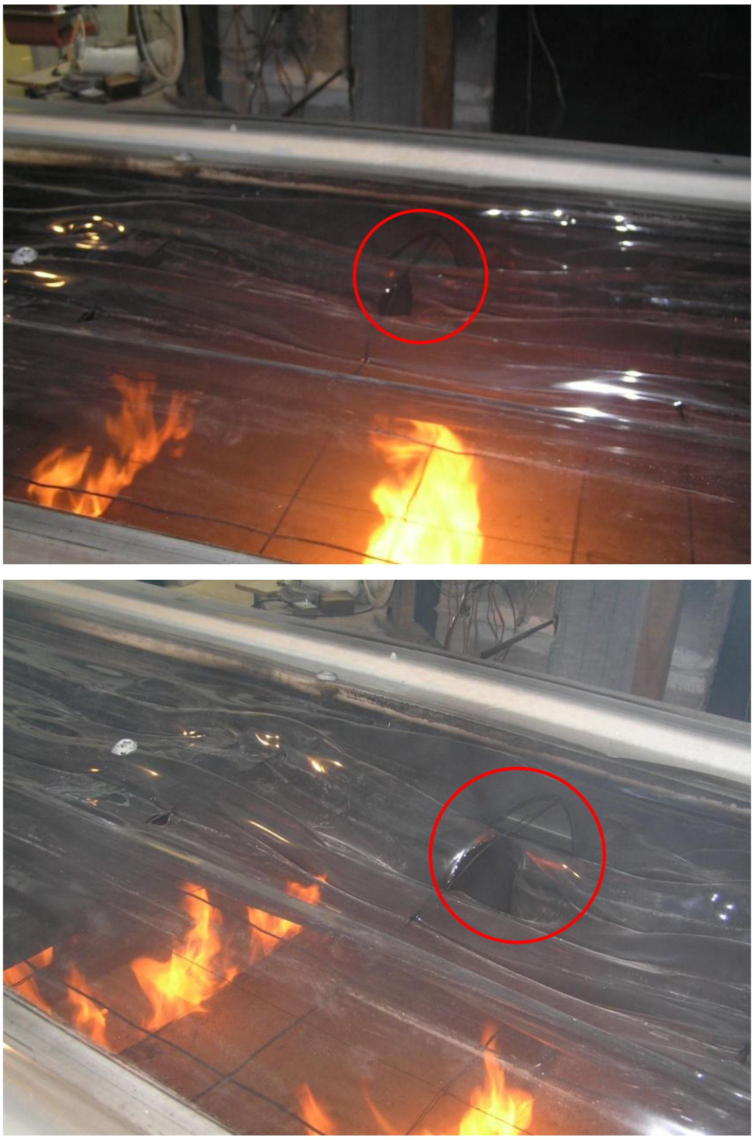


Figure 72: Openings (circled in red) formed in panel. (Test 14 after 18.25 min from burning ignition.)

B.15 Test 15

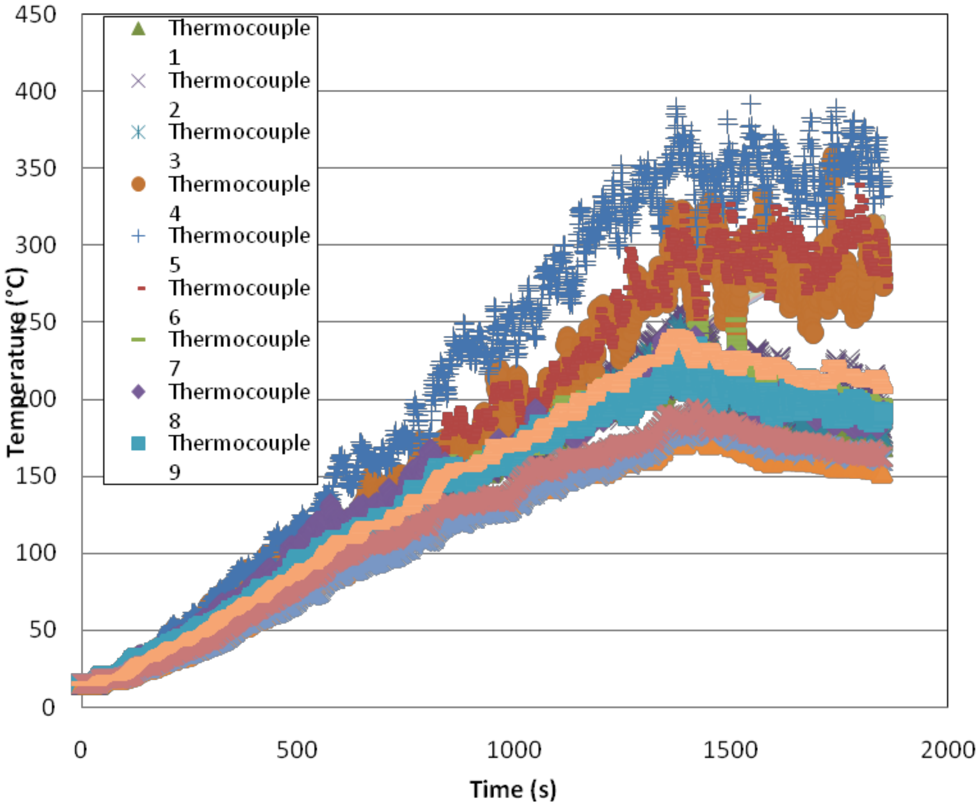


Figure 73: Thermocouple measurements, average of all 12 thermocouple measurements and target temperature for Test 15.

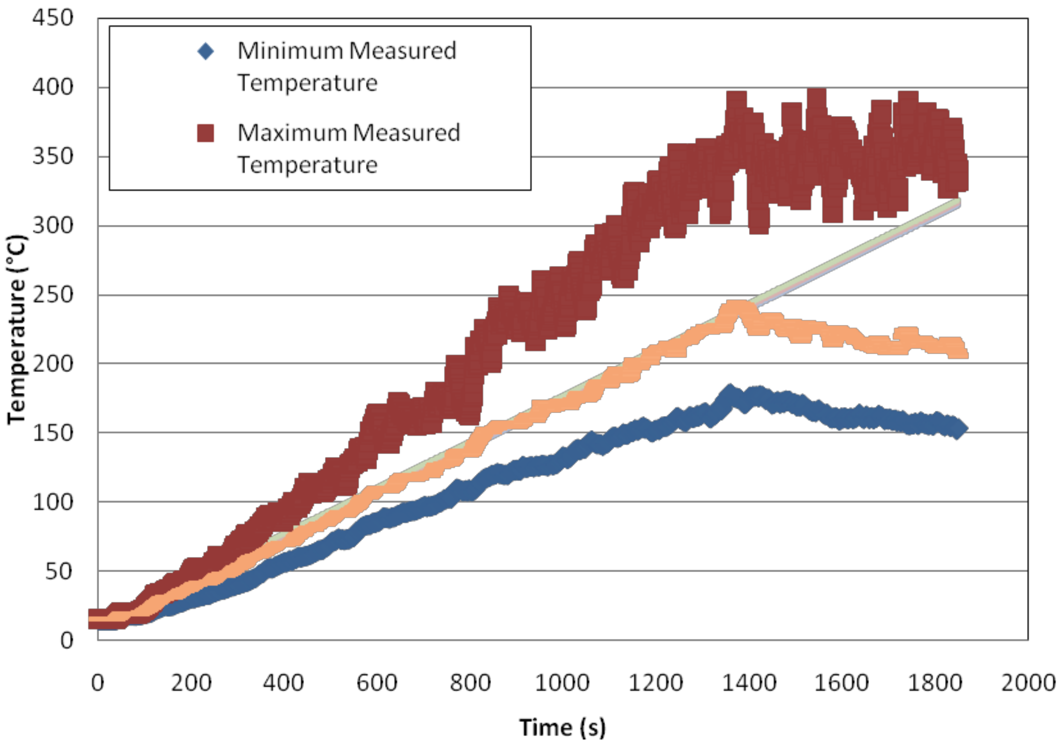


Figure 74: Maximum and minimum thermocouple measurements, average measured temperature and target temperature for Test 15.

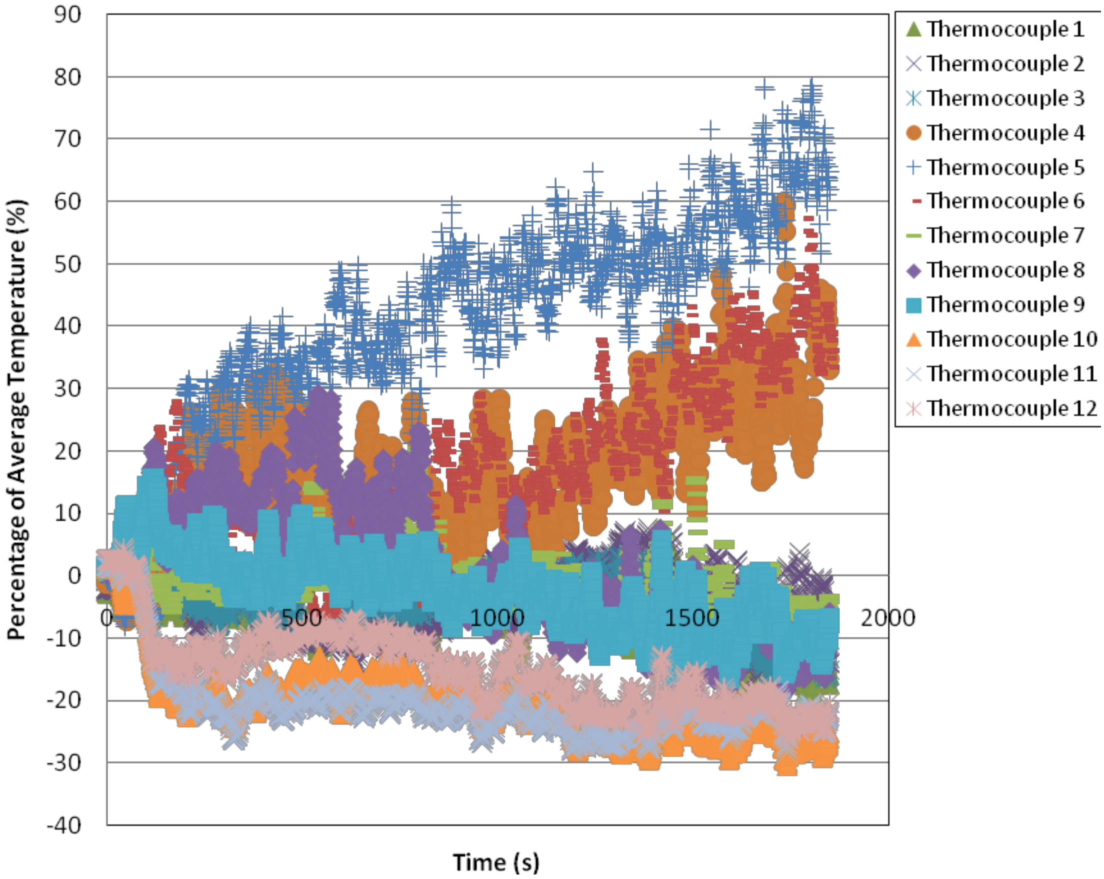


Figure 75: Temperature difference between each thermocouple measurement and the average measured temperature as a percentage of the average temperature for Test 15.

Table 8: Summary of observations during Test 15

Time from Burner Ignition (min)	Description of Observation
0	Burner ignited
13	Deformation of panel between ribs, over section B on right side. (Figure 76)
14	A transient finger of flame seen coming around baffles. No flame impingement on panel.
14.5	Deformation of ribs that are not fastened at the middle purlin. Greatest deformation of ribs on Section B side of the middle purlin. Slight sagging of the panel over Section B. (Figure 77)
15	Smoke rising from surface of panel. (Figure 78)
18.5	Panel over section B has sagged further. (Figure 79)
21	**Opening formed** in panel on Section B side of middle purlin. Mesh showing through opening. (Figure 80)
21 onward	Opening continues to increase in size. (Figure 81 & Figure 82)
24	Glow from burner flames observed between baffles of top layer. No flame impingement on panel. (Figure 83)
31	Burner off. No flaming of panel material.
Post test observations	Post test specimen shown in Figure 84.
Test Method Improvements from Test Results and Observations	1. Determine when to turn off burner in terms of when a test is deemed "successful".

Figure 76: Deformation of the panel. (Test 15 at 13 min from ignition of burner.)

Figure 77: Deformation of the panel. (Test 15 at 14.5 min from ignition of burner.)

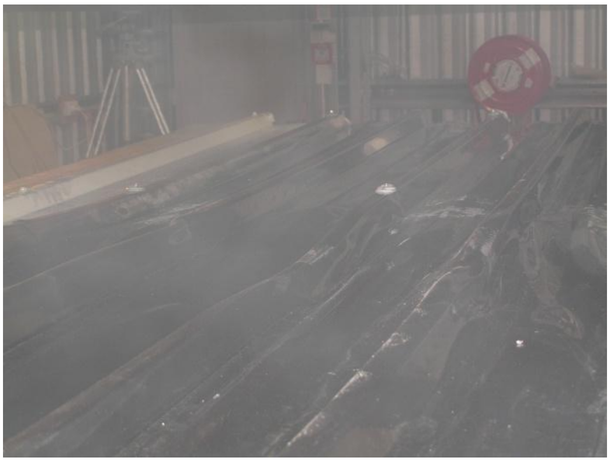
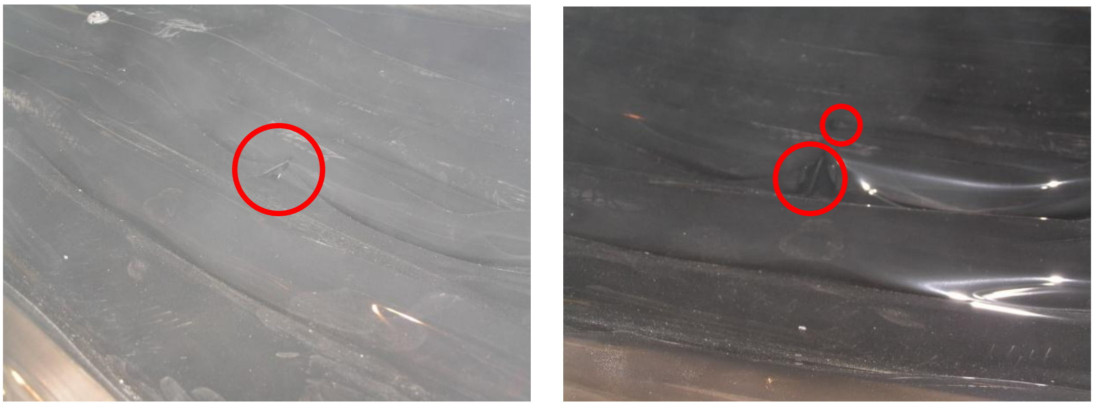


Figure 78: Smoke rising from surface of panel. (Test 15 at 15 min from ignition of burner.)

Figure 79: Panel further sagging. (Test 15 at 18.5 min from ignition of burner.)



(a) (b)

Figure 80: Opening forming. (Test 15 at 21 min from ignition of burner.)

(a) (b)

Figure 81: Opening continuing to form. (Test at 21.5 min from ignition of burner).

Figure 82: Showing opening at 22.5 min after burner ignition.

Figure 83: Showing opening with flames seen around the top layer of baffles at 24 min after burner ignition.

(a) (b)

(c) (d)

(e)

Figure 84: Post-test specimen showing the openings (a) and (b) while still on the test apparatus, and off the test frame (c) topside-up and (d) topside-down and (e) a close up of the opening in the topside-down orientation.

B.16 Test 16

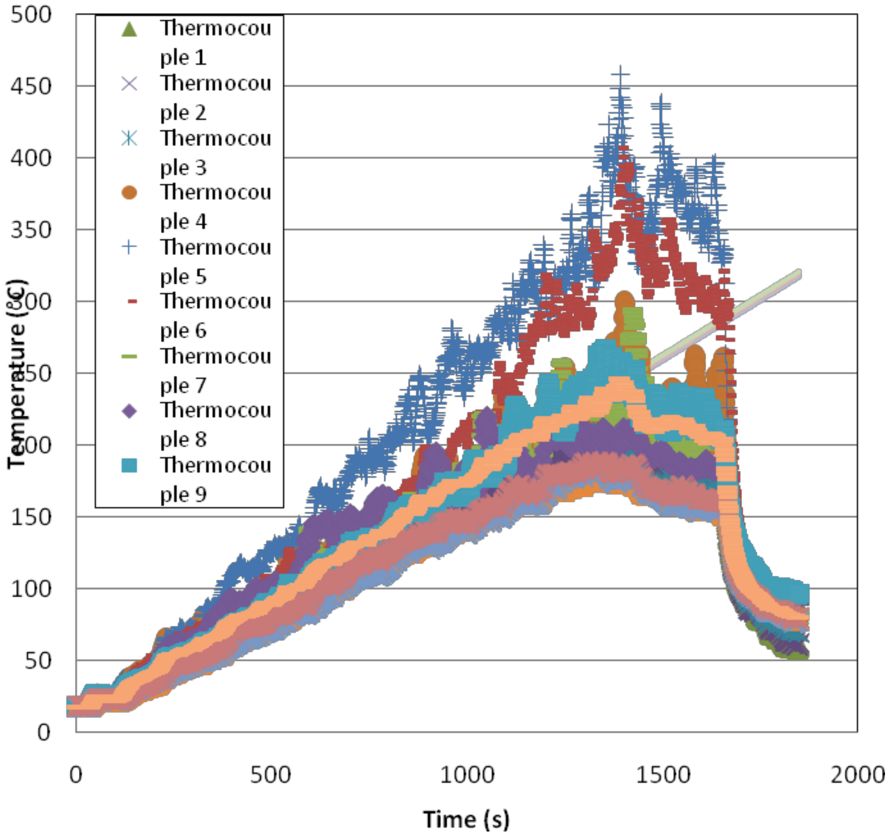


Figure 85: Thermocouple measurements, average of all 12 thermocouple measurements and target temperature for Test 16.

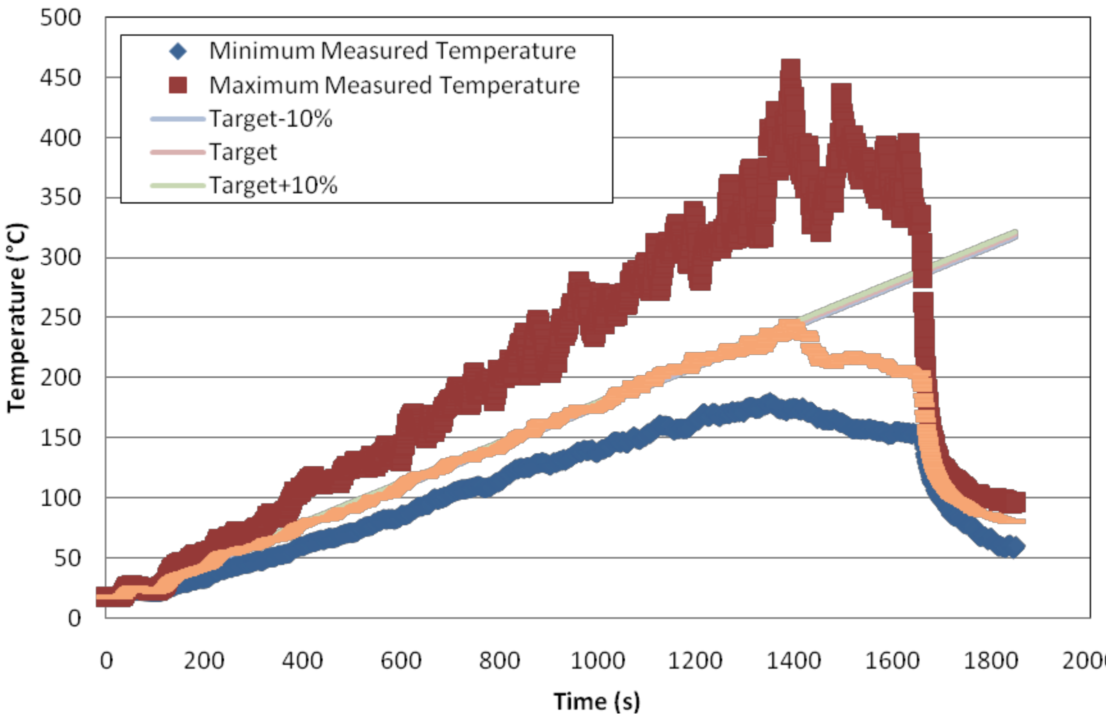


Figure 86: Maximum and minimum thermocouple measurements, average measured temperature and target temperature for Test 16.

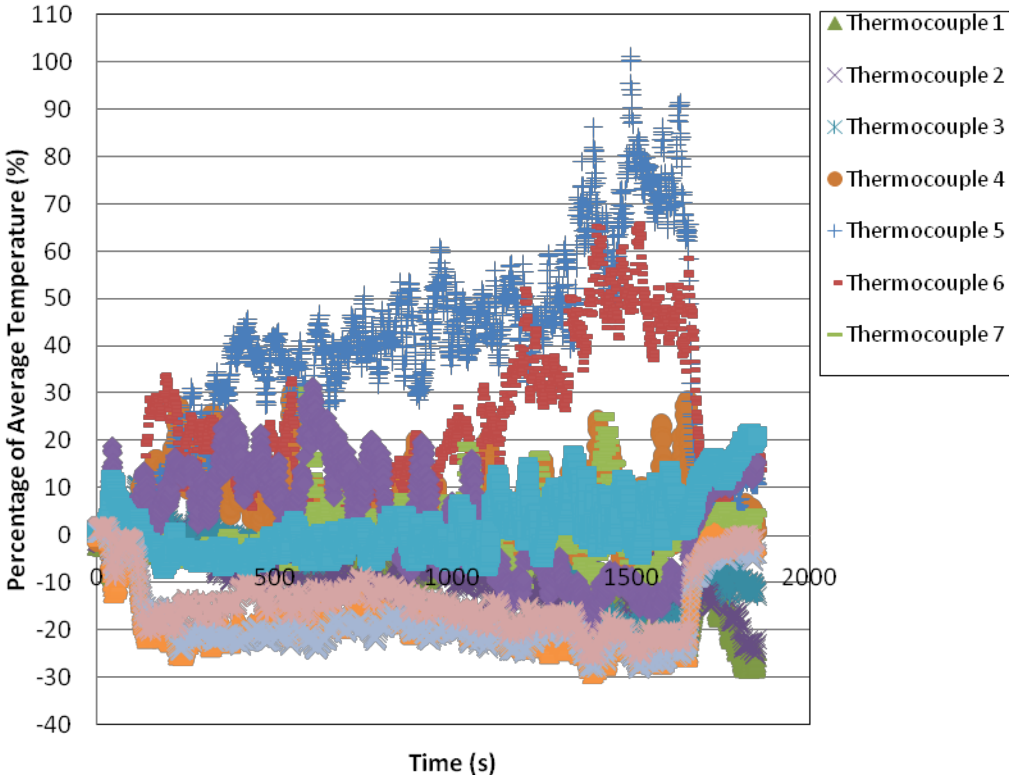


Figure 87: Temperature difference between each thermocouple measurement and the average measured temperature as a percentage of the average temperature for Test 16.

Table 9: Summary of observations during Test 16

Time from Burner Ignition (min)	Description of Observation
0	Burner ignited
9	Deformation of panel, over section B, on righthand side. (Figure 88)
17	Upwards deflection of panel (Figure 89). Smoke rising from around edges of panel.
18.5	Slight sagging of the panel over Section B. (Figure 90)
20.5	Panel sagging down to mesh. (Figure 91)
21	**Opening formed** in panel on Section B side of middle purlin. (Figure 92)
23	Glow from burner flames observed between baffles of top layer. No flame impingement on panel. (Figure 93) Flames observed to lick around righthand outside of apparatus as the burner flame is blown over.
27	Burner off. No flaming of panel material.
Post test observations	Panel shown in Figure 94.
Test Method Improvements from Test Results and Observations	1. Shield burner from draughts to provide a more even heating of the apparatus cross-section.

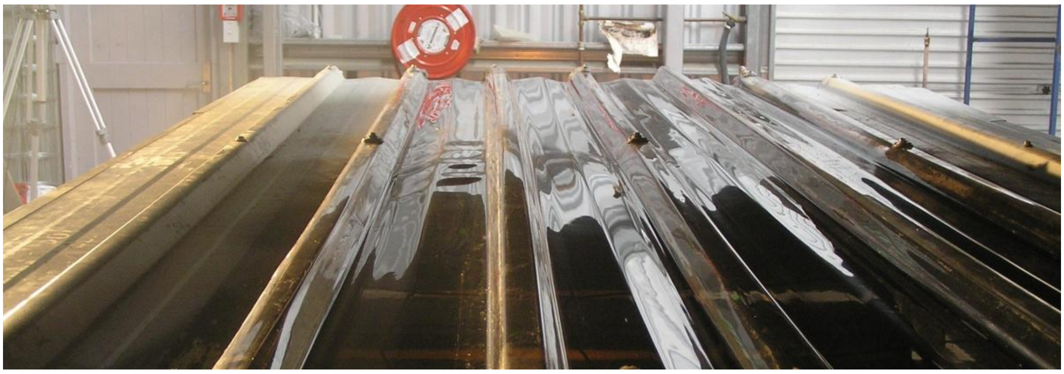


Figure 88: Deformation of panel. (Test 16 at 9 min from ignition of burner.)

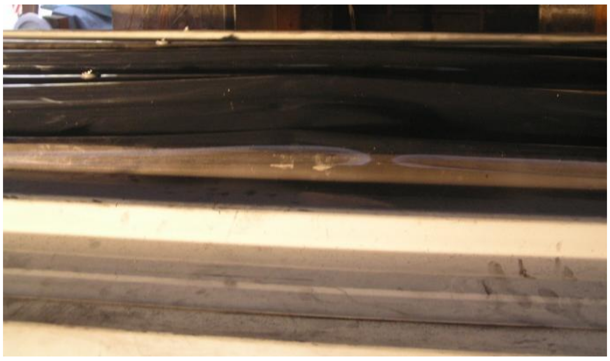


Figure 89: Upwards deflection of panel. (Test 16 at 17 min from ignition of burner.)

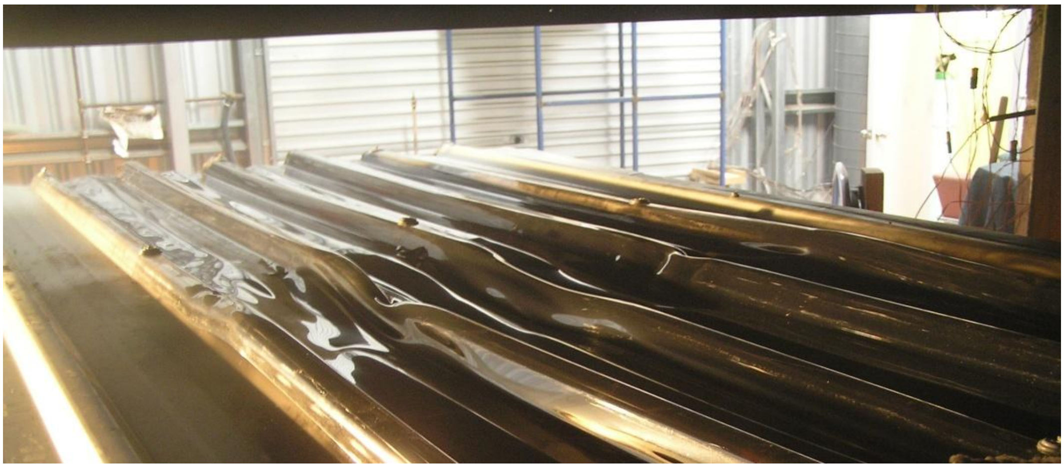


Figure 90: Panel sagging. (Test 16 at 18.5 min from ignition of burner.)

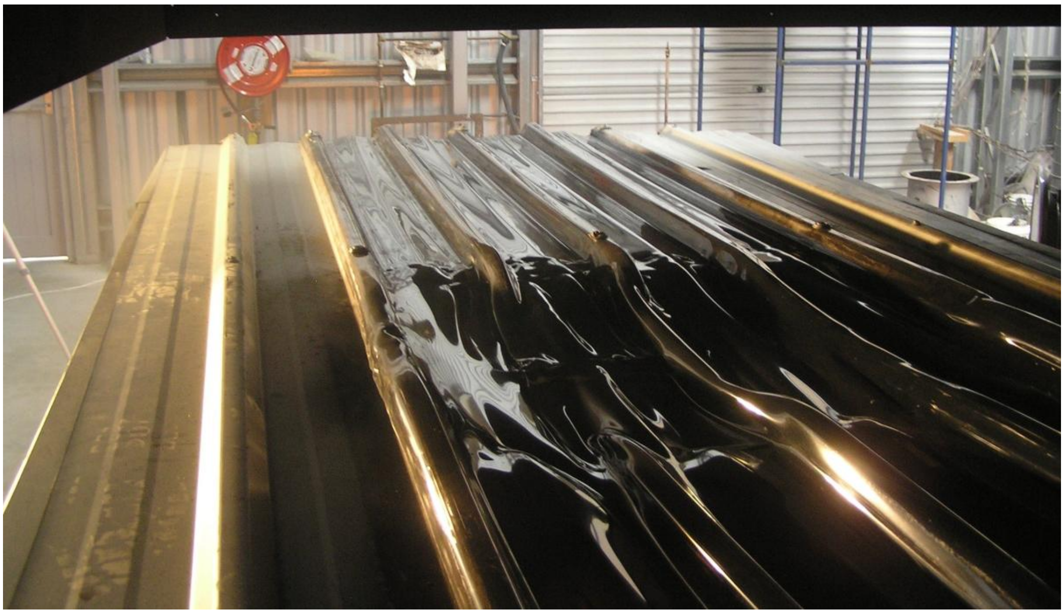


Figure 91: Further sagging of panel. (Test 16 at 20.5 min after ignition of burner.)

Figure 92: Openings formed in panel. (Test 16 at 21 min after ignition of burner.)

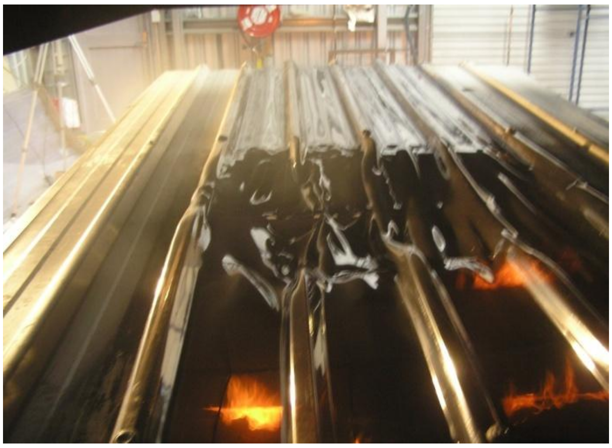


Figure 93: Observed burner flames around edges of panel. (Test 16 at 23 min after ignition of burner.)

(a) **(b)**

(c)

Figure 94: Post-test specimen (a) topside-up, (b) topside-down, and (c) side view of topside-down orientation.

B.17 Test 17

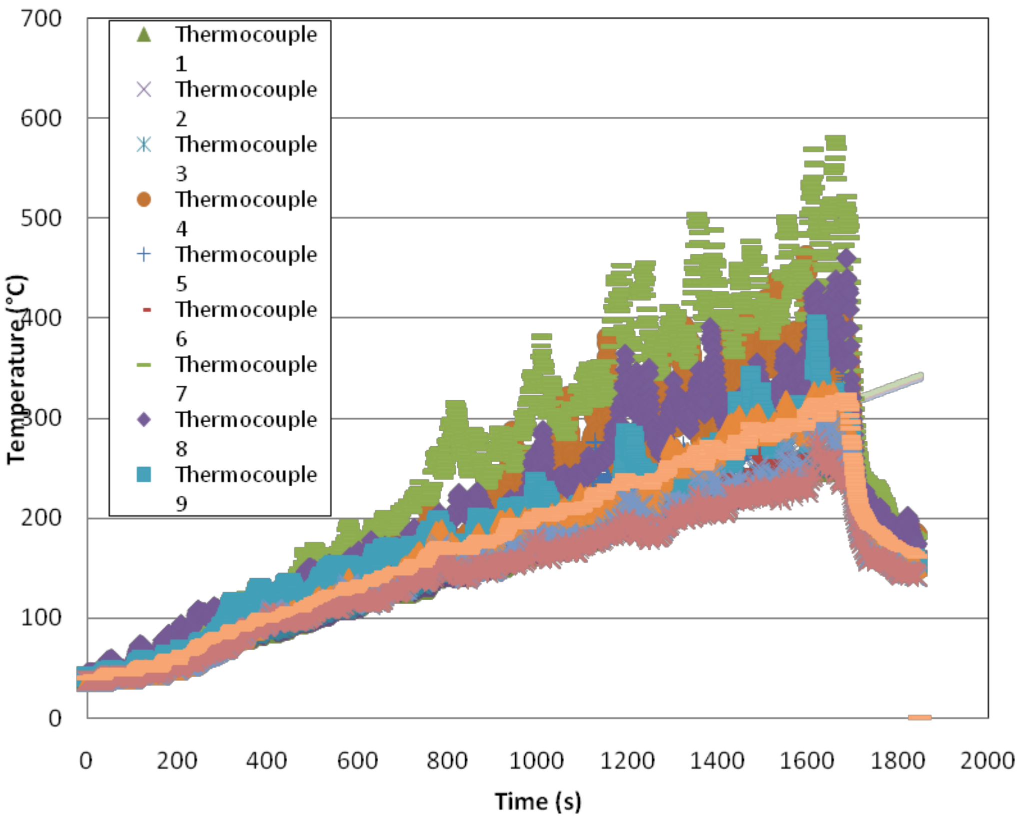


Figure 95: Thermocouple measurements, average of all 12 thermocouple measurements and target temperature for Test 17.

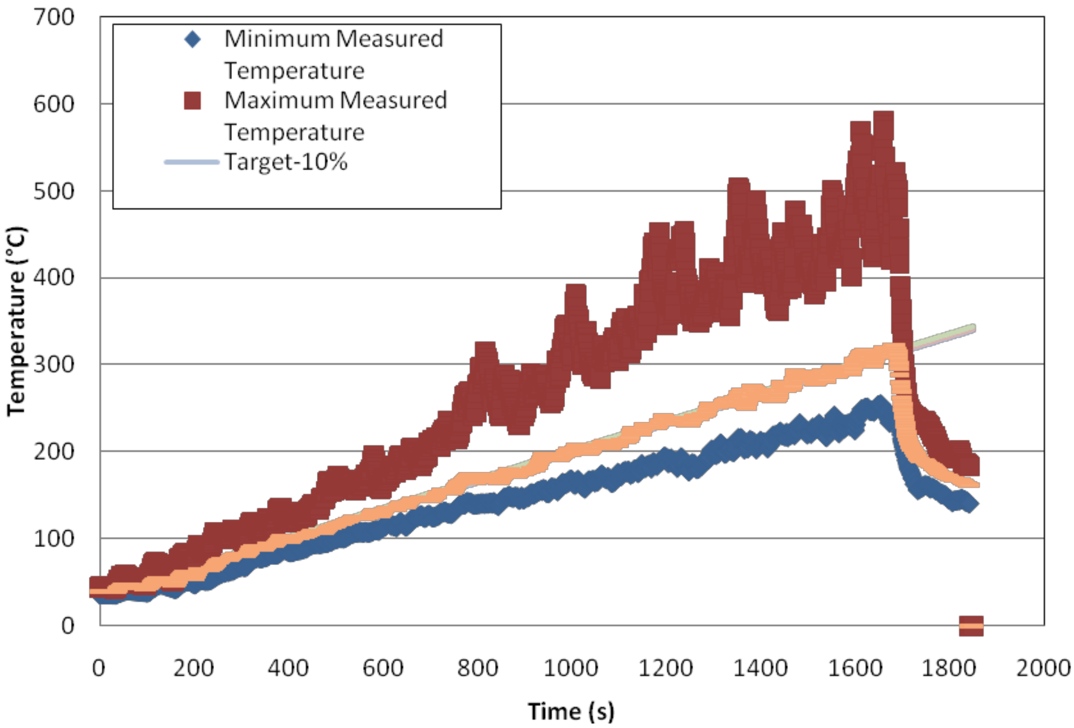


Figure 96: Maximum and minimum thermocouple measurements, average measured temperature and target temperature for Test 17.

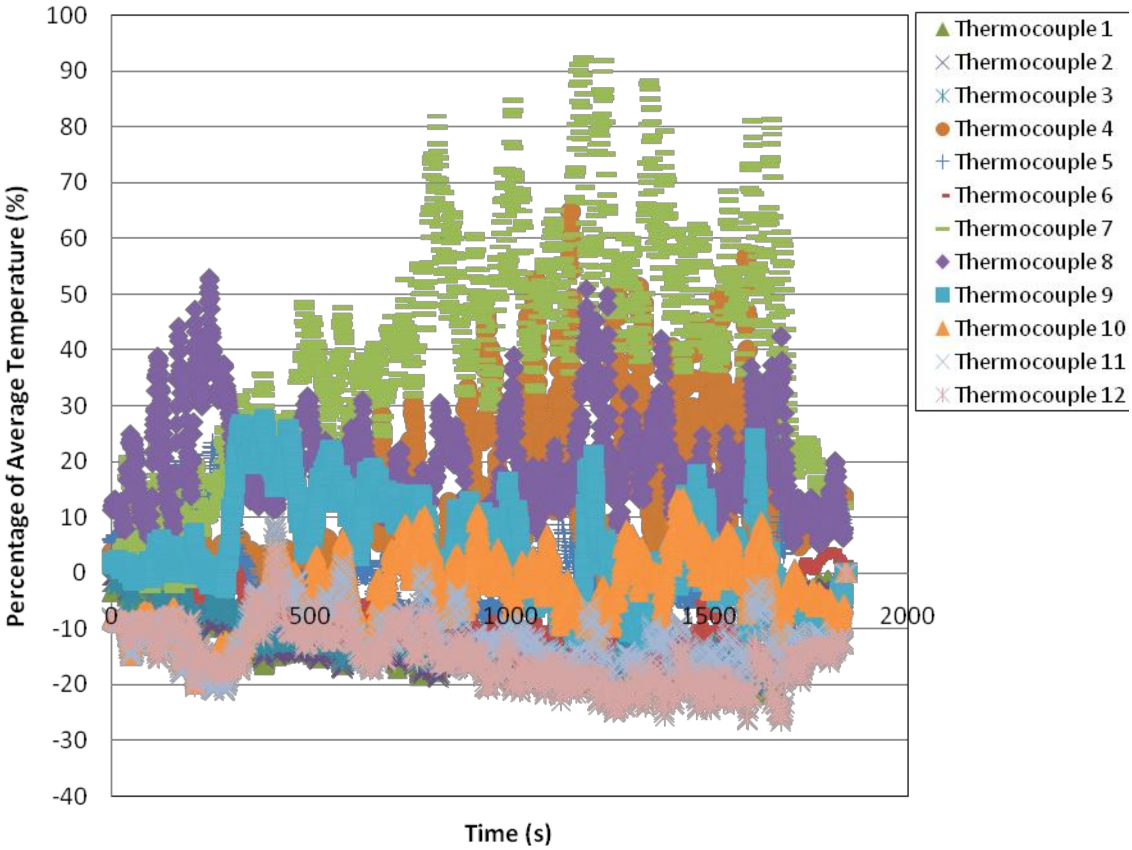


Figure 97: Temperature difference between each thermocouple measurement and the average measured temperature as a percentage of the average temperature for Test 17.

B.18 Test 18

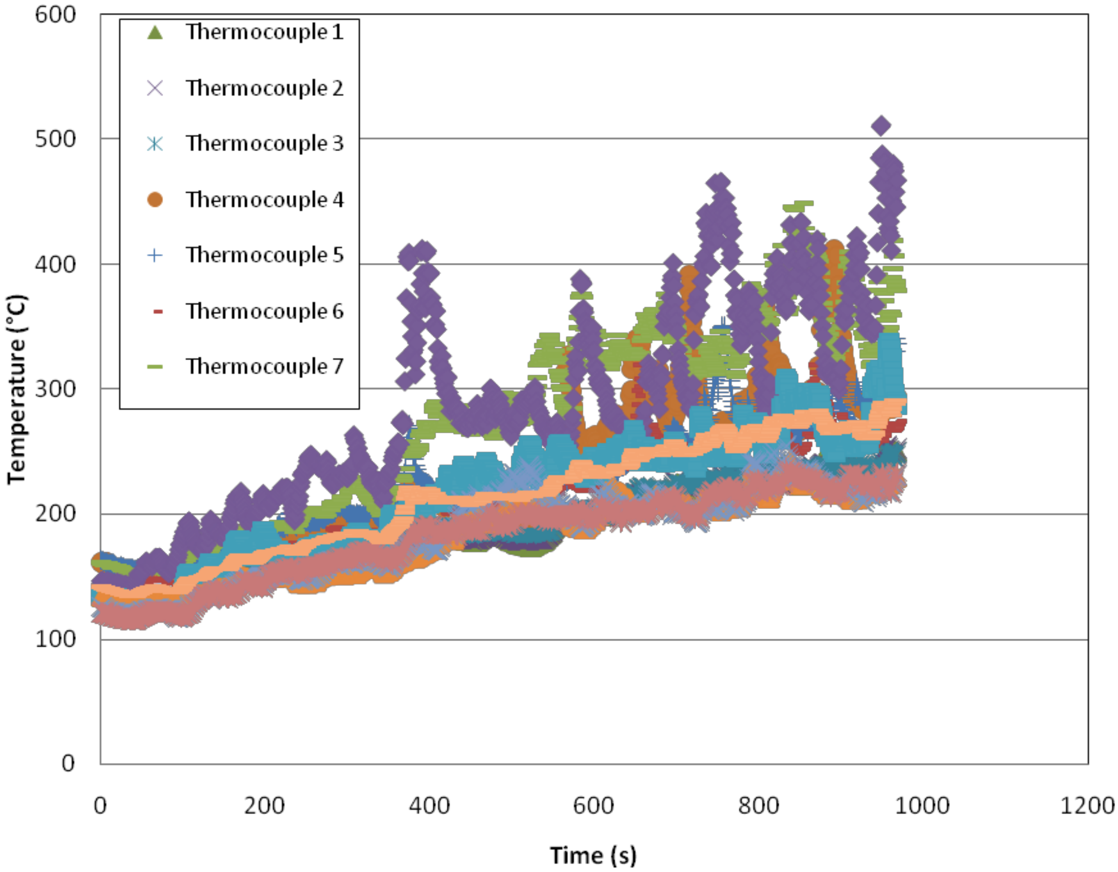


Figure 98: Thermocouple measurements, average of all 12 thermocouple measurements and target temperature for Test 18.

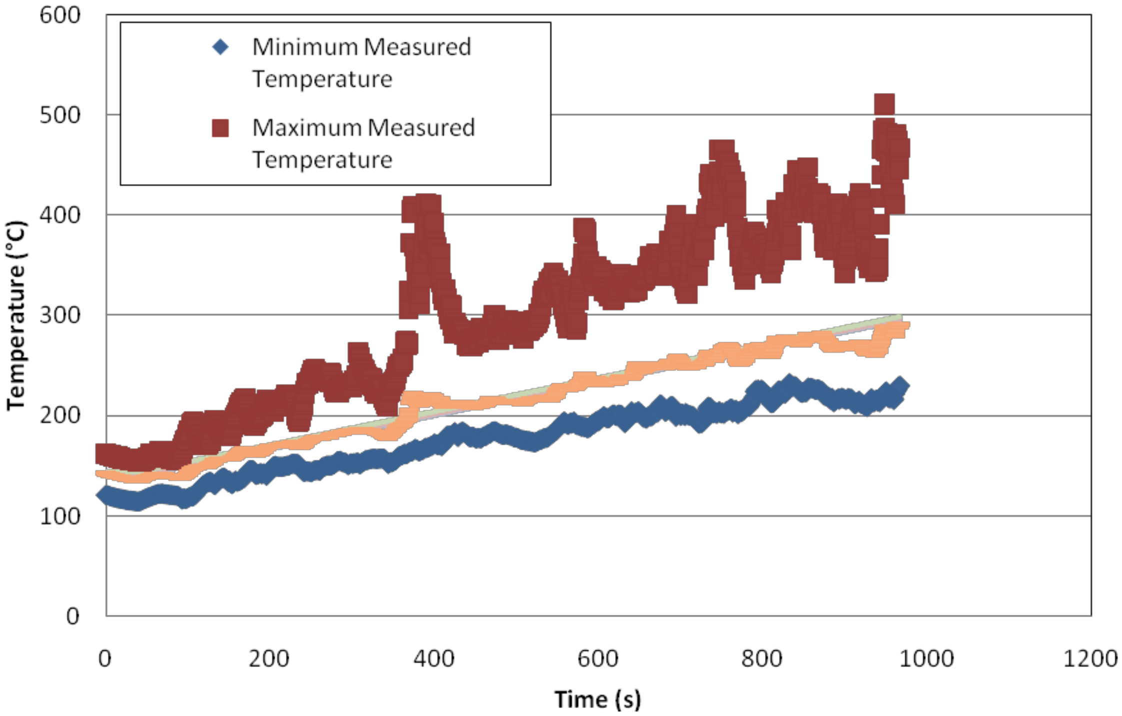


Figure 99: Maximum and minimum thermocouple measurements, average measured temperature and target temperature for Test 18.

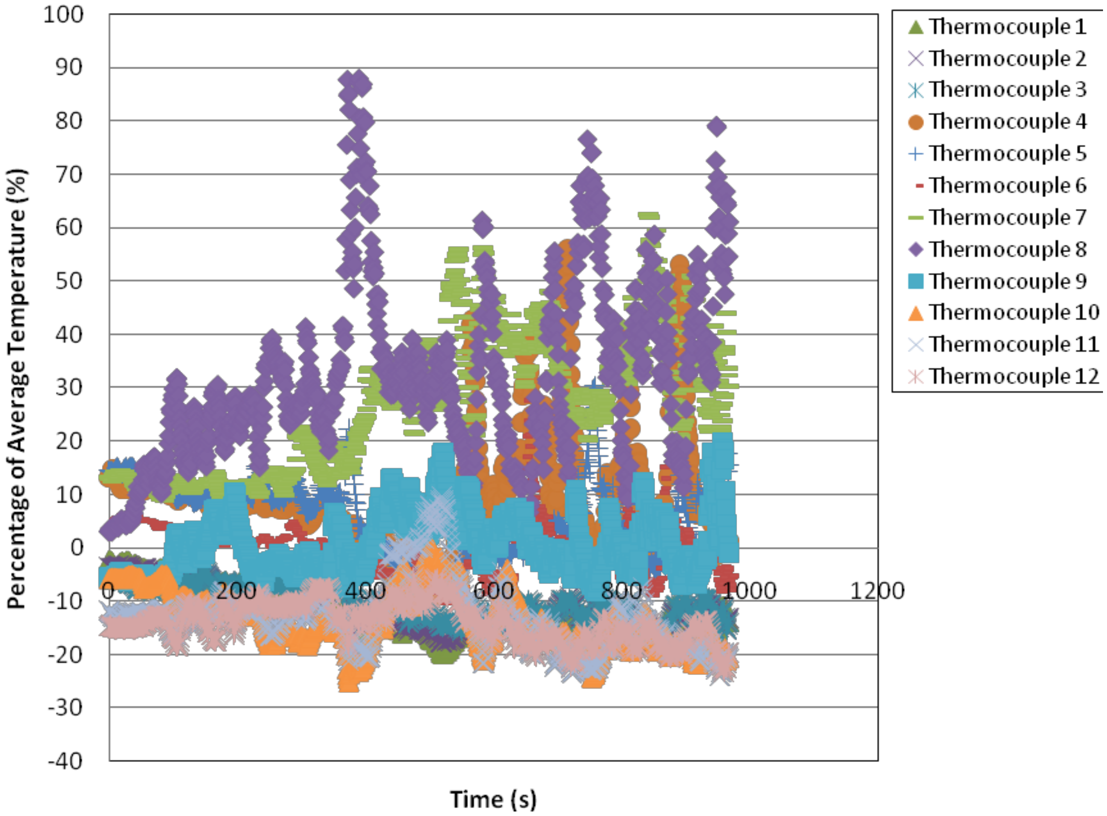


Figure 100: Temperature difference between each thermocouple measurement and the average measured temperature as a percentage of the average temperature for Test 18.

B.19 Test 19

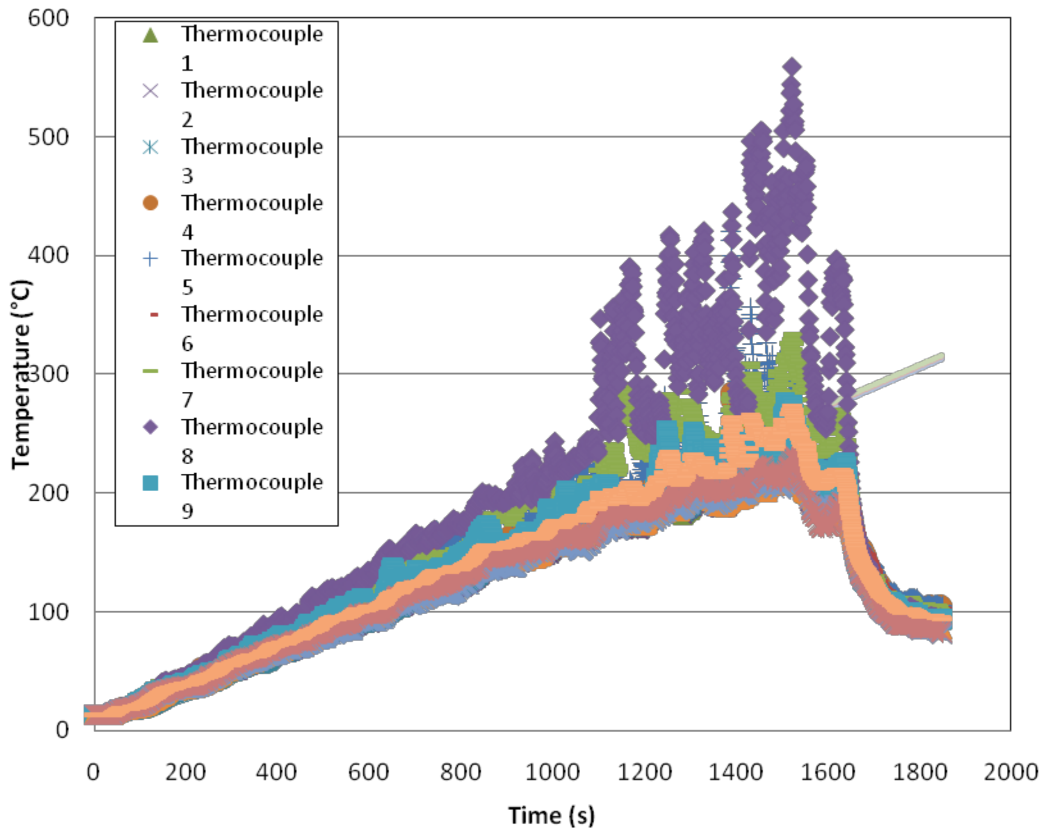


Figure 101: Thermocouple measurements, average of all 12 thermocouple measurements and target temperature for Test 19.

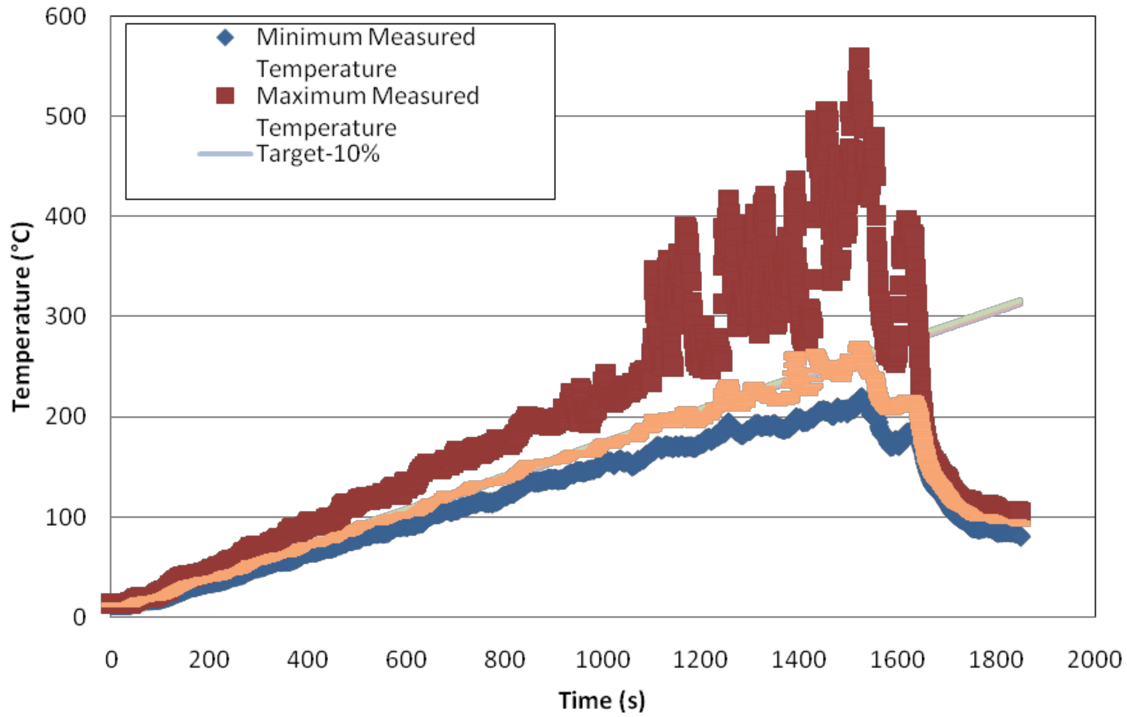


Figure 102: Maximum and minimum thermocouple measurements, average measured temperature and target temperature for Test 19.

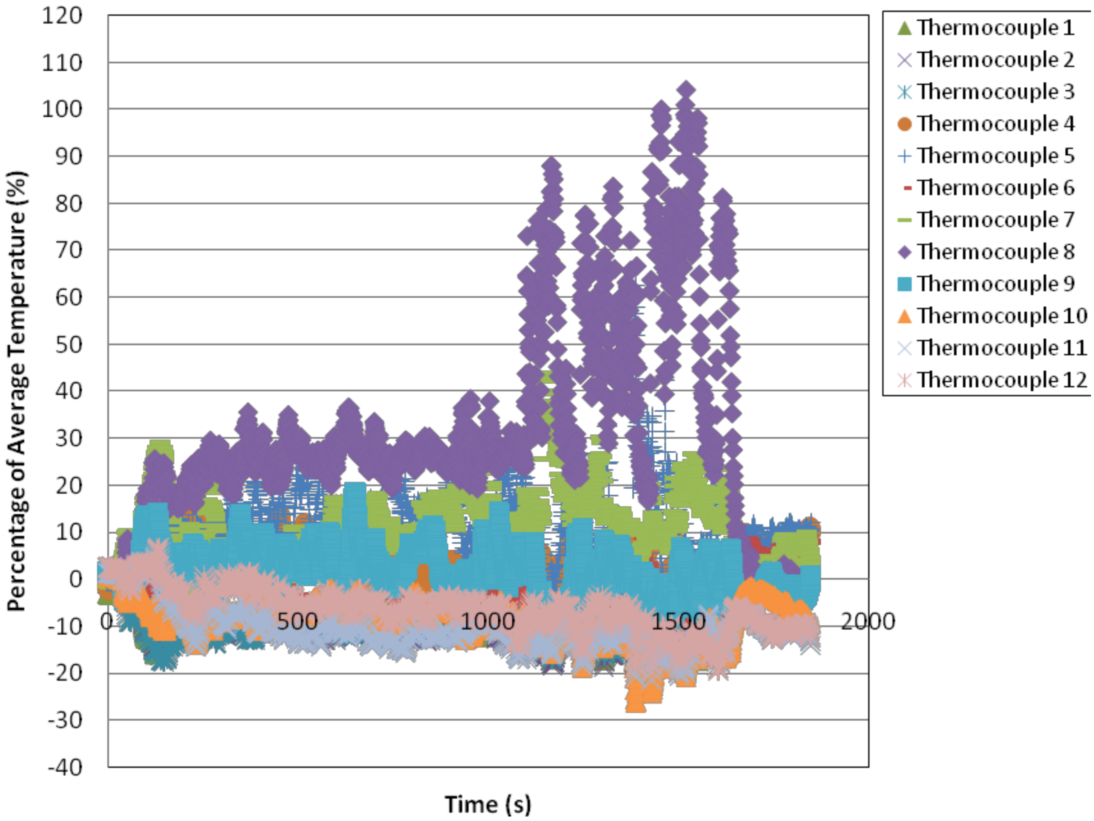


Figure 103: Temperature difference between each thermocouple measurement and the average measured temperature as a percentage of the average temperature for Test 19.

Table 10: Summary of observations during Test 19

Time from Burner Ignition (min)	Description of Observation
0	Burner ignited.
9	Deformation of panel in Section A.
10	Smoke rising from around edges of panel.
12	Deformation of panel, both sides of middle purlin. (Figure 104)
18	Sagging of panel both sides of middle purlin.
20	**Opening formed** in panel on Section B side of middle purlin. (Figure 105)
21.5	Glow from burner flames observed between baffles of top layer. No flame impingement on panel. (Figure 106)
27	Burner off. No flaming of panel material.
Post test observations	Panel shown in Figure 107.

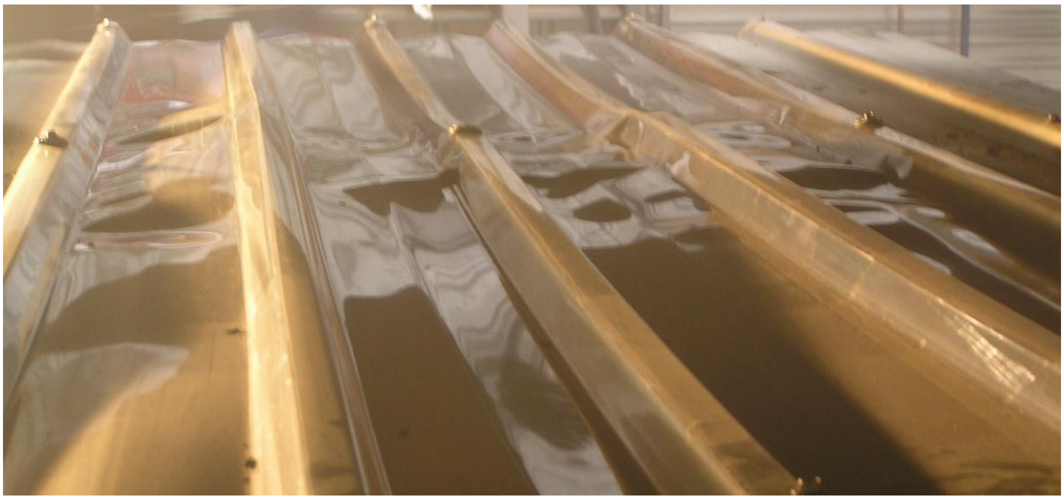
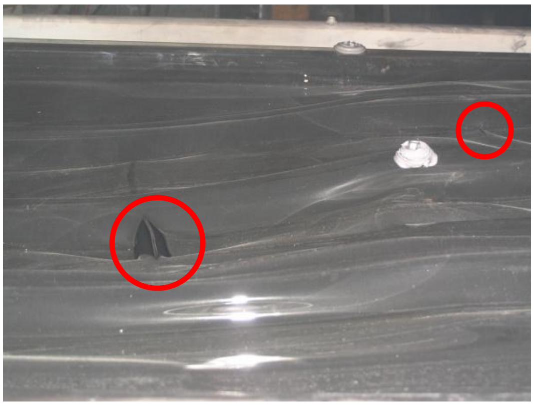


Figure 104: Deformation of panel. (Test 19 at 12 min from ignition of burner.)



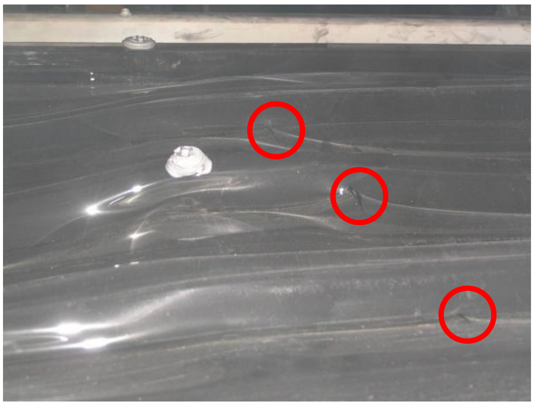


Figure 105: Openings formed in panel. (Test 19 at 20 min from ignition of burner.)

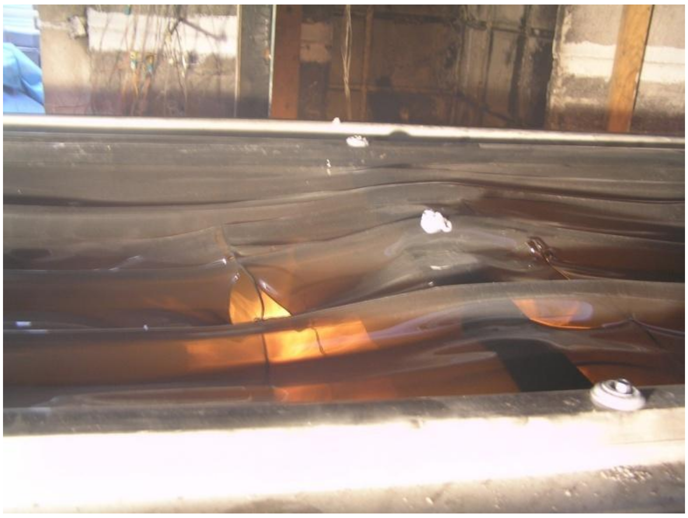
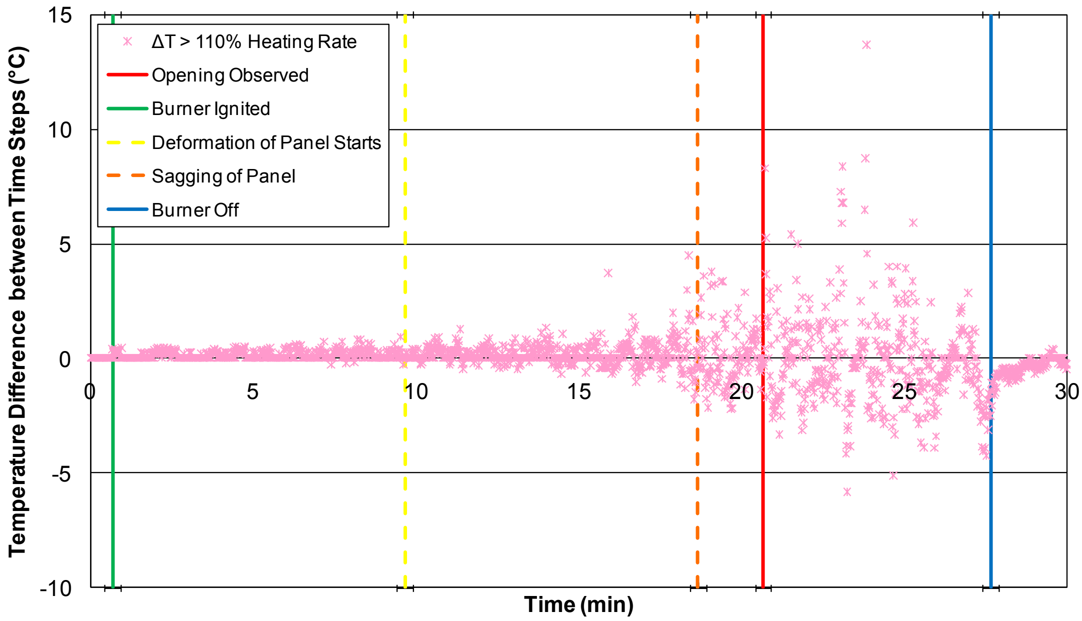


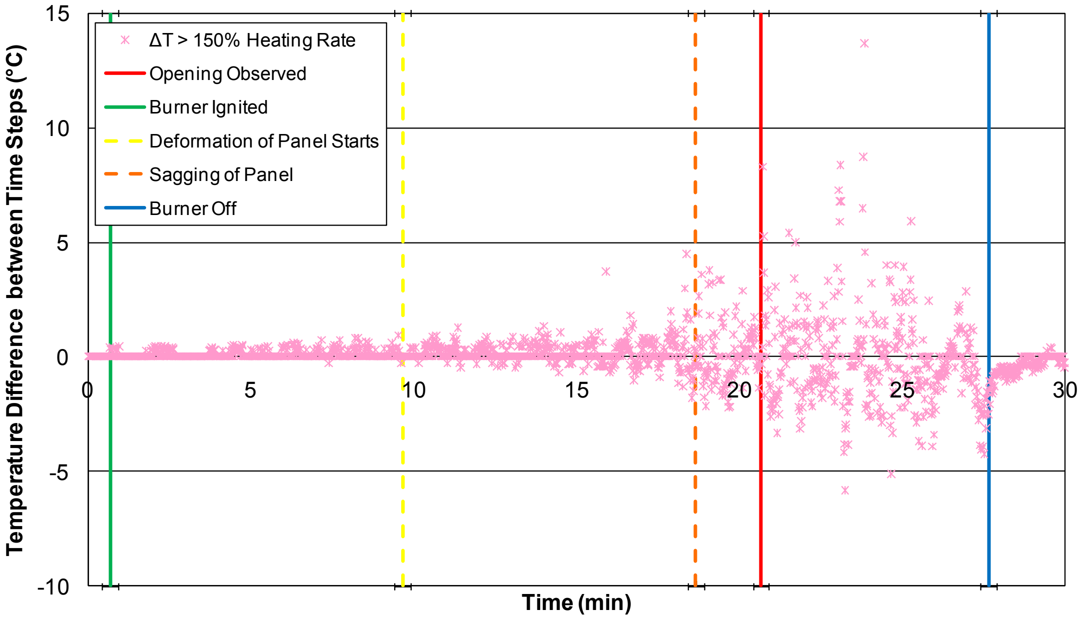
Figure 106: Flames seen around edges of baffles. (Test 19 at 21.5 min from ignition of burner.)

(a) **(b)**

Figure 107: Post-test specimen topside-down from (a) over head and (b) side on. (Test 19)

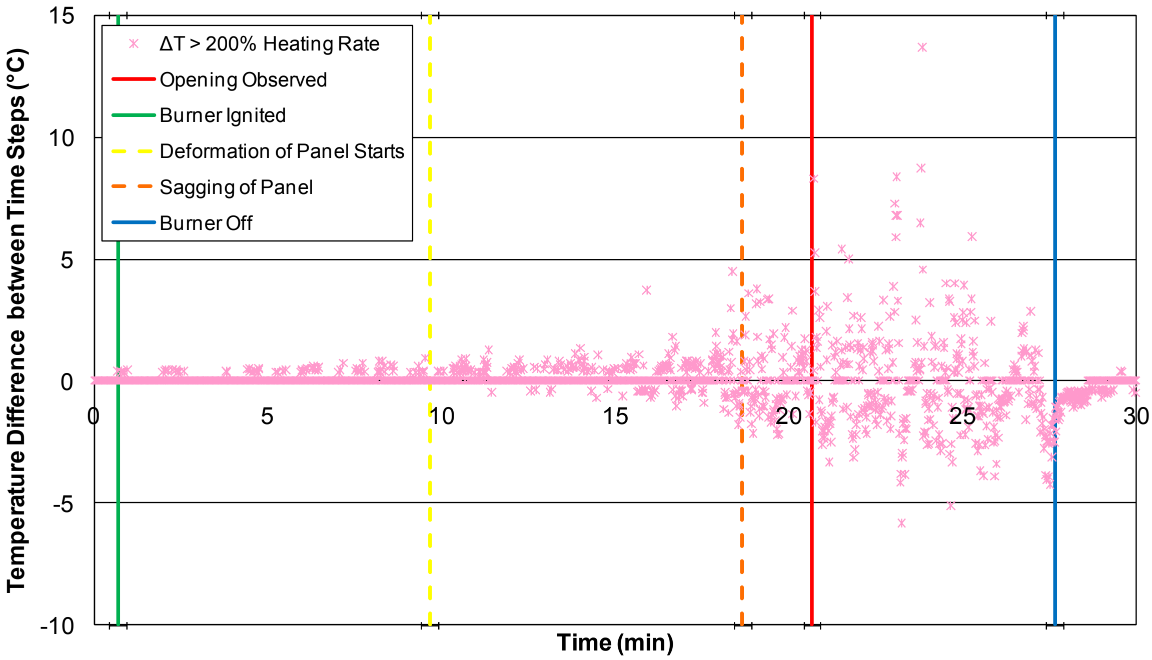


(a)



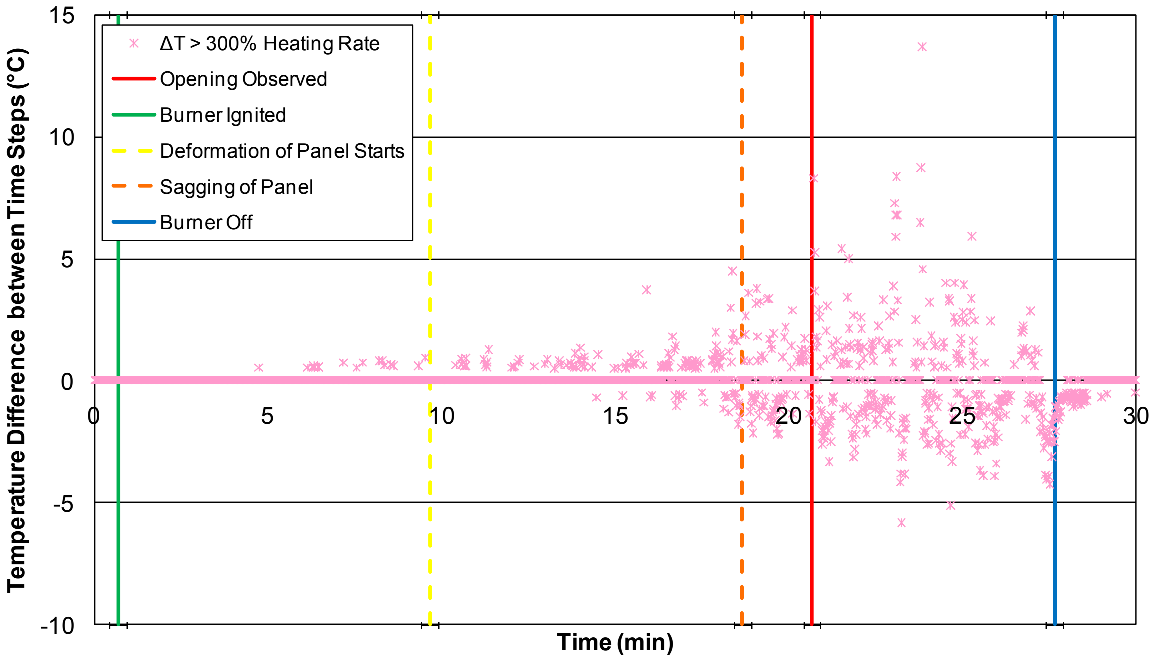
15
10
5
0
-5
-10
0
5
10
15
20
25
30
Temperature Difference between Time Steps (°C)
Time (min)
ΔT > 150% Heating Rate
Opening Observed
Burner Ignited
Deformation of Panel Starts
Sagging of Panel
Burner Off

(b)

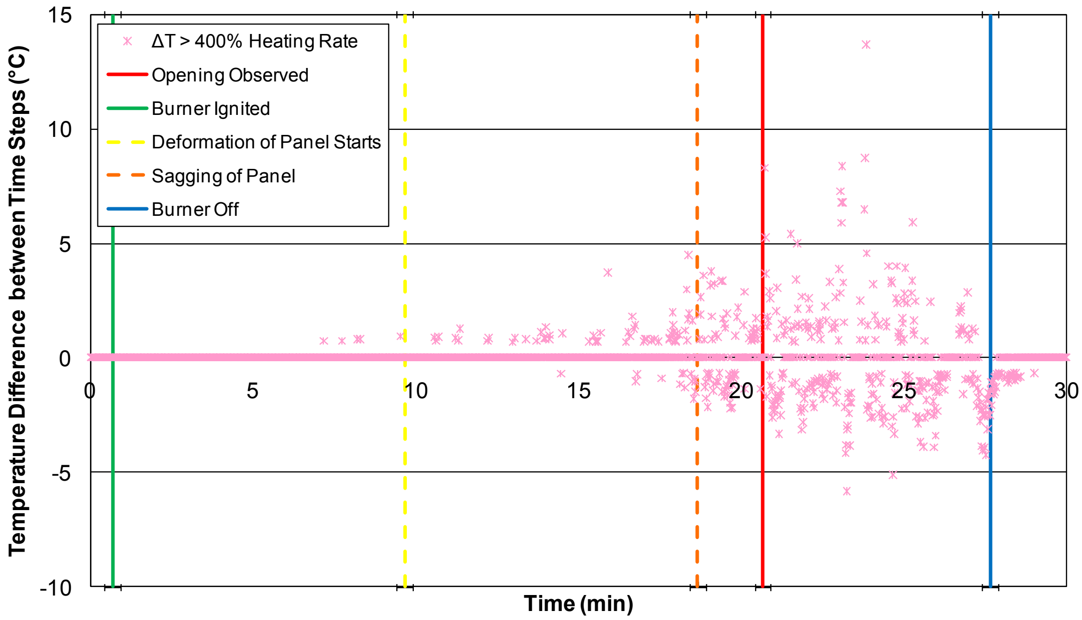


15
10
5
0
-5
-10
0
5
10
15
20
25
30
Temperature Difference between Time Steps (°C)
Time (min)
ΔT > 200% Heating Rate
Opening Observed
Burner Ignited
Deformation of Panel Starts
Sagging of Panel
Burner Off

(c)



(d)



(e)

Figure 108: The temperature difference between two consecutive data points, during Test 19, that are in excess of the target temperature increase.

B.20 Test 20

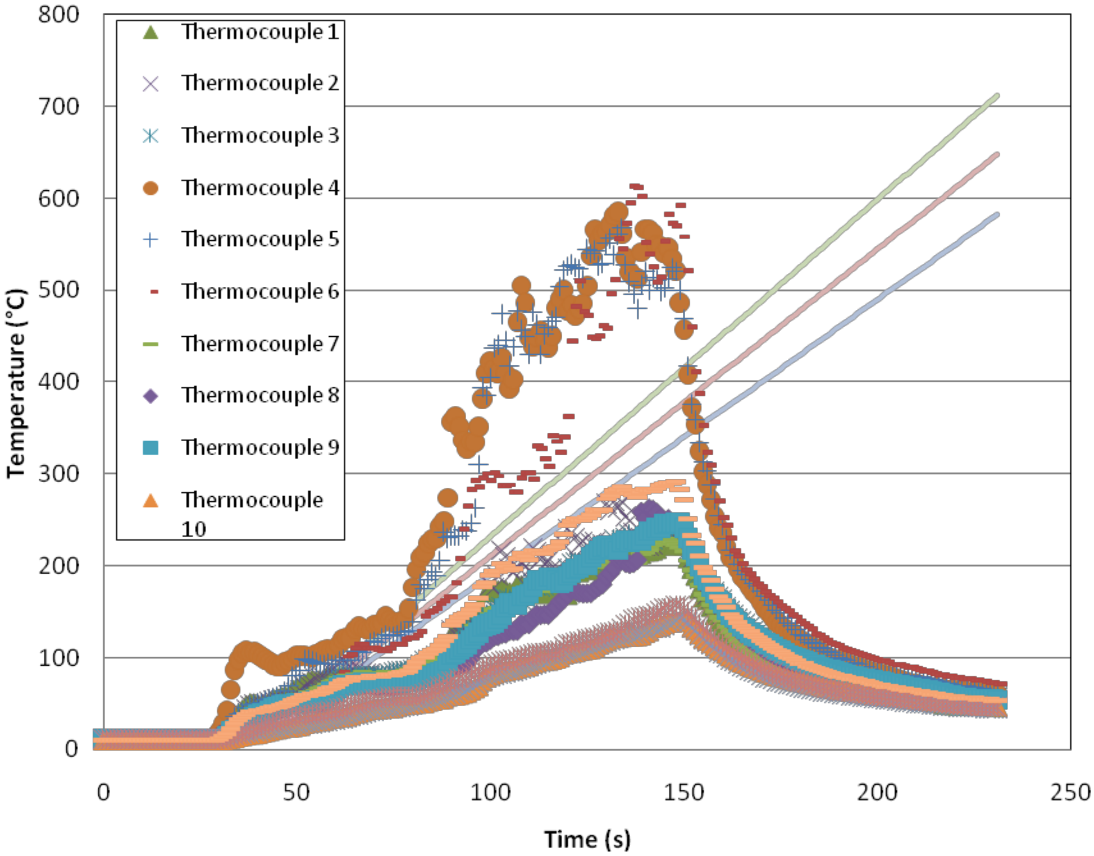


Figure 109: Thermocouple measurements, average of all 12 thermocouple measurements and target temperature for Test 20.

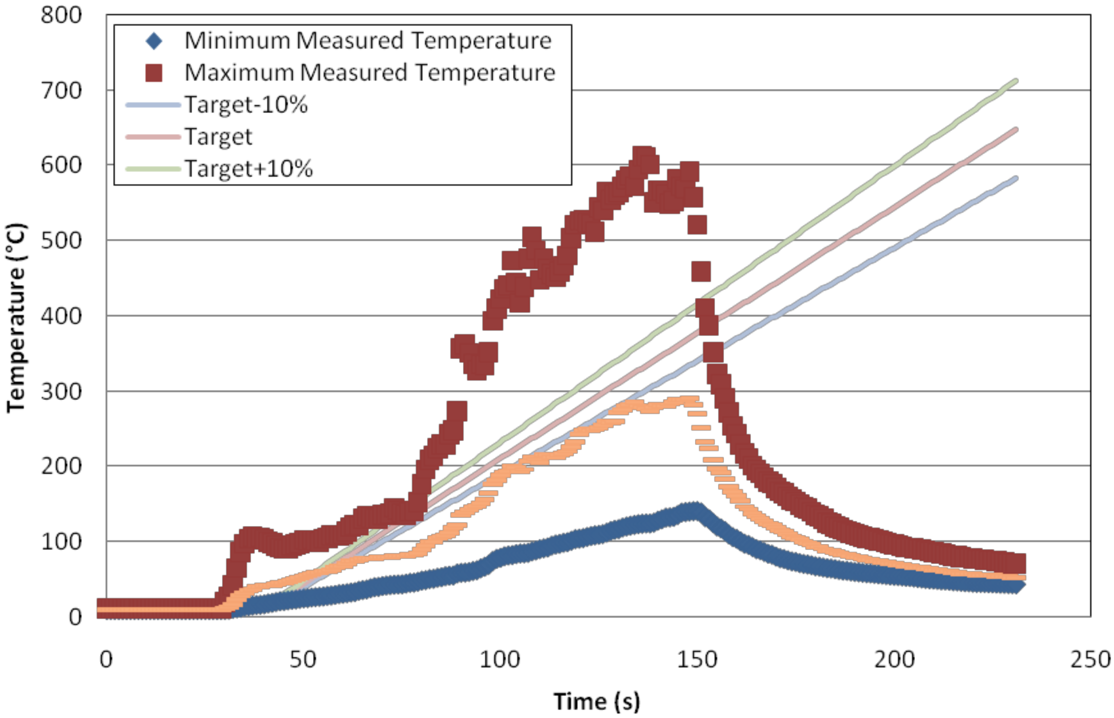


Figure 110: Maximum and minimum thermocouple measurements, average measured temperature and target temperature for Test 20.

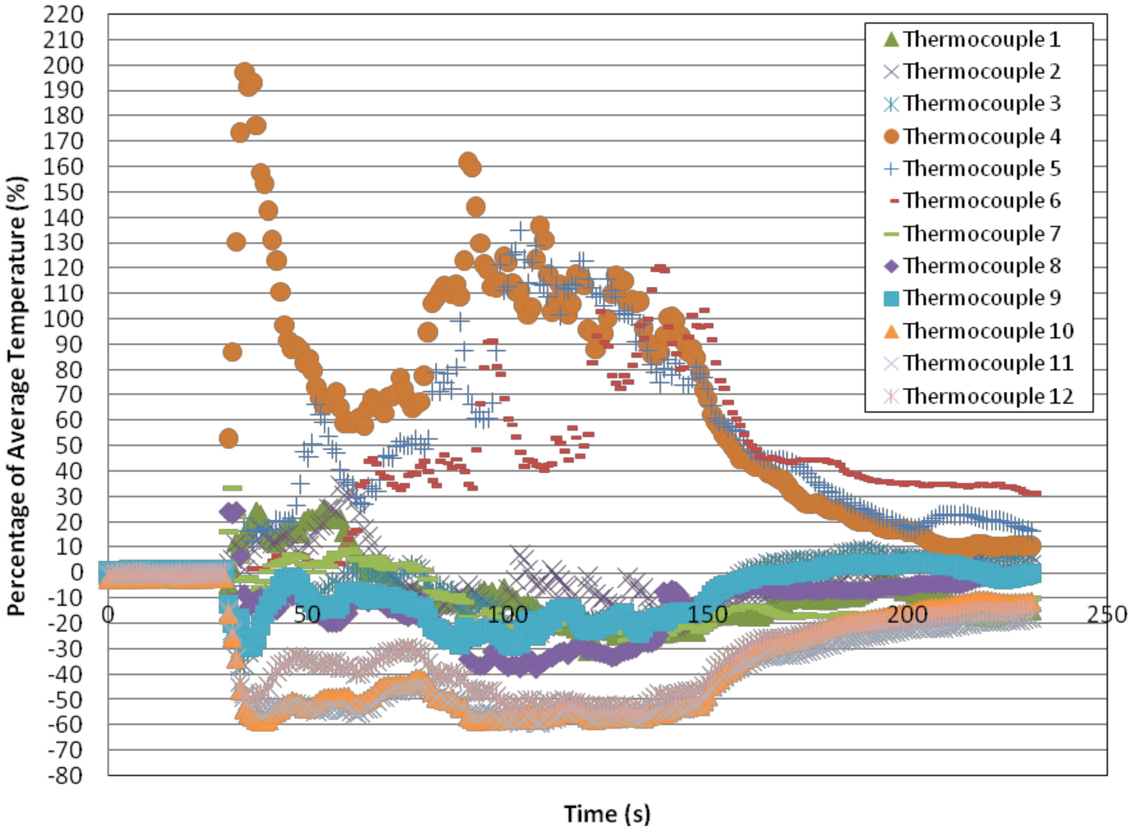
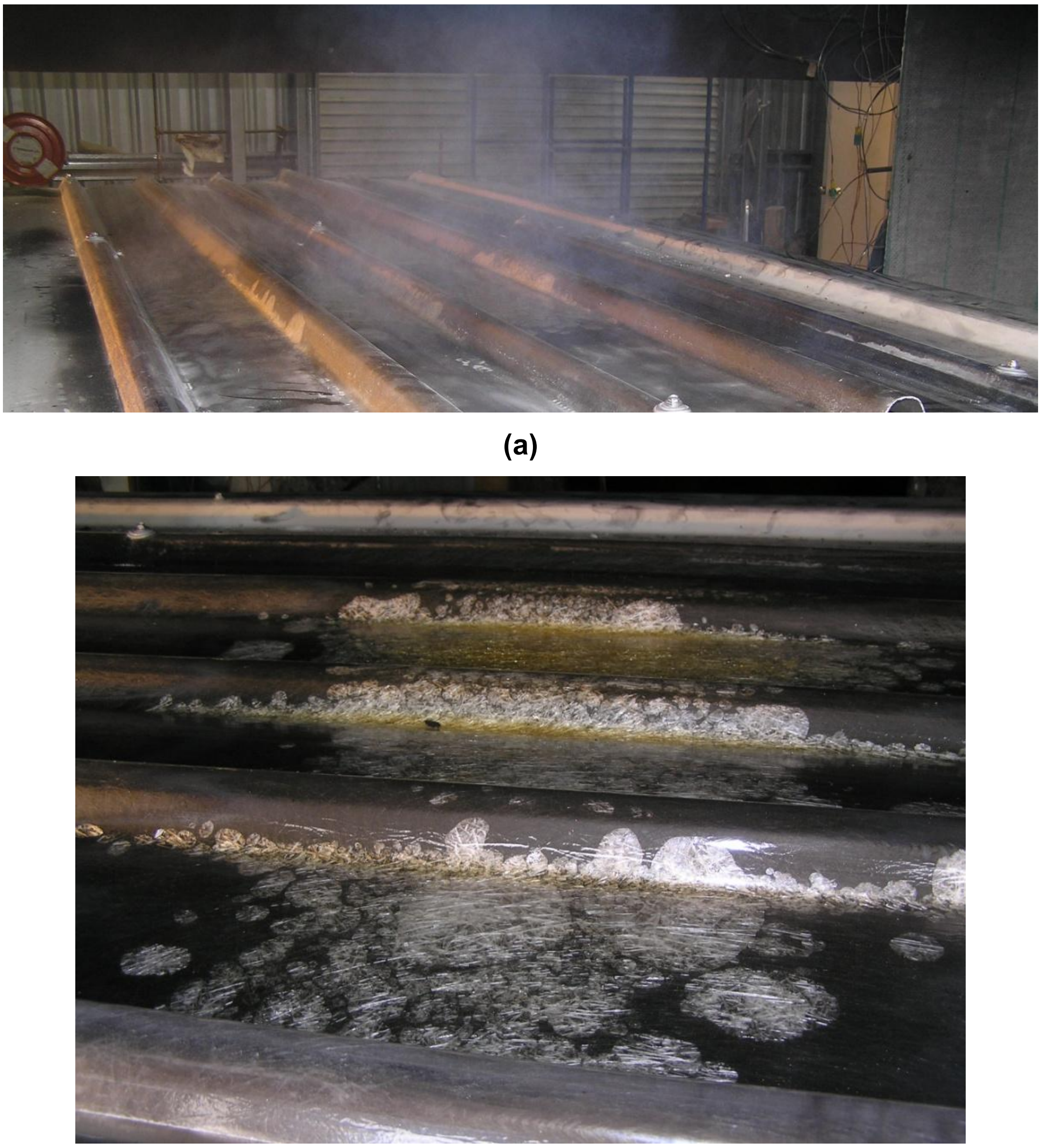


Figure 111: Temperature difference between each thermocouple measurement and the average measured temperature as a percentage of the average temperature for Test 20.

Table 11: Summary of observations during Test 20

Time from Burner Ignition (s)	Description of Observation
0	Burner ignited.
30	Transient glow from burner flames seen through panel.
45	Smoke rising from panel and darkening of panel in section A.
55	Transient flame impingement on panel on left hand side of Section A.
60	Transient flame impingement on panel on right hand side of Section A.
80	Periodic flame impingement on panel on Section A.
105	Flaming on underside of panel (cannot tell whether it is due to panel material burning or only burner flame impingement). Light grey smoke rising from topside of panel. (Figure 112)
110	Burner off. No flaming of panel material.
Post test observations	Panel shown in Figure 113.

Figure 112: Flaming on underside of panel and smoke rising from topside of panel. (Test 20 at 105 s from ignition of burner.)



(a)

(b)

Figure 113: Post-test specimen (a) directly after burner was turned off, and (b) after panel had cooled.

B.21 Summary of Test Results

Table 12: Summary of test results

Test Number	Opening Formed
Test 1	N/A
Test 2	N/A
Test 3	N/A
Test 4	N/A
Test 5	N/A
Test 6	N/A
Test 7	N/A
Test 8	N/A
Test 9	N/A
Test 10	N/A
Test 11	N/A
Test 12	N/A
Test 13	No
Test 14	~18 min
Test 15	~21 min
Test 16	~21 min
Test 17	N/A
Test 18	N/A
Test 19	~20 min
Test 20	No