FIRE TESTING METHODS OF STRUCTURAL ELEMENTS

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A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science in Engineering

Johannesburg, 2018

The financial assistance of the National Research Foundation (NRF) towards this research is hereby acknowledged. Opinions expressed and conclusions arrived at, are those of the author and not necessarily to be attributed to the NRF

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DECLARATION

I declare that this research report is my own unaided work. It is being submitted to the Degree of Master of Science in Engineering, to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

Candidate: Craig Black

Signature: ....

Date: 15/02/2018

ABSTRACT

This report investigates the heating conditions required by various international standards in order to conduct a standard fire test on building elements. This investigation also aims to obtain an understanding of the various methods used in order to conduct standard fire tests, and the various criteria that building elements are required to adhere to during a fire. The outcome of the investigations conducted here is an apparatus and a testing method that can be used in future investigations to conduct full scale fire tests on building elements while complying with international standards. Various tests are conducted with the use of different methods and the viability and repeatability of each method is assessed.

Various methods exist in international standards that propose standard heating conditions and criteria upon which the performance of a building element in a fire is assessed. The most common temperature – time relationship used in fire tests is that of the standard temperature – time curve seen in the British Standard: BS 476 and the South African National Standard: SANS 10177. Another widely used temperature – time relationship is that seen in the American Society for Testing and Materials standard: ASTM E119. Eurocode 1 proposes a natural / parametric compartment fire model that allows one to establish a temperature – time curve specific to a particular enclosure.

By conducting a fire test with temperatures regulated according to a specified temperature – time curve, one may determine the fire resistance rating of a building element. The fire resistance rating is the time period for which an element is able to adhere to certain criteria during a fire.

Through a series of preliminary natural fire tests, shortfalls to the standard temperature – time curve were observed when the natural fire did not behave in a manner similar to the unnatural heating requirements described by the standardized time - temperature curve; as these temperatures will rarely be encountered in a building fire.
By conducting preliminary tests with the use of flammable liquids, however, such as petroleum and diesel, the furnace temperature requirements of SANS 10177 were able to be replicated for a period of 20 to 30 minutes. A test was also conducted with the use of liquefied Petroleum Gas as the fuel type, however, this fuel did not produce a large enough flame for the purpose of achieving the desired furnace temperature.

Through a series of preliminary experiments with the use of flammable liquids, a method of conducting a fire test according to SANS 10177 was developed with the use of a prototype flammable liquid burner capable of controlling furnace temperature with respect to time.
A testing sheet was also proposed that can serve as a generic sheet containing the necessary instructions to conduct a fire test. The test sheet can be used to record all necessary data and observations from the test.

The next series of tests conducted after the preliminary tests aimed to replicate the requirements of international standards, and to test the repeatability of the method used. These tests were conducted with the use of a diesel burner that was fabricated in such a way as to overcome shortfalls noted in the preliminary tests. The burner made use of a diesel – air mixture, to initiate a flame inside the furnace that could be controlled as necessary. An average correlation with respect to the SANS10177 time - temperature curve of 0.944 was achieved for all 8 diesel burner tests conducted.

It was also clear that testing procedures improved significantly with experience as results began to correlate closer with SANS requirements for each subsequent test. Test 8 temperatures fell within the allowable temperature tolerances for 91 percent of the testing time and were also within the allowable range with respect to the ASTM E119 heating requirements.
The diesel burner used in the final tests is a suitable burner to be used when conducting fire tests according to SANS 10177, BS476, and ASTM E119 requirements. A high level of repeatability was achieved in all 8 tests as all results fell within the specified temperature range.

The size of the furnace used in all tests conducted in this study however does not meet the minimum dimensional requirements of any of the international standards. In order to conduct fire tests according to SANS 10177 a full sized furnace will need to be constructed using the principles and apparatus outlined in this report.

ACKNOWLEDGEMENTS

First and foremost I would like to thank my supervisor Professor Alex Elvin whose guidance has made it possible to complete this research report. I have learnt a great deal of patience and persistence through your advice and analytical outlook.

I would also like to thank the team at Firelab. In particular I would like to thank Firelab owner Kobus Strydom and laboratory manager Adri Labuschagne for allowing me to visit the testing facilities on multiple occasions and allowing me to participate in tests and most importantly for sharing your knowledge with me.

All laboratory staff of the school of Civil and Environmental Engineering have played a major role in this research project. All laboratory staff were available to provide assistance when necessary, and were very helpful during the construction and setting up of all testing equipment. Structures lab technician Ralph Mulder was always willing to assist and was very patient throughout.

Lastly I must thank my family and friends for all the support and assistance that I have received throughout my studies. I am fortunate to have friends and family that were willing to assist me at any point.

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1. INTRODUCTION

The performance of structural elements under fire exposure is of major importance in ensuring that all structures are safe and do not pose a risk to neighbouring structures or life. The main objective of fire safety is to protect life, property and the environment by ensuring the safety of the occupants of a structure and maintaining its integrity. For structural engineers, adequate fire design is of importance in order to contain the fire, and to provide structural safety.

One step towards ensuring overall fire safety is to secure a balance of the various components in a single building; in order to do this, it is necessary that the fire resistance of components be measured according to a certain standard, such as BS 476, SANS 10177 or ASTM E119. Multiple international standards exist that deal with specific aspects of passive fire protection in terms of designing structures and their components for adequate load bearing resistance and for limiting fire spread where relevant.

A fire test is a procedure designed to assess the response of a product, component or element of construction, to one or more aspects of fire (BS 476: Part 10, 1983). It is the only realistic method of determining the fire performance of a building element, when the specimen being tested is in the form in which it is to be used in a structure. The standards that describe methods of fire testing and which were reviewed here are as follows:

- South African National Standard (SANS10177): Fire testing of materials, components and elements used in buildings – Part 2: Fire resistance test for building elements
- Eurocode 1: Actions on structures – Part 1-2: General actions – actions on structures exposed to fire
- British Standard (BS 476): Fire tests of building materials and structures – Part 20: Method for determination of the fire resistance of elements of construction (general principles)
- American Society for Testing and Materials (ASTM Standard E119): Standard test methods for fire tests of building construction materials

All of the above mentioned standards require that a component be subjected to fire at a rate following a particular time - temperature curve to obtain its fire resistance. Fire resistance is expressed in minutes and it represents the period for which a building element or component will comply with the requirements for stability, integrity and insulation (SANS 10177-1, 2005).

The time (or times) obtained from a fire resistance test have no direct relationship with the duration of a real fire. A fire test conducted at a laboratory does not always simulate the actual behaviour of the element in a fire due to element size restrictions and the lack of surrounding elements or certain environmental conditions. A fire test does however provide a basis for allowing one to make engineering evaluations of the capability of the element to resist a real fire. This research report reviews the different standards mentioned above in order to gain insight into the methods required to conduct a proper fire test. Investigations are then conducted in order to assess the most viable method of conducting a standard fire test.

1.1. SIGNIFICANCE

In South Africa in 2013, 2227 deaths were recorded due to exposure to smoke, fire and flames; accounting for 4.7 percent of non-natural deaths (Statistics South Africa, 2013). Public fire departments in the United States responded to over 1.2 million fires in 2014, of which 38 percent occurred in structures resulting in property damage of $9.8 billion, 3275 civilian deaths and 15775 civilian injuries (National Fire Protection Association, 2015).

Further research into fire testing and the behaviour of structural elements subjected to fire can help to promote fire safety and as a result, protect life, property and the environment.
The thermal and structural behaviour of elements exposed to fire is a topic that has not yet been extensively researched, as most research institutions do not have access to fire testing furnaces and equipment. By understanding the methods necessary to conduct fire tests, and constructing a burner and furnace capable of conducting these tests, future contributions can be made towards the study of structural fire engineering.

1.2. Objectives of the Study

The objectives of the study are to:

- Obtain a fundamental understanding of the methods used in order to conduct a fire test
- Understand the necessary requirements of various structural elements in order to comply with the criteria of stability, integrity and insulation in a fire
- Develop a method of conducting a fire test by experimenting with different fuels and burning apparatus
- Ensure that the testing method developed is repeatable and reproducible and can be used for a wide range of elements
- Construct a fire testing furnace

2. LITERATURE REVIEW

The South African National Building Regulations set out requirements to ensure that buildings will be designed and built in such a way that people are able to live and work in a healthy and safe environment. SANS 10400 – The application of the National Building Regulations – sets out the different possible ways of demonstrating compliance with functional regulations. SANS 10400 Part T: Fire protection, contains the fire resistance ratings of conventional building materials and components. Clause 4.55 of the standard states that building materials and components that are not listed in the standard, shall be deemed to comply with the performance requirements under fire conditions, provided that a valid test report to an internationally accepted test method or to the relevant part of SANS 10177 is provided; or the component shall be subjected to a rational assessment by a competent person (SANS 10400-T, 2011).

Rational design is design conducted by a competent person involving a process of reasoning and calculation and which may include a design based on the use of a standard or another suitable requirement. SANS 10400 - T lists the fire ratings of multiple generic structural and non-structural components that are often used in everyday construction.

Engineers are constantly seeking ways of optimizing structures by improving on their efficiency and material usage. This requires innovation and the design of unique structural elements, for example composite structural elements. Fire ratings of composite elements do not exist in SANS 10400-T. It is thus important in modern times to be informed of the standard testing process commonly used to determine these fire ratings.

SANS 10177-2 describes a test method aimed at determining the fire resistance rating of building elements. The standard recommends standard heating conditions which a furnace must subject an element to in order to obtain its fire resistance rating.
As mentioned above, multiple international standards exist that describe methods of fire testing. Those which are internationally accepted and which were reviewed here are as follows:

- SANS 10177-2
- ASTM Standard E119
- BS 476: Part 20
- Eurocode 1: Part 1-2

2.1. SANS 10177

2.1.1. Overview

SANS 10177 is the South African National Standard for fire testing of materials, components and elements used in buildings. A brief review of the standard and its subsidiary parts will be conducted here. The test methods explained in parts 2 to 7 are designed to test the performance of building materials, components and elements under fire conditions (SANS 10177-1, 2005). SANS 10177-2 is of particular importance here, as it outlines a method of conducting a fire test. As mentioned above, fire resistance is expressed in minutes and it represents the period for which a building element or component will comply with the requirements for stability, integrity and insulation. These three failure criterion are assessed as follows:

- Stability:
  - An element has failed with respect to stability if it collapses in such a way that it no longer continues to perform its function or,
  - If the deflection of a horizontal specimen exceeds L/30 (where L is the clear span between supports)
- Integrity:
  - A room dividing element (walls, floors, etc) has failed with respect to integrity if cracks, holes, or other openings (through which flames or hot gases can pass) are formed in the test specimen
- Insulation:
  - A room dividing element has failed with respect to insulation if any of the following occurs:
    - The increase in the average temperature of the unexposed face exceeds 140 °C
    - The maximum temperature at any point on this face exceeds the initial temperature by more than 180 °C or,
    - The maximum temperature at any point on the unexposed face exceeds 220 °C

(SANS 10177-2, 2005)

The maximum allowable temperature of 220 °C on the unexposed face is a requirement relating to the ignition temperature of cotton in order to prevent ignition of fabrics that may be in contact with the unexposed surface of an element exposed to fire in an adjacent room. This criterion aims to prevent the spread of building fires between compartments. Gross & Robertson, 1958, conducted various tests on different materials, one of which was cotton fibres. The average ignition temperature determined from the various tests for cotton was approximately 220 °C (Gross & Robertson, 1958). A large majority of clothing and fabrics used in commercial buildings and households contain cotton fibres. Cotton is flammable and burns rapidly. If a building fire were to occur within a compartment, it is important to ensure that the fire cannot spread to the adjacent compartment. By ensuring that the temperature on the unexposed face of the element remains below 220 °C, one can prevent fabric which could likely be touching the unexposed surface of the element from being ignited.

2.1.2. SANS 10177-2: Fire resistance test for building elements

Part 2 of SANS 10177 covers the method used to determine the fire resistance of any of the following elements: wall, partition, column, beam, floor, ceiling system, door and shutter assembly. The standard requires that in order to conduct the fire resistance test, a furnace must be used that is capable of subjecting the specimen to the following heating conditions:

$$T - T_0 = 345log_{10}(8t + 1)$$

Where:

t = time in minutes

T = Furnace temperature at time t (°C)

T_0 = Initial furnace temperature (°C)

The standard time - temperature curve can be seen in Figure 1 below:

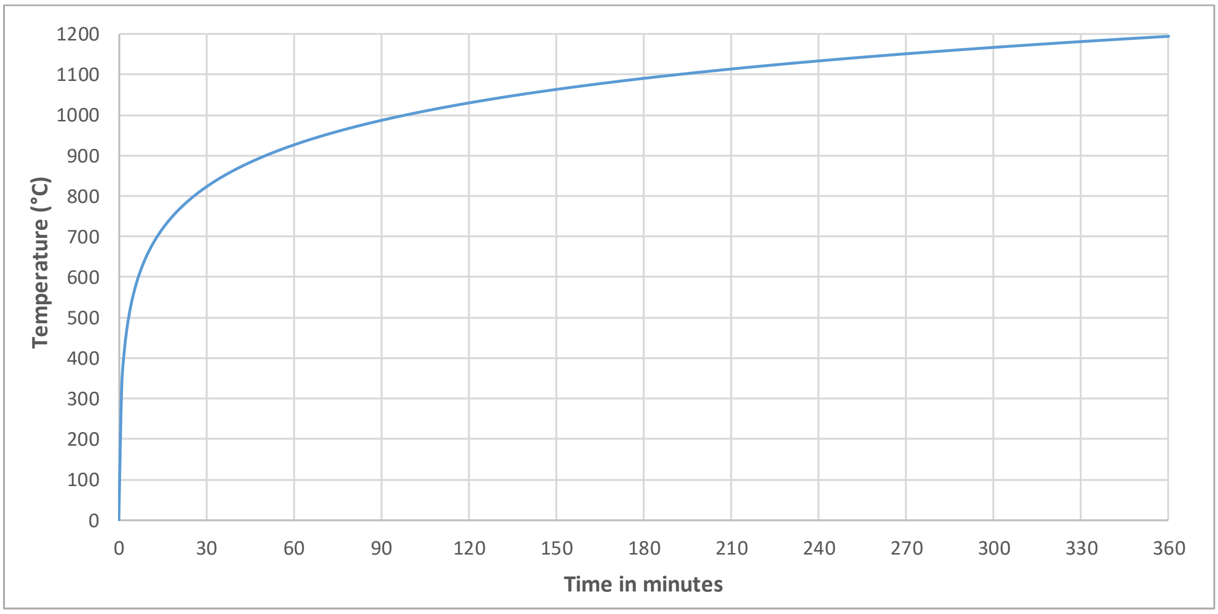

Figure 1: Standard time - temperature curve according to SANS 10177-2, 2005

2.1.2.1. *Tolerance for furnace temperatures*

Realistically it is impossible to achieve a furnace temperature that will follow the standard time - temperature curve perfectly. SANS 10177-2 allows for a temperature deviation during testing. The accuracy of the temperature control must be such that the mean deviation of the furnace temperature does not exceed the following limits:

- ± 15% during the first 10 minutes
- ± 10% between the tenth and thirtieth minute
- ± 5% after the first 30 minutes

2.1.2.2. *Specimen requirements*

SANS 10177 requires that full sized test specimens be used wherever possible, however if this is not possible, specimens with the minimum dimensions in Table 1 below should be used. It should also be ensured that the specimen is representative of the complete element whose fire resistance is to be assessed. A summary of the failure criterion of each element from SANS 10177-1 is also provided in Table 1.

Table 1: Specimen requirements and method of expressing its fire resistance rating according to SANS 10177-2

Element	Dimensional requirements	Fire resistance requirements
Vertical fixed room dividing element	Height: 2.8 m Width: 2 m	Stability, integrity and insulation (all three simultaneously)
Horizontal fixed room dividing element	Span: 4 m Width: 2 m	Stability, integrity and insulation (all three simultaneously)
Load bearing walls	Height: 2.8 m Width: 2 m	Integrity and insulation; stability
Fire protective external cladding	None	Stability and integrity (simultaneously)
Columns	Height: 3 m	Stability
Roofs and roof assemblies	Span: 4 m Width: 2 m	Stability and integrity (simultaneously)

There are no explicitly stated requirements for furnace size, burner locations or even methods of conducting the test in the standard. It is mentioned, however, than the furnace used must be large enough to accommodate specimens that meet the minimum dimensions seen in Table 1. It is up to the individual conducting the test to decide on fuel type, ignition technique and a method of controlling the fire.

2.1.2.3. Application of external forces and heating

SANS 10177-2 states that one must ensure, as far as is possible, that the restraints at the ends or sides of a test specimen are similar in nature to those of the element in service that is being tested. If possible, a load bearing element should be subjected to loading, at least 30 minutes prior to testing, to a magnitude of load that produces similar stresses to what would be produced in the full size element when subjected to its design load.

This load can be applied in any way and must be maintained throughout the test period. It is also important that non-load bearing elements should be subjected to zero load during testing; in order to replicate real conditions.

Specimens should also be placed in the furnace and exposed to fire in a manner in which the full sized element could be exposed in a real fire.

2.1.2.4. Observations during test

During a fire resistance test, the following observations must be made, and the time of occurrence must be noted:

a. Stability
   - Deformation of the test specimen, the moment of collapse or time taken until the test load cannot be supported, or the maximum permissible deflections in the case of horizontal elements
b. Integrity
   - In the case of separating elements, observations must be made of cracks, holes or openings through which flames or gases could pass.
c. Insulation
   - The highest average temperature reached on the unexposed face must be recorded with the use of thermocouples.
d. Additional observations
   - General observations must also be made during testing. These observations may not be regarded as failure criteria but could be hazardous if they were to occur in a real building or public space.

2.2. ASTM E119

ASTM (American Society for Testing and Materials) E119 is the American standard for fire test methods of building construction and materials. The ASTM E119 and ISO 834 time – temperature curves are the most common furnace exposures used in fire resistance testing worldwide (Beyler, et al., 2007).

The test methods described in the ASTM E119 standard prescribe a standard temperature – time curve similar to that seen in SANS 10177-2; in the sense that it is of controlled extent and severity. Performance is defined as the period of resistance to standard exposure elapsing before the first critical point in behaviour is observed (ASTM International, 2010).
The methods described in ASTM E119 are applicable to masonry units, composite structural elements, load bearing or non-load bearing room dividing elements, columns, girders, beams and slabs.

It is stated in ASTM E119 that no data has been collected on which assumptions can be made about repeatability of fire tests conducted according to the methods described. A brief overview of the requirements of the standard is presented below.

2.2.1. Furnace heating requirements

ASTM E119 requires that furnace temperatures be controlled to follow the standard time – temperature curve seen in Figure 2 below.

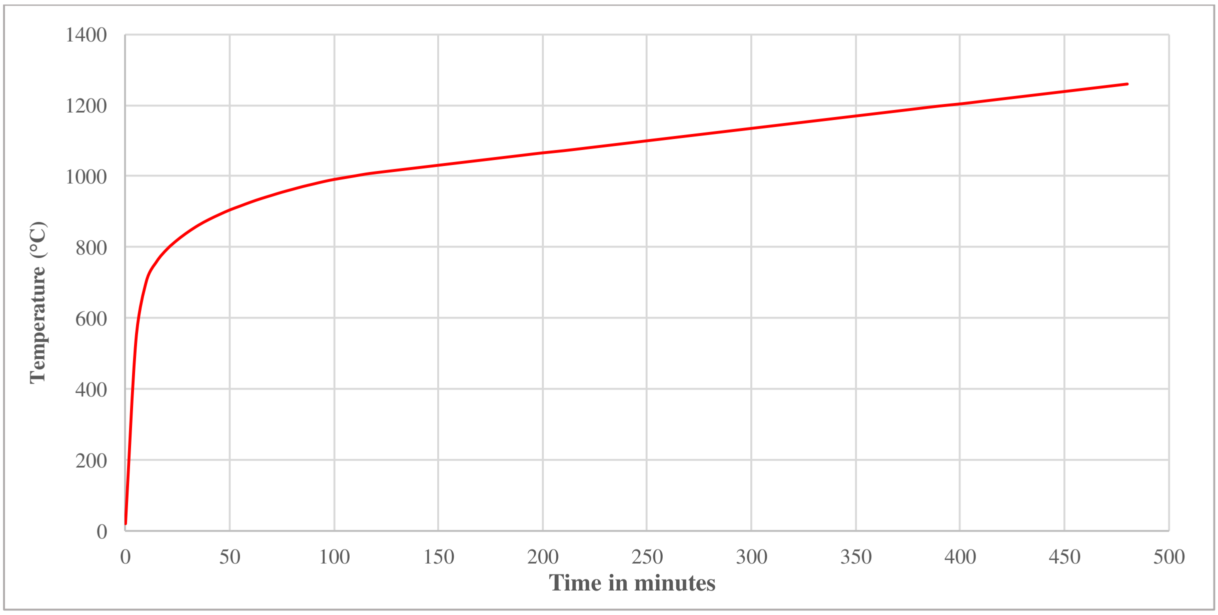

Figure 2: ASTM E119 Standard time-temperature curve

The time - temperature curve seen in Figure 2 does not correspond to a particular equation, unlike the curve seen in SANS 10177-2, but rather consists of a series of data points that have been determined through experience of severe building fires.

2.2.2. Furnace Temperatures and tolerances

The temperature curve in Figure 2 must be the average temperature from nine or more thermocouples for a floor, roof, wall, or partition and eight or more thermocouples for a column. Furnace temperatures must be read at time intervals of less than five minutes during the first two hours and thereafter the intervals must not exceed 10 minutes.
The accuracy of the furnace control must be such that the area under the time - temperature curve produced is:

- Within 10 % of the corresponding area under the standard time - temperature curve for tests of one hour or less,
- Within 7,5 % for those over one hour and not more than two hours and,
- Within 5 % for tests exceeding two hours in duration

2.2.3. Hose stream test

ASTM E119 outlines the procedure for conducting a hose stream test which subjects a specimen to the impact, erosion and cooling effects of a hose stream that an element may experience during attempts to extinguish a real building fire.

This test is not required for elements that are to have a fire resistance rating of less than 60 minutes. The test must be conducted on a duplicate specimen which must be immediately exposed to the hose stream after being subjected to a fire test for half the time of the full test endured by the original specimen. Alternatively, the test may also be conducted on the initially tested specimen. The hose must be directed towards the middle of the exposed face, and then moved slowly over all parts, and the element's behaviour must be noted.

2.2.4. Failure criteria / conditions of acceptance

The failure criteria of ASTM E119 are assessed as follows:

- Stability:
    - An element has failed with respect to stability if it does not sustain the applied load without passage of flame or gas

- Integrity:
    - A room dividing element (walls, floors, etc) has failed with respect to integrity if the passage of flame or gases hot enough to ignite cotton waste occurs
- Insulation:
    - A room dividing element has failed with respect to insulation if transmission of heat through the wall / partition is such as to raise the temperature on its unexposed surface by more than 139 °C
- Hose stream test:
    - An element fails with respect to the hose stream test if it is unable to sustain the applied load without the passage of flame or gas and,
    - If an opening develops that permits a projection of water from the stream beyond the unexposed surface during the time of the test

2.2.5. Test Specimen requirements

One of the main challenges faced during any fire test is the simulation of a real life event that could occur causing an element to be subjected to fire. In order to obtain an accurate fire resistance rating of an element, the size, material and boundary conditions of the test specimen must be as close as possible to the size, material and boundary conditions of the element to be used in construction.

ASTM E119 states that the test specimen must be representative of the construction that the test is intended to assess. The materials, workmanship, and details such as dimensions of parts must represent the element as it will be during and post construction. The specimen must also be built under conditions representative of those applied in building construction and operation.

Table 2: Specimen requirements according to ASTM E119

Element	Dimensional requirements	Fire resistance requirements
Vertical fixed room dividing element	> 9 m^2 of exposed area; no dimension less than 2.7 m	Stability, integrity and insulation (all three simultaneously)
Floors and roofs	> 16 m^2 of exposed area; no dimension less than 3.7 m	Stability, integrity and insulation (all three simultaneously)
Load bearing walls and partitions	> 9 m^2 of exposed area; no dimension less than 2.7 m	Integrity and insulation; stability
Protective membranes	That of vertical dividing elements or floors or roofs	Integrity and insulation (simultaneously)
Columns	Height: 2.7 m	Stability
Beams (loaded restrained)	Length: 3.7 m	Stability

2.3. BS 476: PART 20

BS 476 is the British standard for fire tests on building materials and structures. The part that will be looked at here is Part 20: Method for determination of the fire resistance of elements of construction (general principles).

BS 476 categorizes elements of construction into two main groups, namely elements that have a fire resistance and elements that make a contribution to the fire resistance of a structure. Many of the requirements outlined in BS 476 are adopted from ISO 834: Fire resistance tests – elements of building construction.

Something that is important to note is the test equipment requirements outlined in ISO 834-1: General requirements; the standard suggests the following equipment necessary in order to conduct a fire test:

- A furnace capable of subjecting the specimen to test conditions
- Control equipment to enable temperature to be regulated
- Equipment to control and monitor the pressure of hot gases within the furnace
- A frame to erect the test specimen
- Loading and restraint mechanisms
- Temperature recording equipment inside the furnace and on any unexposed faces
- Deformation measuring equipment
- Equipment to evaluate performance with respect to the required criteria

(ISO834-1, 1999)

2.3.1. Overview

The heating conditions outlined in BS 476 are the same as those mentioned in SANS 10177. The standard time - temperature curve follows the relationship:

$$T - T_0 = 345log_{10}(8t + 1)$$

Where:

t = time in minutes

T = Furnace temperature at time t (°C)

T_0 = Initial furnace temperature (°C)

Similarly, tolerances for furnace temperatures, specimen requirements, application of external forces and heating, and observations during test are precisely the same as those requirements outlined in SANS 10177. These requirements can be seen in sections 2.1.2.1 to 2.1.2.4 above.

A significant difference that is worth noting between BS 476 and SANS 10177 is that the British standard contains more information regarding apparatus requirements. These requirements can be seen in section 6 of the standard and summarized below.

2.3.2. Apparatus and testing requirements

BS 476 states that the heat that the specimen in a fire test receives must be that of radiated heat received from the surface of the furnace chamber opposite the surface of the specimen (BS 476: Part 20, 1990). The nature of this radiation is determined by the emissivity, thermal conductivity and specific heat of the materials used in the construction of the surface. It is recommended in the standard that the fuel be limited to gaseous fuels such as natural gas or liquid petroleum gas.

The main requirements of a testing furnace according to BS 476 is that the furnace is able to subject vertical separating elements to the required heating conditions on one face, horizontal separating elements on the underside, beams to three faces, and free standing columns to all four faces. The furnace must also be large enough to accommodate the full sized element or to meet the minimum dimensional requirements as outlined in section 2.1.2.2 above. The furnace opening must always be greater in area than the exposed face of the specimen by a ratio of at least 1.5:1.

The chamber depth of a furnace is the distance between the exposed face of the specimen (or soffit of a floor or beam) and the face of the furnace lining immediately opposite the specimen. The following chamber sizes are recommended in BS 476:

- Vertical furnace: Should have a chamber depth of not less than 600 millimetres and not more than 1300 millimetres. The total area of flues or openings must not exceed 25 % of the surface area of the wall in which they occur.
- Horizontal furnace: Should have a chamber depth of not less than 1000 millimetres and not more than 2000 millimetres. The total area of flues or openings must not exceed 33% of the floor area.

2.4. HISTORY OF THE STANDARD TIME - TEMPERATURE CURVE

The standard time - temperature curve as seen in the international standards is used as a means of ensuring that fire tests are globally standardized, and does not represent real life fire conditions. This ASTM E119 heating condition was prescribed in 1917 and is an idealization of time - temperature curves measured in furnaces at various laboratories; it is deemed to represent a severe building fire (Cooper & Steckler, 1996).

The curve was adopted as a result of several conferences by eleven technical organizations, including testing laboratories, insurance underwriters, fire protection associations, and technical societies (ASTM International, 2010).

The time - temperature relationship of the test methods mentioned above represent only one fire situation. There is various methods available to evaluate the performance of specimens under fire conditions that may be more representative of realistic fire situations, provided that the test is conducted by a competent person.

BS 476: Part 20, mentions that the standardized time - temperature conditions are representative of a fire exposure condition at the fully developed (or steady state) fire stage (BS 476: Part 20, 1990). The fully developed stage of a fire is the point at which all combustible materials that are closely available are burning steadily (BS 476: Part 10, 1983). According to Cooper & Steckler, 1996, temperatures of real fires can rise faster than the standard ASTM E119 curve. This will be investigated in this research report.

2.5. HEAT TRANSFER

In order to determine the correct process of conducting a fire test, one must have a general understanding of the various ways in which heat is transferred. The primary objective of a fire test is to subject the test specimen to certain conditions in order to assess its capability of withstanding a real life fire. In order to do this, heat must be generated within a furnace with sufficient energy to be transferred to the face (or faces) of the test specimen.

Energy transferred between a system and its surroundings is divided into two categories: heat and work; heat is transferred because of a temperature difference and work is all other forms of energy transferred (Ragone, 1995). There are three modes of heat transfer: conduction, convection and radiation.

2.5.1. Conduction heat transfer

When a temperature gradient exists in a body, there is an energy transfer from the high temperature region to the low temperature region (Holman, 1997). Energy transferred by conduction is a function of the thermal conductivity of the material, the area concerned and the temperature gradient. Thermal energy is conducted in solids by two modes: lattice vibration and transport by free electrons, where free electrons carry thermal energy from a high temperature region to a low temperature region (Holman, 1997). In general, electron transport accounts for a larger part of conduction heat transfer. In electrical conductors, free electrons transport the electrical charge. This implies that in general, good electrical conductors will also be good heat conductors and therefore offer poor insulation.

Jewett & Serway, 2010, define thermal conduction as the process of energy transfer by heat. The transfer can be described on an atomic scale as an exchange of kinetic energy between molecules, atoms, and free electrons; in which less energetic particles gain energy in collisions with more energetic particles (Jewett & Serway, 2010). The rate of thermal conduction depends on the properties of the substance being heated, such as separation of particles and number of free electrons able to transport energy over large distances.

Substances that are good thermal conductors have large thermal conductivity values, whereas good thermal insulators have low thermal conductivity values. Heat is not transferred to the exposed face of specimen in a fire test through conduction, as the exposed face of the specimen is never in contact with the heat emitting surface. However, the rise in temperature experienced by the exposed face will cause a rise in temperature on the unexposed face due to conduction through the structural member as a result of the difference in temperature.

2.5.2. Convection heat transfer

Energy transferred by the movement of a warm substance is said to have been transferred by convection (Jewett & Serway, 2010). In the case of an open flame, air directly above the flame is heated and expands, as a result the density of the air decreases and the air rises. Convection resulting from differences in density as with air around a fire, is referred to as natural convection (Jewett & Serway, 2010).

In a furnace used for the purpose of a fire test, air inside the furnace chamber will be heated, the hot air will begin to rise and circulate within the furnace. This air will contribute to raising the temperature of the exposed surface of the element being tested.

2.5.3. Radiation heat transfer

All objects radiate energy continuously in the form of electromagnetic waves produced by thermal vibrations of the molecules (Jewett & Serway, 2010). The rate at which an object radiates energy is expressed with the following equation known as Stefan's law:

$$P = \sigma A e T^4$$

Where,

P = Power in Watts of electromagnetic waves radiated from the surface of the object

$\sigma = 5.6696 \times 10^{-8}$ W/m$^2 \cdot$ K^4

A = Surface area of the object

e = Emissivity*

T = Surface temperature in Kelvin

*Emissivity is a material property which is the ratio of energy radiated from a materials surface to that radiated from a black body which is a perfect emitter (a perfect black body will have an emissivity of 1).

In conduction and convection heat transfer, energy is transferred through a material medium; however heat transfer may also occur through regions where a perfect vacuum exists, the mechanism in this case is electromagnetic radiation (Holman, 1997). Thermal radiation is electromagnetic radiation propagated as a result of a temperature difference. Radiation is the main mechanism of heat transfer in a fire testing furnace as the flame produced never actually touches the surface of the specimen. BS 476: Part 20, 1987, suggests recording the irradiance (which is the flux of radiant energy per unit area normal to the direction of flow of radiant energy) during a fire test at a certain distance from the unexposed face of the test specimen. This information can be of value when determining safe storage locations for goods and materials.

2.6. TIME - TEMPERATURE CURVE COMPARISON

The standard heating conditions required within a furnace according to SANS 10177-2, Eurocode 1 and BS 476-20 are the same and are governed by the relationship:

$$T - T_0 = 345log_{10}(8t + 1)$$

Where

t = time in minutes

T = Furnace temperature at time t (°C)

T_0 = Initial furnace temperature (°C)

The standard heating condition prescribed by ASTM Standard E119 is slightly different.

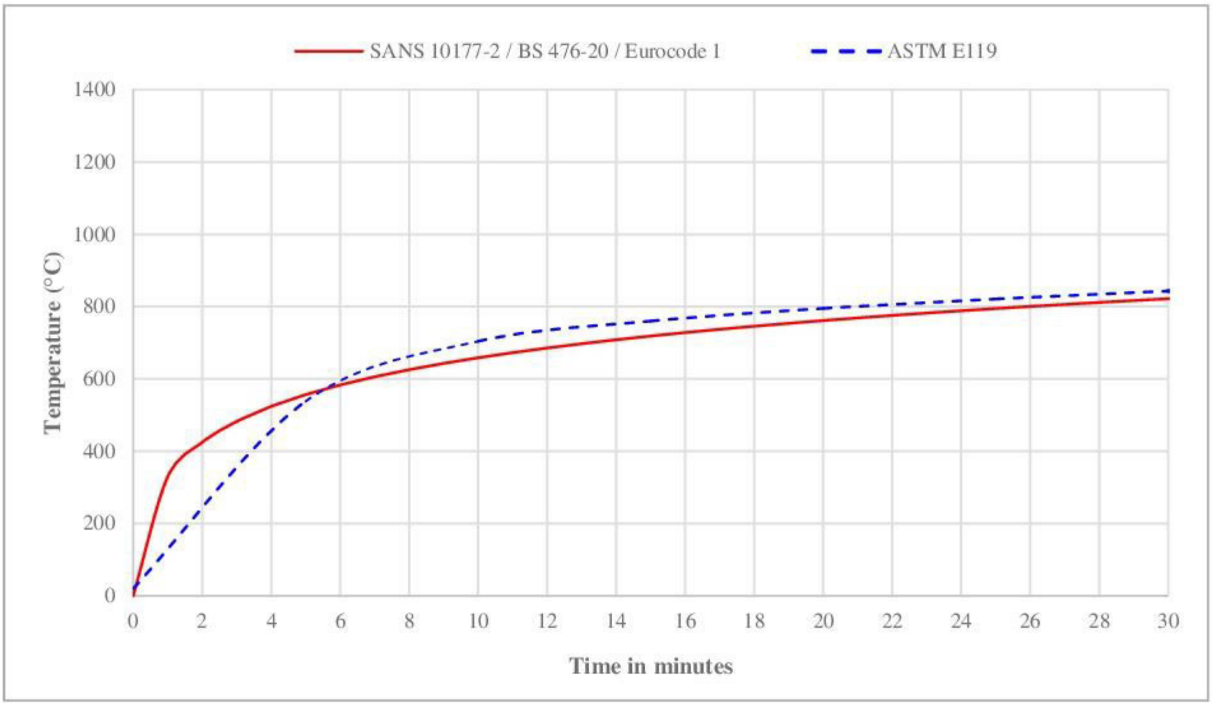

Figure 3: Time - temperature curve comparison for various international standards

A comparison of the two types of standardized time - temperature curves can be seen in Figure 3. The two heating conditions do not vary significantly after they intersect at five minutes. SANS 10177 requires that furnace temperatures be increased far more rapidly within the first five minutes than ASTM E119.

2.7. COMPARTMENT FIRES

In fire design, knowledge of the behaviour of fire growth is critical. The exposure conditions outlined in the various standards do not represent all fire conditions. Fire damage caused to a building element is usually as a result of a compartment fire occurring in a confined space. In order to understand how elements will behave during a fire, it is important to understand the behaviour of compartment fires.

The real life behaviour of fire growth governs issues such as life safety and structural fire protection requirements. Quintiere (2006) defines a compartment as any confined space that controls the ultimate air supply and thermal environment of a fire.

A well designed structure divided into strategically planned fire compartments may also help to limit the spread of the flame and smoke and prevent the spread of gases.

Fires in enclosures progress in three phases over time. These phases are characterized as the fire development phase, the fully developed phase and the cooling phase (Quintiere, 2006).

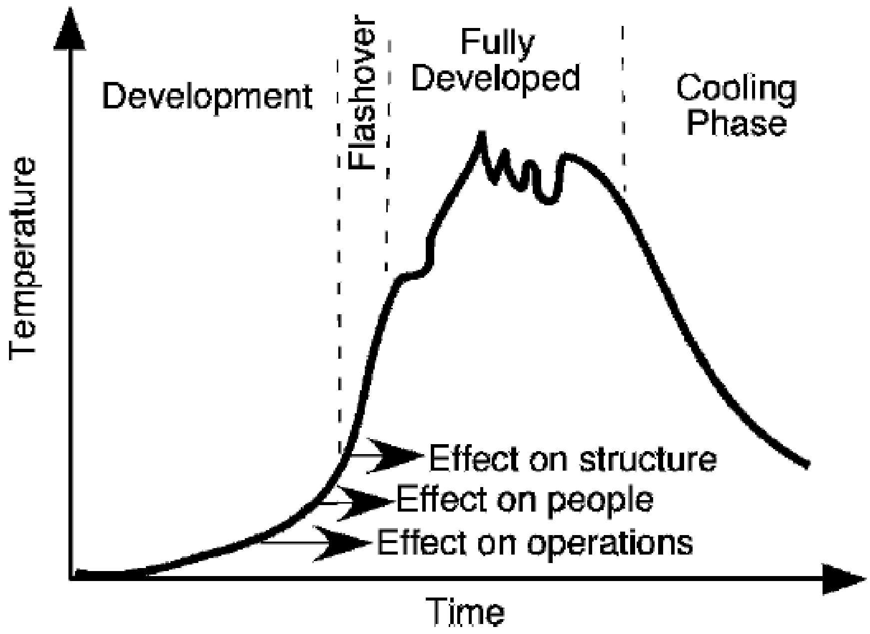

Figure 4: Phases of fire development (Quintiere, 2006)

In the fire development phase the fire grows from a small fire, and if no action is taken to supress it, it will grow to a maximum size that is controlled by the amount of fuel present or the amount of air available through ventilation openings.

Flashover is referred to as the transition to full room involvement that occurs when a fire moves from an initial slow growth process to a rapid acceleration in growth (Thomas & Bullen, 1980).

BS 476: Part 10, 1983, describes flashover as the stage in the development of a contained fire at which fire spreads rapidly to give large merged flames throughout the space.
In terms of compartment fires, flashover occurs at the point at which all fuel within a compartment has ignited leading to the fully developed fire stage.

A fully developed fire is affected by the following:

a. Size and shape of the enclosure
b. The amount, distribution and type of fuel present
c. The amount and type of ventilation of the enclosure
d. The form and type of construction materials of the enclosure

These factors determine both the severity and the duration of the compartment fire. Fifty kilograms of combustible material per square metre of floor area will produce a fire of one hour duration (ASTM International, 2010). According to ASTM E119, fire severity as well as the time - temperature relationship of a fire depends on the following factors:

1. Fire load – amount and type
2. Distribution of this fire load
3. Specific surface characteristics of the fire load
4. Ventilation, as determined by the size and shape of openings
5. Geometry of the fire compartment – size and shape
6. Thermal characteristics of the enclosure boundaries
7. Relative humidity of the atmosphere

(ASTM International, 2010)

BS 476: Part 10, 1983, describes uncontrolled compartment fires as seen in Figure 5 below. The standard states that the ultimate severity of a fire is dependent on a number of interrelated factors.

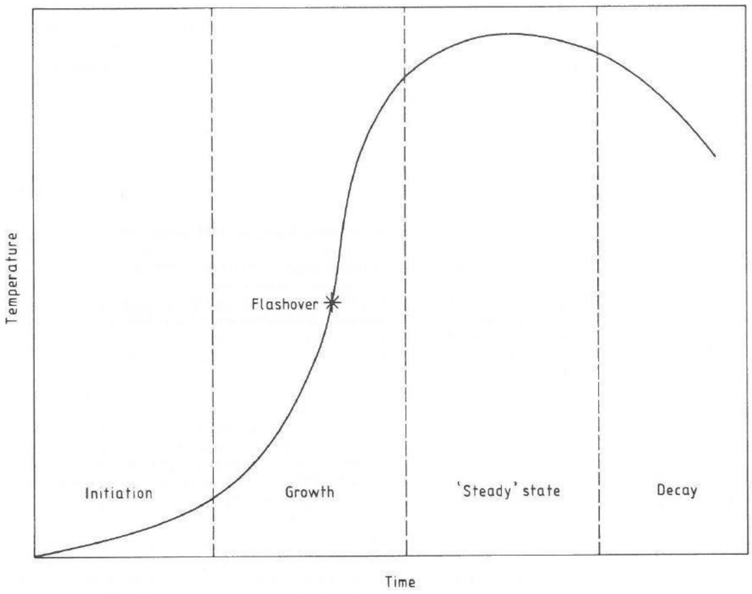

Figure 5: The stages of a typical uncontrolled fire in a compartment (BS 476: Part 10, 1983)

Real fires are random, uncontrolled and unpredictable occurrences that are difficult to simulate. The standard time - temperature curve does not simulate all stages of a compartment fire and therefore the behaviour of the specimen when tested under the standardized conditions will not represent the specimen's actual behaviour in a real fire.

Eurocode 1 proposes a method of determining a natural (or parametric) compartment fire time - temperature curve that is more specific to the particular factors mentioned above for a given compartment. This method is described in section 3 below.

2.8. FIRE TESTING IN SOUTH AFRICA

The largest fire research and testing laboratory in South Africa is located at Firelab situated within the Council for Scientific and Industrial Research (CSIR) in Pretoria. All tests conducted at Firelab are controlled in a manner such that the heating conditions follow the standard time - temperature curve according to SANS 10177-2. Firelab makes use of three furnace types when determining the fire resistance rating of various building elements: a cubical furnace, a vertical furnace and a horizontal furnace.

2.8.1. Cubical furnace

This is a 600 millimetre cubical brick furnace used to test small scale specimens in order to determine the feasibility of performing a large scale test. Tests conducted in this furnace are fuelled with propane. The propane is fed through a permeable fire brick and ignited by hand. Once the cubical chamber is sealed with the small scale specimen placed inside, the furnace temperature can be controlled with the use of a tap restricting the flow of gas.

Figure 6: Firelab's cubical furnace

2.8.2. Vertical furnace

This is a three metre square vertical brick furnace used to test walling or partition systems, columns, and various passive fire protection methods. This furnace is fuelled with 16 diesel burners. The burners work by combining rapid flowing air and diesel. The air produced by two large blowers' flows at a constant rate through a network of pipes towards an outlet at each burner. A separate pipe allows the diesel to flow to the same location. The rapid flowing air acts to atomize the diesel in order to aid with ignition of the fuel. The vapour, which sprays into the furnace through each burner, is ignited manually through a small gap. The 16 burner holes can be seen in Figure 7 below. Temperatures within the furnace and on the exposed and non-exposed faces of the specimen are measured with the use of thermocouples placed in positions in accordance with the specifications in SANS 10177-2. Multiple temperature probes are also inserted into the sides of the furnace in order to monitor the furnace temperature during a fire test. For each test, a full sized brick wall is constructed on a frame adjacent to the furnace face. The frame is then moved next to the furnace opening and the brick wall is used to seal off the furnace preventing heat losses.

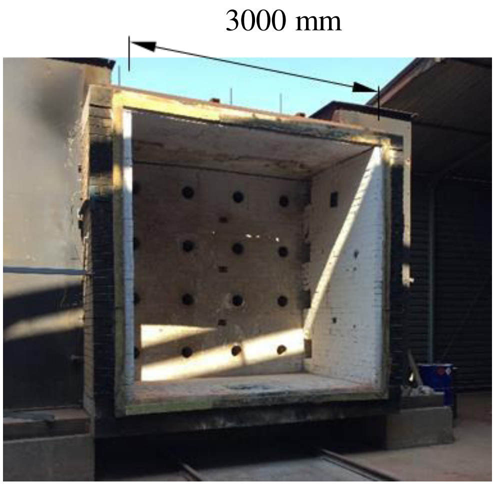

Figure 7: Firelab's vertical furnace

2.8.3. Horizontal furnace

This is a six by three metre rectangular horizontal brick furnace used to test floor systems, floor slabs, and beams. The furnace is fuelled with diesel burners that act to inject the diesel into both sides of the furnace at regular spacing. Temperature is measured in a similar manner and the heating process is manually controlled to follow the standard time - temperature curve by varying the flow of diesel into the furnace. Figure 8 shows a wooden floor system in place over the furnace opening. The placement of the specimen allows the underside to be heated approximately uniformly. Load can be applied to the specimen through the placement of solid steel masses that can be placed at various positions on the span.

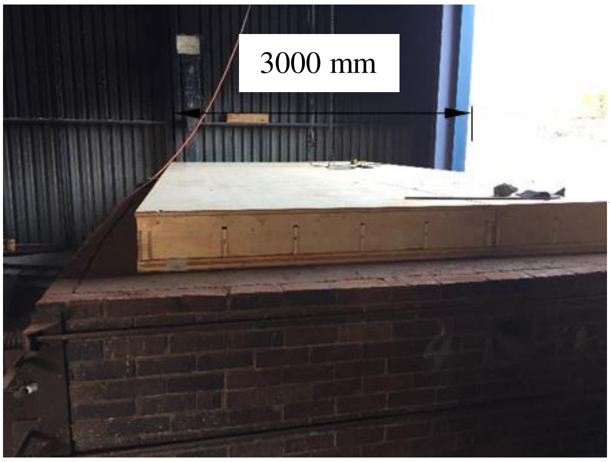

Figure 8: Firelab's horizontal furnace - wooden floor specimen in place

Figure 9: Firelab's horizontal furnace - diesel burners

2.8.4. Testing procedure

A fire test conducted by Firelab was witnessed on a fire door in order to gain insight into the different procedures followed. The test was conducted with the use of the vertical furnace and a full brick wall was erected around the specimen in order to contain the heat within the furnace compartment and to simulate a realistic environment.

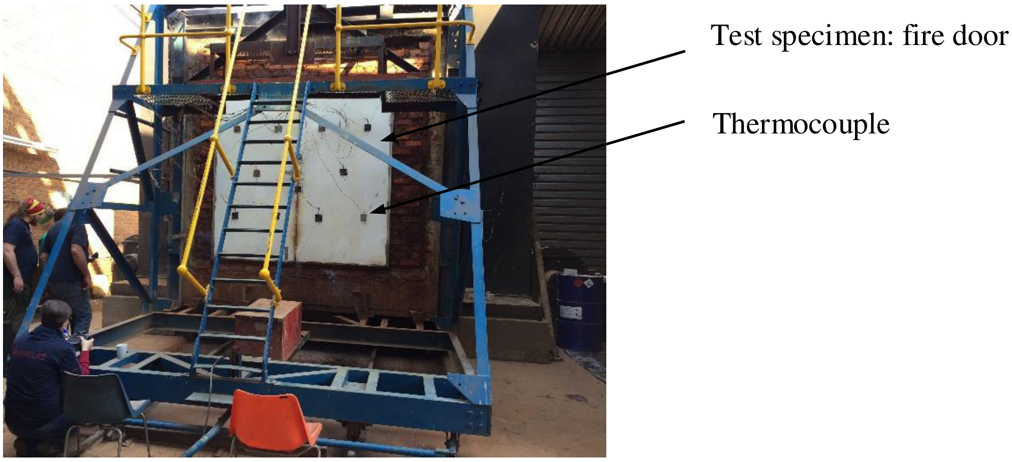

Figure 10: Firelab's vertical furnace with test specimen in place

Figure 10 shows the fire door in place adjacent to the vertical furnace opening. 12 thermocouples can be seen attached to the unexposed face of the specimen. Six temperature probes were inserted into the sides of the furnace midway between the burners and the exposed face of the specimen in order to monitor furnace temperature.

The test was initiated by activating the diesel and air flow to a few burners simultaneously. Each of the 16 burners have their own diesel control allowing temperature to be regulated. The temperature within the furnace was monitored and recorded continually. An experienced lab technician observed the furnace temperature closely and instructed his colleagues to ignite various burners when necessary in order to ensure that the furnace temperature remained within the allowable tolerances as specified in SANS 10177-2.

The unexposed face of the specimen was also observed throughout the test and any changes in the surface appearance were noted. The test was stopped immediately when a flame passing through the gap between the two doors ignited the unexposed face.

Figure 11: Flame on unexposed face of test specimen during test conducted by Firelab.

The time was noted and the specimen was deemed to have failed with respect to integrity due to the fact that a gap formed that was large enough to allow a flame to pass. The gap formed due to warping of the two doors.

2.8.5. Firelab's Time - Temperature curve

Figure 12 shows the time – temperature curve from a 30 minute fire test conducted by Firelab on a fire door. The furnace temperatures recorded during the test are shown superimposed with the standard time – temperature curve according to SANS 10177. The broken lines represent the allowable tolerance for furnace temperatures according to SANS 10177-2 as mentioned in section 2.1.2.1. The furnace control during testing must be such that the furnace temperatures remain within those specified limits.

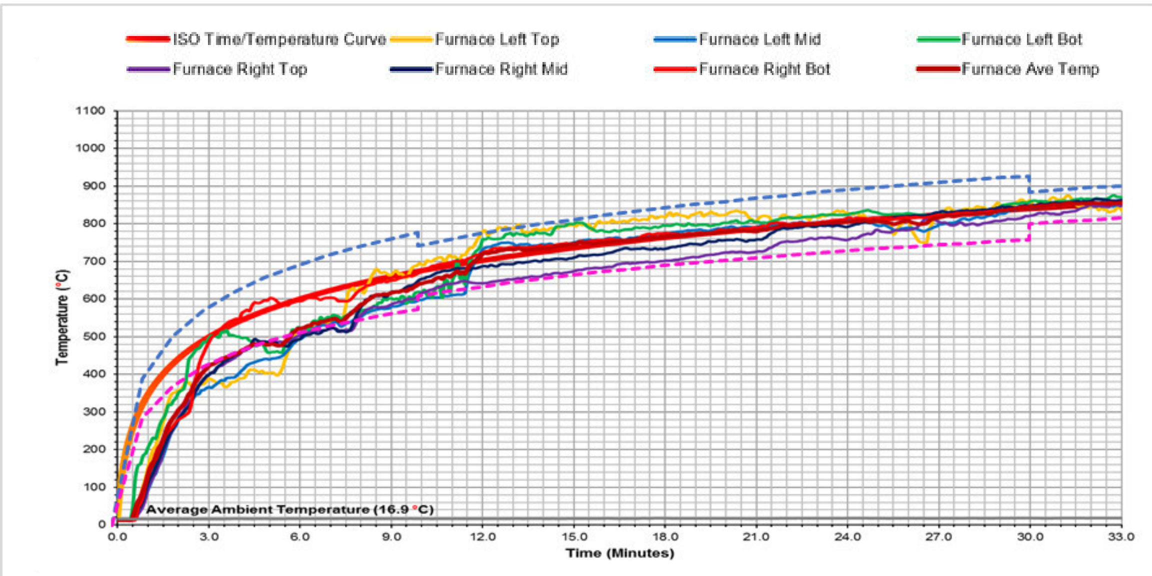

Figure 12: Firelab's 30 minute fire test curve compared to SANS 10177 time - temperature curve

3. NATURAL / PARAMETRIC COMPARTMENT FIRE MODEL

Eurocode 1: Part 1-2 (2002) proposes a natural compartment fire model whereby gas temperatures are determined on the basis of physical parameters (Eurocode 1, 2002). With the use of a standard time - temperature curve, for example as seen in SANS 10177 and ASTM E119, the temperature analysis is conducted for a specified period of time without any cooling phase. However, with a natural compartment fire model, the temperature analysis of a structural element is made for the full duration of the fire including its cooling phase.

The parametric time - temperature curves in Eurocode 1 are valid for fire compartments up to 500 m^2, without openings in the roof, and for a maximum compartment height of four metres. Two time - temperature curves are determined; one for the fire in the heating phase assuming that the fire load of the compartment is completely burnt out, and a linear curve for the fire in the cooling phase. In order to achieve the decreasing temperature in the cooling phase, one could gradually decrease the flow of fuel to the burners or use some type of liquid in the furnace to rapidly lower the temperature.

The time - temperature curves are used to estimate the gas temperature in the fire compartment as a function of the following parameters:

- Density, specific heat and thermal conductivity of the boundary of the enclosure at ambient temperature
- Ventilation conditions - vertical openings on all walls
- Surface area of the floor and total area of enclosure
- Fire load density – this takes into account the fire activation risk due to the size and type of occupancy of the compartment, different active firefighting measures, characteristic fire load density for a particular occupancy, etc.
- Fire growth rate – this is characterised as either slow, medium or fast depending on the type of occupancy

Appendix A contains the calculations that were made in order to determine the time – temperature curve for the heating and cooling phase for a square 5 metre wide by 3 metre high dwelling with one vertical opening with total area of 1.6 square metres, which represents a typical compartment found in residential structures.

Figure 13 shows the time - temperature curves obtained through calculation in comparison with the standard time - temperature curves found in SANS 10177-2 and ASTM E119.

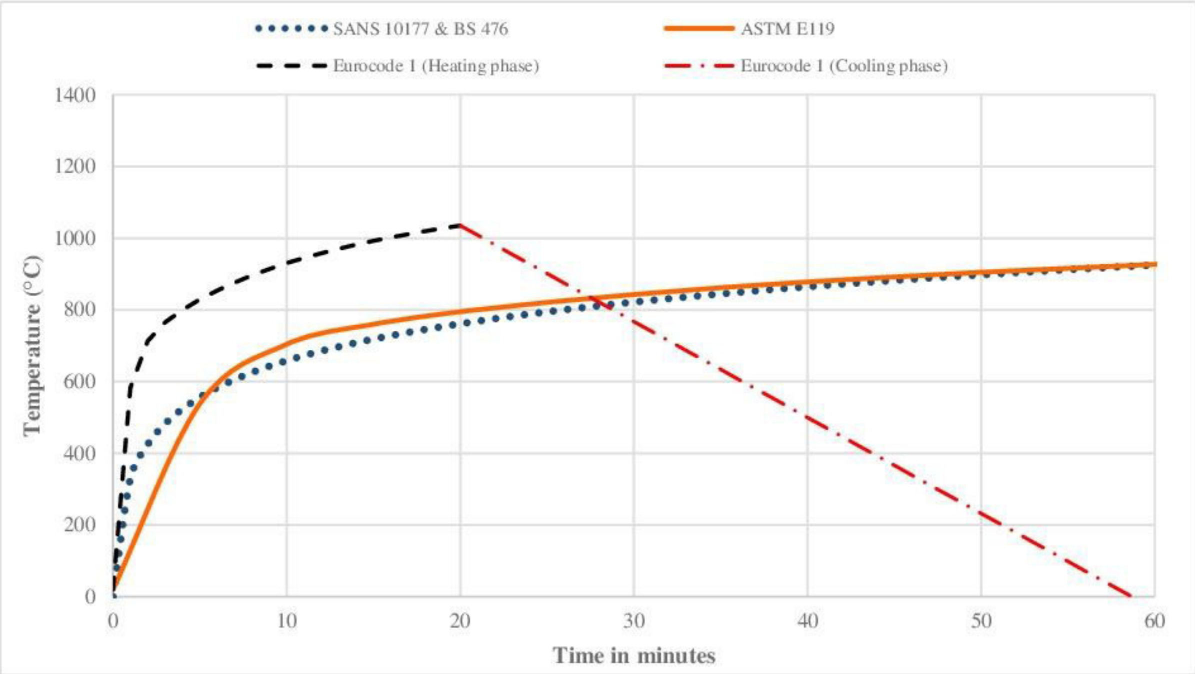

Figure 13: Comparison of standard time - temperature curves with the Eurocode parametric curve

4. PROPOSED TEST SHEET

Based on the literature reviewed above, a template is proposed that may be used for future testing procedures. The template will follow the requirements of SANS 10177-2, and will be applicable to all types of building elements. It may be adapted to be specific to one type of element if necessary.

FIRE TEST ACCORDING TO SANS 10177-2

PROJECT NUMBER:____________________________ DATE: ______________________________

CLIENT: ____

PRODUCT TYPE: ____

TESTING REQUIREMENTS:

- Temperature within the furnace must be controlled according to the standard time – temperature curve with the following tolerances:
  - ± 15 % during the first 10 min of test
  - ± 10 % between the tenth and thirtieth minute of test
  - ± 5 % after the first 30 min of test
- Use at least 5 thermocouples and not fewer than the following:
  - Wall and floor: One to each 1.5 m^2 of surface
  - Beam: One to each 1 m length
  - Column: Two to each 1 m of height
- Fix and support the specimen as it is / will be fixed and supported in service
- Subject a load bearing specimen to load producing stresses of the same magnitude as its design load, at least 30 minutes prior to testing

SPECIMEN DESCRIPTION:

- Size: ____________________________________
- Fixing and supporting conditions: ______________________
- Loading conditions: ______________________________
- Requirements in terms of:
  - Stability: ____________________________
  - Integrity: ____________________________
  - Insulation: ___________________________

SPECIMEN SKETCH: (Showing thermocouple locations)

OBSERVATIONS DURING TEST:

1. Stability:
   - Deformation / collapse:
2. Integrity:
   - Cracks / holes / openings:
   - Smoke:
3. Insulation:
   - Highest average temperature reached by unexposed face:
4. Additional observations:

FIRE RESISTANCE RATING:

- Stability:
- Integrity:
- Insulation:

FUEL CONSUMPTION:

COMMENTS:

5. TEST LOCATION

All tests were conducted on the roof of the Hillman Building at the University of the Witwatersrand, in Johannesburg, within the School of Civil and Environmental Engineering. The Hillman Building Co-ordinates are:

- Latitude: 26°11'32.37"S
- Longitude: 28°01'46.78"E

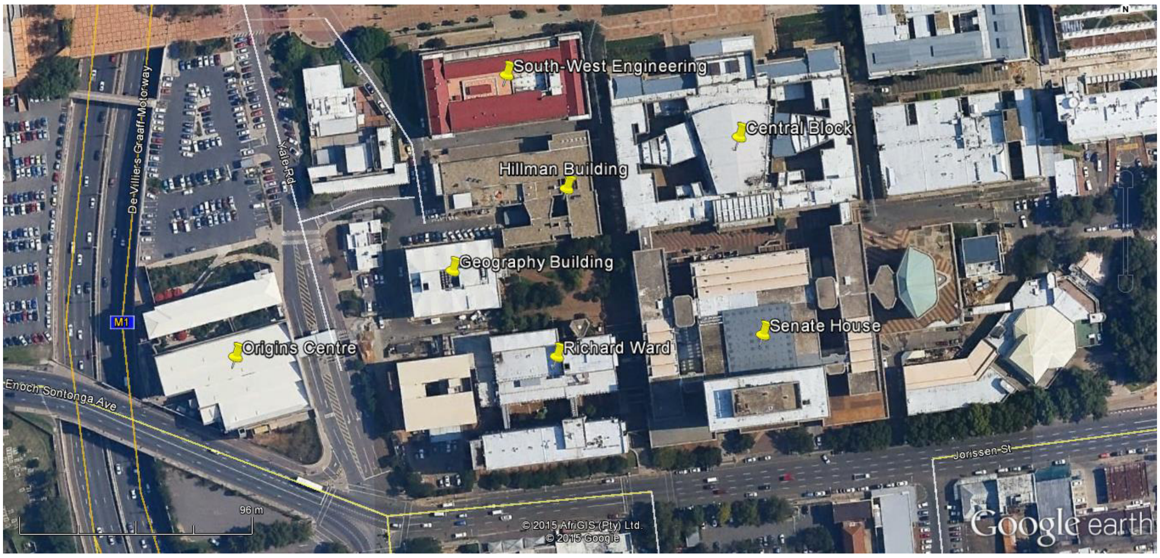

Figure 14: Aerial photograph of Hillman Building and surrounds (Google Earth, 2017)

The position of the furnace used in all tests can be seen in the figure below.

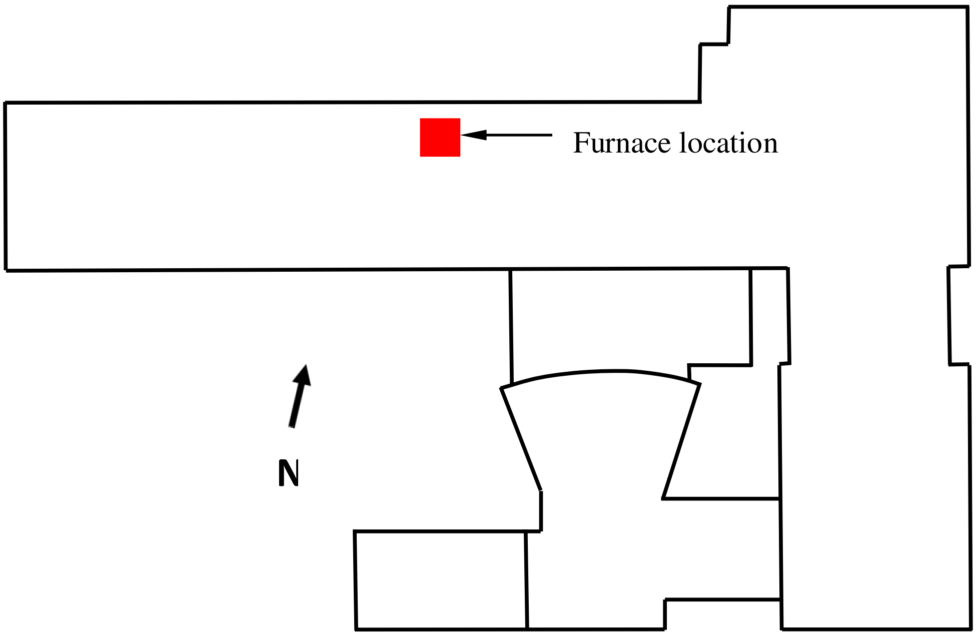

Figure 15: Plan view of the Hillman building

The Hillman Building is a three storey concrete framed structure. The buildings directly adjacent to it are either the same height or lower. It is for this reason that all tests were conducted on the roof, as the smoke emitted from the test would not affect the surrounding buildings. The roof of the Hillman building is also equipped with running water, which was necessary as a safety measure during the fire tests.

Prior to conducting each test, all relevant staff in the building were informed, and a strict safety procedure was planned and followed. Large buckets of water were filled and placed near the furnace to be used in the event of an uncontrollable fire, and each test was conducted bearing safety issues in mind.

6. EXPERIMENTAL SETUP AND APPARATUS

6.1. FURNACE

In order to investigate the time - temperature curves mentioned above, a furnace was required in order to conduct numerous controlled and safe fire tests. A four millimetre thick steel pipe with the following dimensions was used as the main structure of the furnace.

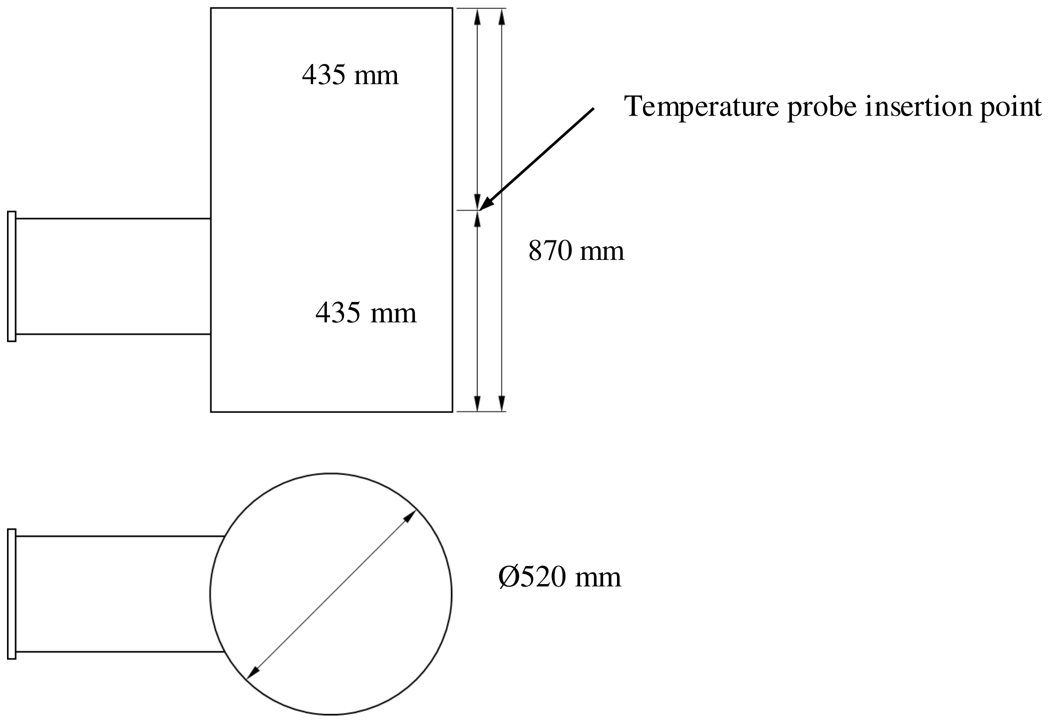

Figure 16: Elevation (top) and plan view (bottom) of the steel furnace used for testing

Figure 17: Furnace in testing position

The secondary pipe seen orientated horizontally out of the side of the furnace was used as a ventilation hole in order to generate a draft through the furnace. Covers for the ventilation hole and the top of the furnace were cut out of a stainless steel plate. The covers were then used to vary the level of ventilation into the furnace.

6.2. DATA LOGGING

6.2.1. Temperature probes

Four temperature probes with the following specifications, were used to record furnace temperature throughout each test:

- Thermocouple type: Type K (NiCr – NiAl)
- Measurement range: -200°C to 1200°C
- Probe cover material: Inconel
- Model: TP - 03
- Dimensions:
  - Probe head – 120 mm tube, 8 mm diameter
  - Probe handle – 100 mm in length

Figure 18: Temperature probe (Lutron Electronic Enterprise CO., LTD)

6.2.2. Data logger

In order to record furnace temperatures, the temperature probe was inserted into a data recorder. The data recorder used is a MotherTool digital thermometer; model: TM-947SD. The data recorder is a 4 channel thermometer which accommodates a maximum of four temperature probes. Data was logged to an SD card. After each test the data was read from the SD card.

Figure 19:MotherTool digital SD card thermometer – TM-947SD

7. EXPERIMENTAL INVESTIGATION

The experimental investigation was divided into two parts:

(i) Preliminary tests and,

(ii) Diesel blower tests

The preliminary tests were conducted to assess the effectiveness of various types of fuels in achieving the desired time - temperature relationship according to SANS 10177-2; and to assess the relationship between furnace temperature and fuel type. The preliminary tests also aimed to assess the validity of the standard time - temperature curve.

The diesel blower tests were conducted to expand on a successful method of test as determined in the preliminary tests, and to determine the correct methodology of conducting a fire test in order to meet the code requirements.

7.1. PRELIMINARY TESTS

A series of preliminary tests were conducted using the cylindrical steel furnace shown in Figure 17. Various fuel types were used that would normally be encountered in a structural building fire, and the burning temperatures of these fuels were assessed. Two sets of preliminary tests were conducted:

(a) Real fire tests carried out using wood as the fuel type in order to assess the behaviour of a natural fire in a compartment.

(b) Flammable liquid fire tests carried out with the use of both petrol and diesel as the fuel type.

7.1.1. Methodology

During both sets of preliminary tests, the time - temperature relationship within the furnace was measured with the use of a temperature probe inserted through a small hole in the side of the furnace at mid height as seen in Figure 16. Each test was run for approximately 20 minutes and the furnace temperature throughout each test was recorded on the data logger connected to the probe. The data logger was set to record the temperature at 10 second intervals.

The following fuel types were used in the preliminary investigations:

(a) Real fire tests:

- Soft wood
- Hard wood

(b) Flammable liquid fire tests:

- Propane
- Petrol
- Diesel

The efficacy of forced air in the furnace was also assessed by introducing an air current with the use of either a 1.2 kW hairdryer or a 1.0 kW Martindale cyclone blower. The pumped air through the furnace accelerated the rate of combustion.

Each test was conducted in a similar manner: a small flame was ignited inside the furnace with the use of standard firelighters, and the flame was then fuelled by adding the various fuel types.

7.1.2. Burning apparatus

In order to conduct the preliminary tests with the use of flammable liquids, a method of injecting the flammable liquid into the furnace was required. In order for the flammable liquid to ignite in the furnace, it would need to be vaporized and sprayed at a high velocity. The burner below was fabricated prior to testing.

Figure 20: Burner used for preliminary flammable liquid tests

The manner in which the burner in Figure 20 works is to allow the flammable liquid to trickle in slowly through the secondary pipe, the primary pipe is connected to a high powered air blower. The flow of flammable liquid then intersects the air flow perpendicularly and the liquid is subsequently sprayed out of the pipe at a high velocity. This spraying action causes the liquid to atomize, allowing it to be ignited inside the furnace.

In order to generate the flow of flammable liquid in the preliminary tests, the fuel tank supply was placed in an elevated position, with a tube connected from the tank to the inlet of the burner. This constant pressure head ensured that a constant flow of flammable liquid could be maintained, allowing the liquid fuel to be supplied to the burner via gravity flow. A tap was connected in the tube between the tank and the liquid inlet pipe to allow the flow to be controlled to ensure the correct furnace temperature.

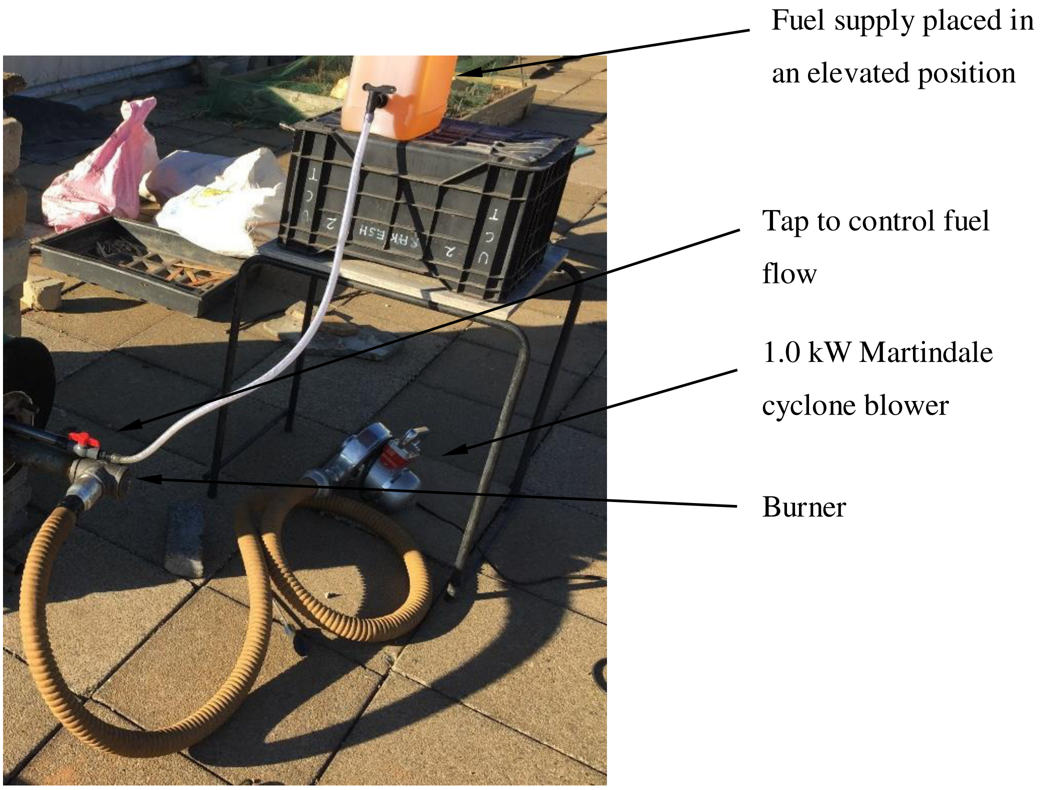

Figure 21: Set up for the flammable liquid preliminary tests

7.1.3. Test results and discussion

7.1.3.1. Real fire tests - Wood as fuel type

Six initial tests were conducted to assess if a wood fire within a contained environment would achieve the furnace temperatures required by SANS 10177-2. Various wood types and burning techniques were used to conduct each test. The results from the first 20 minutes of each test are presented in Figure 22. For comparison, the SANS allowable tolerances are also plotted. Tests 1 to 6 were conducted using the following wood types:

Table 3: Preliminary test fuel types

Test	Fuel type	Maximum dimension (mm)
1	Large hard wood logs	400
2	Small hard wood logs	200
3	Large soft wood offcuts	300
4	Small soft wood offcuts	100
5	Large wood shavings / saw dust	50
6	Small wood shavings / saw dust	20

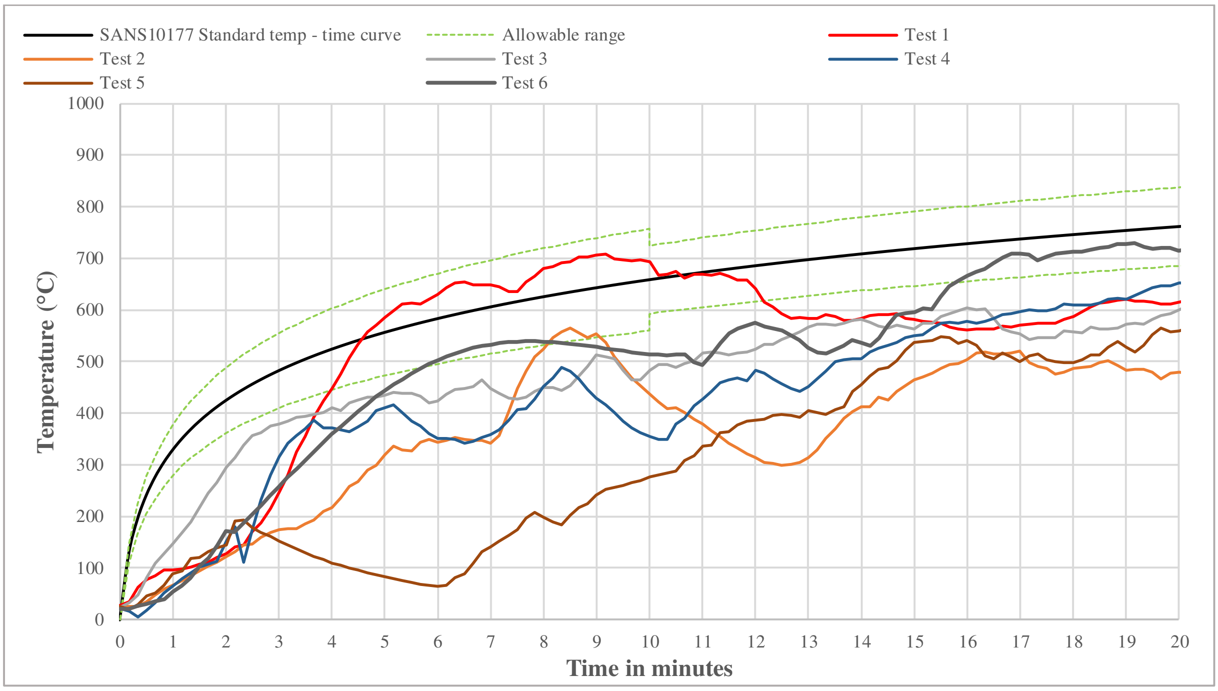

Figure 22: Preliminary tests with wood as primary fuel type

Each of the six tests mentioned above were conducted by igniting a fire within the furnace, and supplying the fire with more fuel when necessary in order to achieve the highest possible temperatures in the shortest amount of time. It is clear that Test 1 conducted with hard wood achieved the highest temperature in the shortest amount of time, however the hard wood did not burn as rapidly as other wood types, and the temperature of the fire rapidly decreased when additional wood was inserted at approximately 10 minutes.

The tests conducted with the softer wood types resulted in a more uniform increase in furnace temperature due to the fact that additional fuel was loaded at shorter intervals; as the time taken for the soft wood inside the furnace to reach the flashover point is significantly lower than that of the hard wood.

From the results of the preliminary real fire tests it is clear that natural wood fires do not burn at temperatures as hot as those seen in the standard time - temperature curve, and the temperature of the natural wood fire increases at a much slower rate. The time - temperature relationship of a natural fire is difficult to control due to the inconsistent nature of natural fires. It was concluded that wood is not an adequate fuel type to be used for a standard fire test since furnace temperatures rarely fall within the required range, and there is a wide band of variation of temperatures throughout the test.

7.1.3.2. Flammable liquid fire tests - Petrol and diesel as fuel types

Petrol and diesel have very different ignition characteristics. Petrol is more volatile than diesel, jet fuel and paraffin because of its lighter base components (Department of Energy, 2011). Petrol is a mixture of volatile, flammable liquid hydrocarbons known to have a high energy of combustion.

Volatility is quantified by the tendency of a substance to vaporize. It is for this reason that petrol is not an ideal substance to be used in a hot environment as 'vapour lock' could occur, where combustion could fail to occur because the liquid fuel could change to a gaseous fuel in a fuel line, causing it to block.

The cetane number of diesel is a measure of its susceptibility for self-ignition; the higher the cetane value, the lower the temperature required for self-ignition (Department of Energy, 2011). The self-ignition temperature of a flammable liquid is the minimum temperature from which a combustible mixture with air will pass into a condition of observable combustion (Setchkin, 1954). With the use of a heating apparatus, Setchkin, 1954, conducted a series of tests to determine the self-ignition temperatures of various combustible liquids. Three types of petroleum products were tested, as well as four types of diesel fuels. The results are shown in Table 4:

Table 4: Self-ignition temperatures of petroleum and diesel products (Setchkin, 1954)

Product	Self-ignition temperature (°C)	Average temperature (°C)
Petroleum (65 octane)	248	306
Petroleum (73 octane)	258	
Petroleum (87 octane)	412	
Diesel (41 cetane)	233	229
Diesel (55 cetane)	230	
Diesel (60 cetane)	225	
Diesel (68 cetane)	226	

On average, the petroleum products tested were found to have a self-ignition temperature of 306 degrees Celsius, which is 77 degrees higher than the average self-ignition temperature of the diesel products.

Two preliminary tests were conducted with the use of petrol and diesel as the fuel type in order to determine if either of the flammable liquids burn at temperatures hot enough to be used as the fuel type in a structural fire test. The blower described above in 7.1.2 was used for both tests.

The testing procedure for both tests was precisely the same; a small flame was initiated inside the furnace prior to spraying the fuel. The fuel was then sprayed in to the side of the furnace and ignited by the flame. The results of both the petrol and diesel tests are shown in Figure 23.

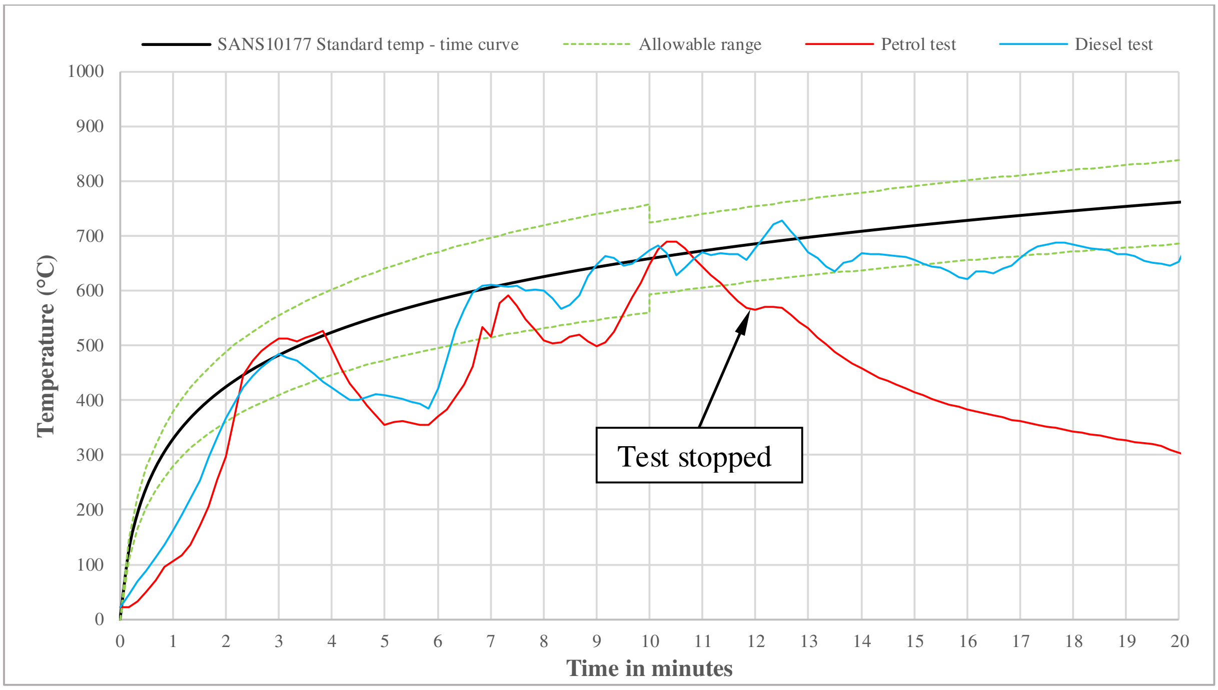

Figure 23: Preliminary tests with petrol and diesel as fuel

<u>Petrol test</u>

The results in Figure 23 showed that the petrol ignited slightly later than the diesel due to its higher self – ignition temperature. Higher initial furnace temperatures were achieved during the petrol test during the first five minutes. The immediate vaporization of the petrol in the pipe lead to rapid ignition once the fuel was blown onto the small flame inside the furnace. The intensity of ignition of the petrol in the furnace was explosive making it difficult to control and to achieve a consistent furnace temperature. A very small amount of fuel was required to achieve high furnace temperatures; however due to the volatility of the fuel, the test was stopped around the 12 minute mark due to a gaseous build up within the furnace. A maximum furnace temperature of 689 °C was achieved during the petrol test. No further tests were conducted with the use of petrol as the fuel type.

Diesel test

For the diesel test, ignition occurred earlier than in the petrol test due to the lower self-ignition temperature of diesel. The intensity of ignition was far less explosive than that of the petrol test and a more consistent temperature could be achieved due to the less volatile nature of diesel. The diesel sprayed into the furnace produced a normal flame that was easier to monitor and control. A higher volume of diesel was required to achieve the necessary furnace temperature and a maximum temperature of 727 °C was achieved during the test.

It was decided that diesel would be used as the fuel type for all subsequent fire tests. During the preliminary test it was observed that the diesel was not being sufficiently vaporized with the use of the burner setup. Liquid diesel could be seen trickling through the blower pipe into the furnace, resulting in fuel wastage. In order to conduct an economical fire test that complies with SANS requirements, an atomizer had to be designed to vaporize all diesel flowing into the system. The atomizer used in all subsequent diesel blower tests is described in section 7.2.1.2.

7.2. DIESEL BLOWER TESTS

An atomizer was designed and fabricated as described below to be used for all the subsequent tests. The primary aim of the diesel blower tests is to expand on a successful method of test as determined in the preliminary tests, and determine the correct methodology of conducting a fire test in order to meet the code requirements. These tests are aimed at developing a feasible and cost effective method of conducting a fire test that will follow temperatures required by SANS 10177-2. The diesel blower tests also aim to achieve a high level of repeatability.

7.2.1. Burning apparatus

After conducting a series of preliminary tests, it was determined than an atomizer was required that would enable the liquid diesel to be vaporized sufficiently to allow ignition to take place, while minimizing wastage of fuel.

7.2.1.1. Burner concept

Fire tests in South Africa are often conducted with the use of a diesel and air mixture injected into a furnace with the use of one or multiple burners; as seen at Firelab, described in section 2.8 of this report. The nature of a flame produced by a burner will depend on the richness of the mixture of fuel and oxygen at the burner. Where a mixture of fuel and air is fed to the burner, the flame produced is likely to be less dependent on the oxygen content of the gases inside the furnace than where the burner is fed with fuel only (BS 476: Part 20, 1990).

In order to conduct controlled fire tests, a burner was required that would allow sensitive temperature control, in order to steadily control the heat output from the burner. Two variables can be controlled in a burner: the amount of forced air released, and the rate of flow of diesel.

Diesel was chosen as the primary fuel in all subsequent fire tests due to the fact that it is not as volatile as other fuels such as petrol, it is relatively inexpensive, and it burns at high temperatures. Liquid diesel does not ignite easily making it safe to store and to work with. This lack of ignitability does however cause complications when using diesel for a fire test.

A simple preliminary burner seen in Figure 24 was assembled in order to test the suitability of combining forced air and diesel in a chamber to promote atomization.

The burner was assembled with the use of pipe components used to create a chamber with two inlet holes and an outlet hole, a clear reinforced pvc tube, a compressed air cylinder, a fuel pump, a hand held gas blow torch and a 12 volt battery.

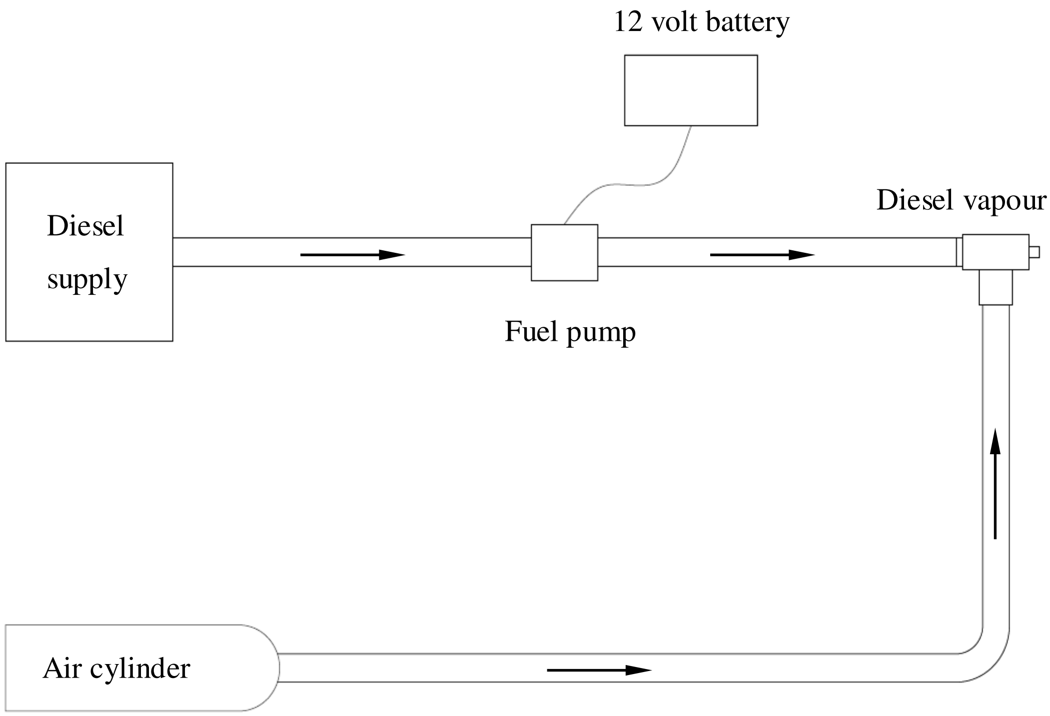

Figure 24: Layout of test conducted to assess the feasibility of the burner concept

The fuel pump was connected to the back of the chamber while the compressed air cylinder was connected to the side of the chamber. The air and diesel was then allowed to flow simultaneously. This resulted in a vapour at the outlet which could be ignited resulting in the steady flame seen in Figure 25.

Figure 25: Atomizer concept test

The test was regarded as successful as all diesel entering the chamber was successfully atomized, and a steady flame could be produced. This concept was then used for construction of the main burner to be used in the diesel burner tests. Control was added in the main burner seen in section 7.2.1.2, to allow the flow of air and diesel to be regulated during testing.

7.2.1.2. Final burner construction

A larger burner was then constructed as follows:

The burner required two inlet points: one for the diesel and the other for the forced air, and one outlet point for the vaporized air-diesel mixture. Figure 26 shows the various components attached together to create the main chamber of the burner.

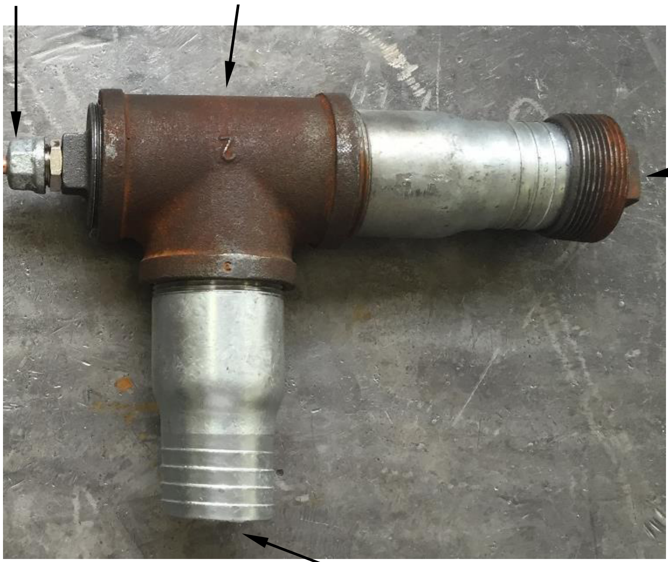

Figure 26: Diesel burner

An eight millimetre hole and a two millimetre hole were drilled through the diesel inlet and vapour outlet portions of the burner respectively.

In order to vapourize the diesel flowing into the burner, it was required that the liquid diesel be mixed with fast flowing air.

A narrow copper tube was used to transport the flow of diesel into the burner. The tube, eight millimetres in diameter, was inserted through the diesel inlet until it was pushed against the two millimetre vapour outlet opening. The tube was crimped at the end (with the use of a three-jaw drill chuck), creating an outlet hole one millimetre in diameter seen in Figure 26.

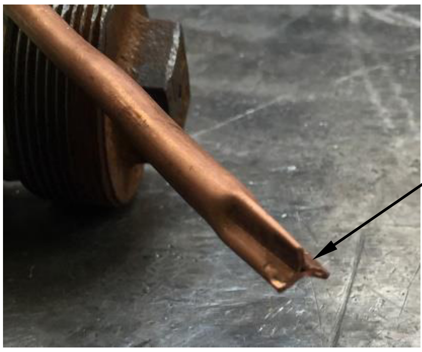

Figure 27: Crimped copper tube used for diesel injection

The tube was crimped to decrease its outlet area in order to increase the velocity of diesel flow. The crimped portion also assisted with air flow through the vapour outlet. The copper tube was fixed in such a way that its one millimetre outlet hole was positioned against the centre of the two millimetre burner outlet.

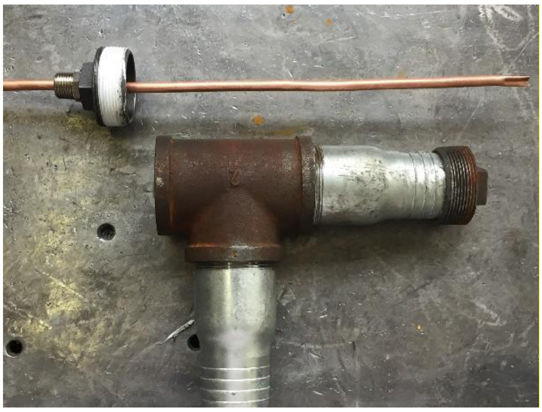

Figure 28: Diesel inlet tube

The burner was then assembled and all openings in the burner other than the air inlet and vapour outlet holes were sealed with the use of water resistant silicone sealant.

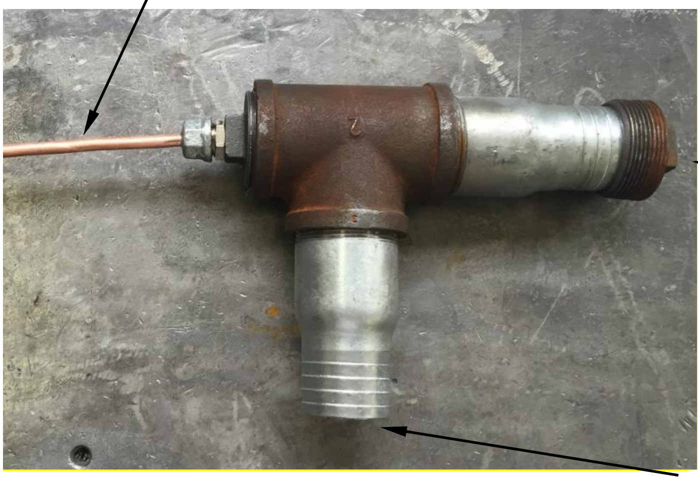

Figure 29: Complete diesel burner

Vapourization of the liquid diesel occurred as follows:

- Liquid diesel was pumped from a tank through the eight millimetre diameter copper tube
- Liquid diesel flowed rapidly out of the one millimetre outlet hole in the copper tube, placed against the vapour outlet
- Air was forced into the chamber simultaneously. Once air enters the chamber it is forced through the two millimetre outlet at the same position where the copper tube outlet is placed.
- The air was forced to flow around the copper tube outlet at a high velocity
- As the rapidly flowing air passes the copper tube outlet, it combines with the rapidly flowing liquid diesel and vapourization of the liquid occurs
- This vapour is then sprayed through the vapour outlet opening

7.2.2. Methodology and testing procedure

Figure 30 below shows a schematic of the test set up used for all diesel blower tests. A 1000 Watt electrical Martindale cyclone blower was used for all tests; the blower outlet tube was attached to the air inlet tube of the burner with a sealed connection. A tap to control the diesel flow was installed in a reinforced pvc tube which was attached to the copper diesel inlet tube. A standard fuel pump was connected to the tube which was then attached to a 12 volt battery.
At a later stage an air release valve was attached to the top of the air chamber to allow the release of excess air; however the primary source of control of the burner is the tap which allows one to regulate the flow of diesel from the pump.

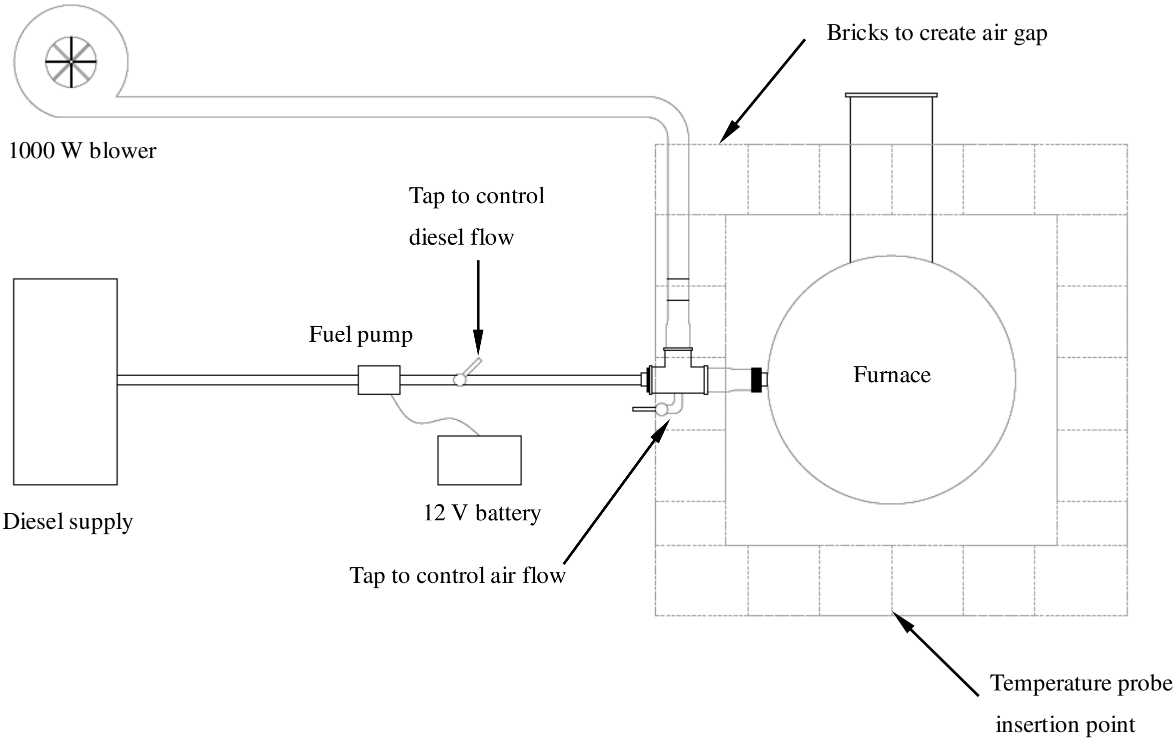

Figure 30: Schematic of diesel blower test set up

For this series of tests, an air gap was introduced around the perimeter of the furnace by constructing a full size square perimeter approximately 10 cm away from the furnace using interlocking earth bricks as seen in Figure 30. The air gap acted as insulation and as a wind barrier in order to assist in achieving higher furnace temperatures. If the furnace were to be exposed to wind, a large amount of the heat during a fire test would be lost due to convection.

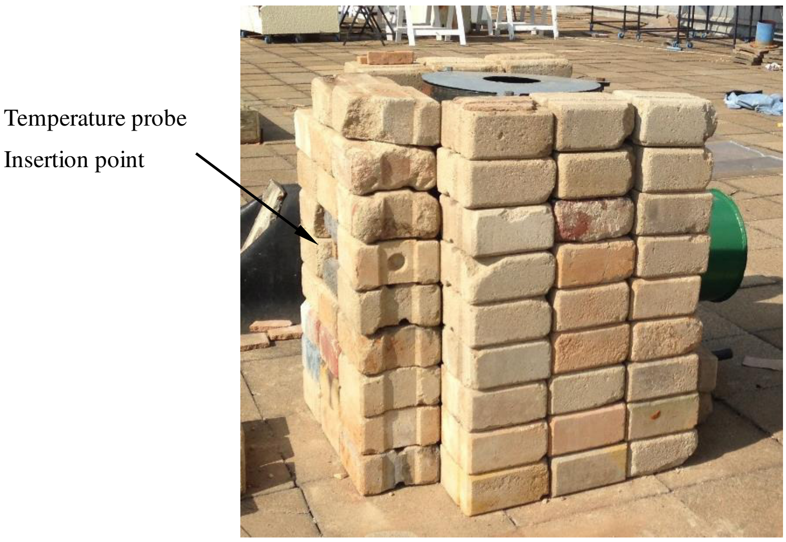

Figure 31: Earth bricks used to create an air gap and wind barrier around the furnace

The bricks were placed in such a manner that a small gap was left open to allow the temperature probe to be inserted and removed. A total of 10 tests were performed, each for a period of 20 minutes. The test setup for each test was precisely the same as seen in Figures 30 and 32.

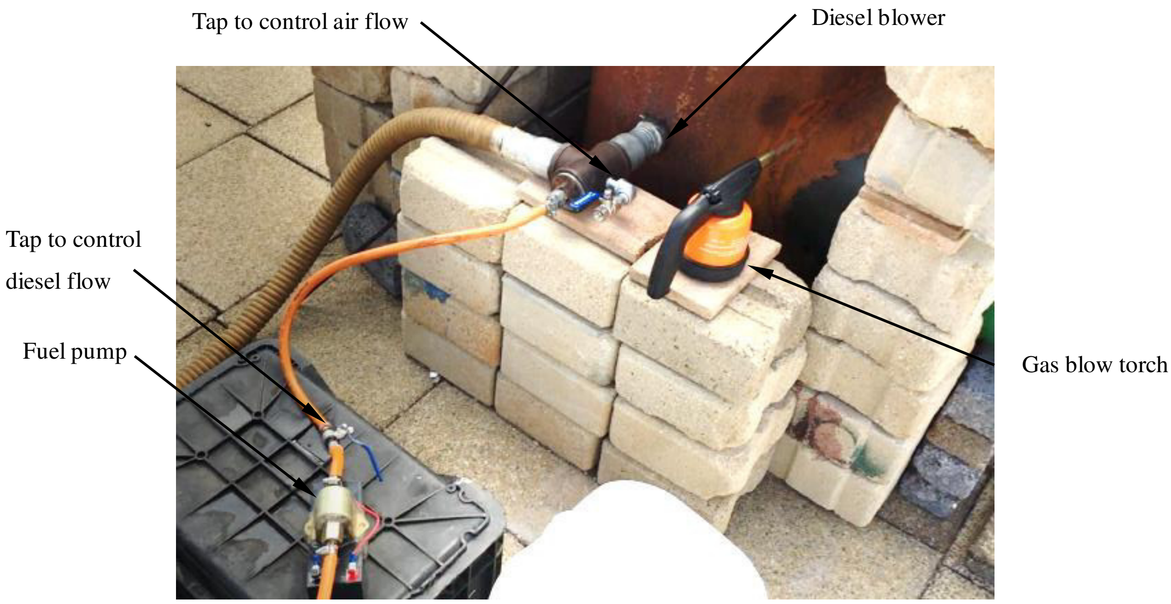

Figure 32: Diesel blower test setup

A small hole was drilled in the side of the furnace and the blower was placed at that location. The diesel was pumped into the blower with the use of a small fuel pump powered by a 12 volt battery. The tap to control diesel flow was adjusted accordingly throughout each test in order to ensure that the furnace temperature increased at a rate corresponding to the standard time - temperature curve.

Preliminary tests of the tap to control air flow showed that the difference that it made to the atomization process was insignificant and it was therefore kept closed throughout the tests.

The propane hand held blow torch seen in Figure 32 was used to ignite the vaporized diesel within the furnace.

Throughout each test, the furnace temperature was monitored and the diesel flow was adjusted accordingly in order to ensure that the furnace temperatures remained within the target range.

The testing procedure for each test was as follows:

- Ensure furnace is clean and free of any liquid or gases
- Ensure that two large buckets of water are available close by as a safety measure
- Place burner in correct position and insert temperature probe
- Initiate data logger
- Adjust tap at diesel outlet
- Ignite the propane burner used to ignite the vaporized diesel
- Initiate test by connecting the fuel pump to the 12 volt battery and turning on the air blower simultaneously
- Ignite the vaporized diesel inside the furnace
- Monitor the furnace temperatures with respect to time and adjust the diesel outlet tap accordingly
- After 20 minutes of burning time, disconnect the fuel pump and deactivate the blower causing the flame to die out immediately
- Allow the furnace to cool down and rinse thoroughly with water to ensure the vapour content within the furnace has diminished

7.2.3. Test results and discussion

7.2.3.1. Results and discussion

Preliminary tests showed that furnace temperatures after 20 minutes of testing time remained precisely constant for this particular testing setup; it is for this reason that tests were conducted for 20 minute periods.

After each test, the data was extracted from the data logger and the results were recorded and plotted. These results were assessed and shortfalls were noted in order to improve on results in subsequent tests.

The results are compared to the SANS 10177 standard time - temperature curve as well as the tolerances for furnace temperatures in order to assess the validity of this particular testing method. Eight successful tests were conducted with precisely the same testing method mentioned above. Tests 1 to 8 are plotted in Figure 33.

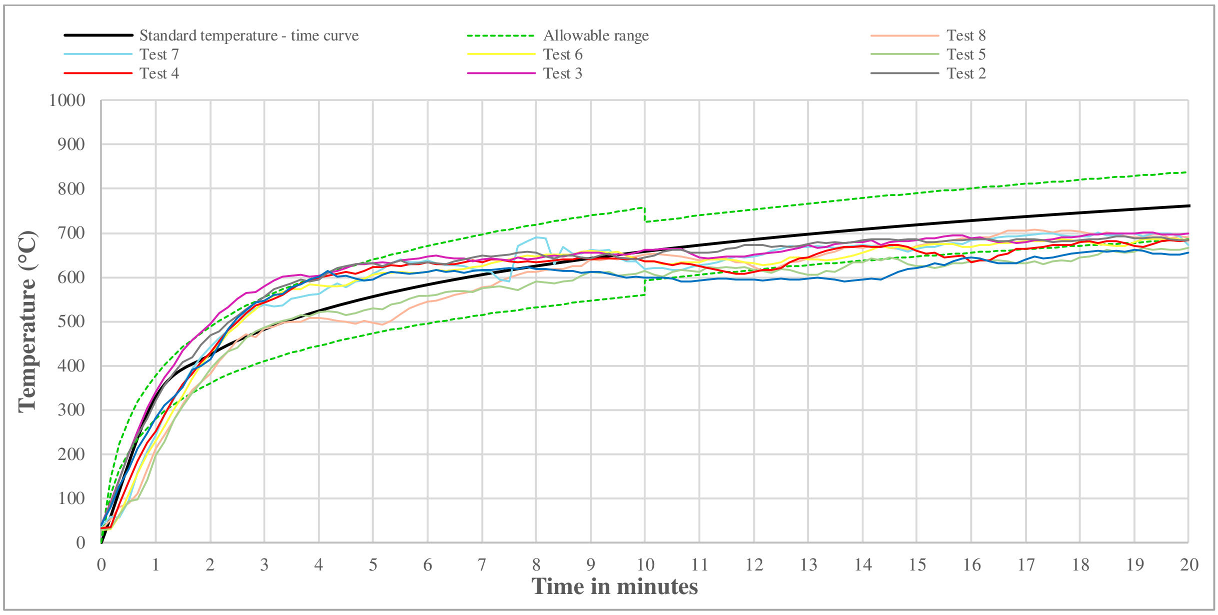

Figure 33: Comparison of 8 fire test time – temperature curves with the SANS 10177 standard time - temperature curve

Figure 33 shows that the 8 test results follow the same trend. Each test produced consistent results with the use of the diesel burner due to the sensitive diesel outlet tap allowing the burner to be adjusted accurately.

In order to assess if the method of test used was adequate to conduct a fire test according to the requirements of SANS 10177, the test data was compared to the standard time - temperature curve of SANS 10177. In order to compare the relationships between the test data and the standard time - temperature curve, the correlation between the two data sets (variables) was determined. To determine the correlation between the two variables, the following sample correlation coefficient estimator was used (Montgomery & Runger, 2011):

$$R = \frac{\sum_{i=1}^{n} Y_i (X_i - \bar{X})}{\sqrt{\sum_{i=1}^{n} (X_i - \bar{X})^2 \sum_{i=1}^{n} (Y_i - \bar{Y})^2}}$$

Where:

- X = SANS 10177 Standard time - temperature data set for 20 minute period
- Y = 20 minute test result data set
- n = Total number of data points in data set

The correlation coefficients for each test were found to be the following:

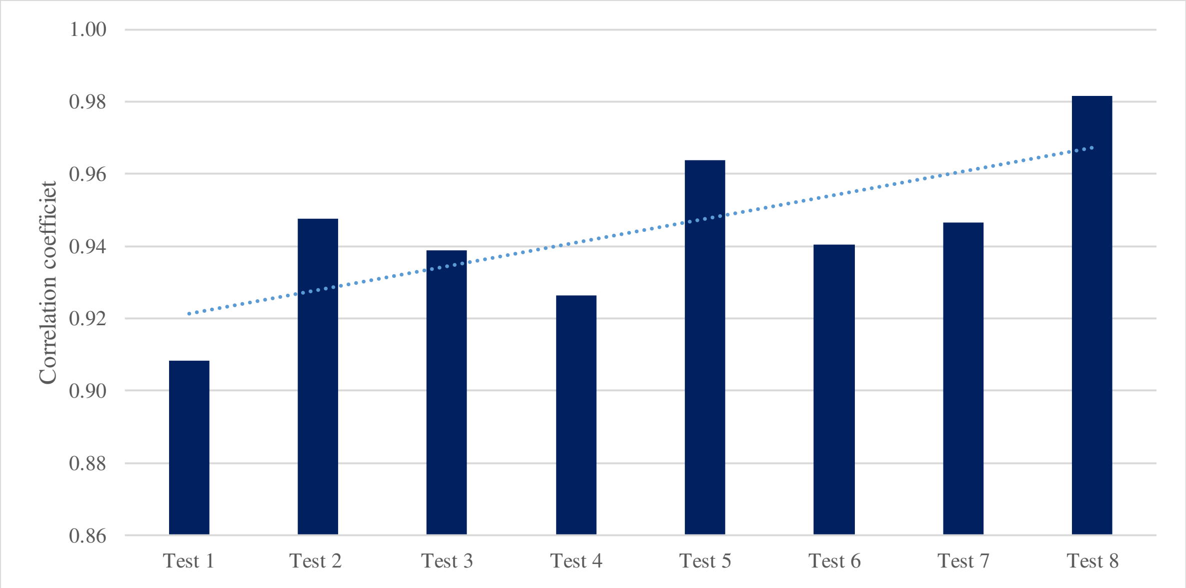

Figure 34: Correlation coefficient for each test data set in comparison with the SANS 10177 standard time - temperature curve

The final test (Test 8) has the strongest positive linear correlation with the SANS 10177 curve and the first test has the weakest positive linear correlation. Fire testing with the use of a diesel burner is a procedure that improves with experience of the operator. Shortfalls can be noted from previous tests and improved upon.

It was therefore observed that the results correlated closer with the SANS requirements as more tests were conducted. If tests were to continue it can be expected that the results would correlate better than those seen from the first 8 tests.

SANS 10177 requires that the tolerances depicted by the dashed lines in Figure 33 are not exceeded at all during a fire test. In all 8 of the tests conducted, the tolerances were exceeded at some points.

The approximate percentage of time for which the furnace temperature was out of the allowable range for each test was as follows:

Table 5: Time spent out of the allowable temperature range as a percentage of total test time

Test number	Percentage of total test time (Full 20 minute data set)	Percentage of total test time (First 1.5 minutes excluded)
Test 1	53.3	48.3
Test 2	10	7.5
Test 3	15.8	13.3
Test 4	20.8	15.0
Test 5	45.8	38.3
Test 6	9.2	2.5
Test 7	6.7	0.8
Test 8	9.2	1.7

Improvement as operator gains experience

Common to all 8 tests is a period of approximately 1.5 minutes during the start of the test that the furnace temperature is below the allowable range. The results from Test 8 show the strongest correlation with the standard requirements; and the furnace temperatures were out of range for 9.2 percent of the total test time. For emphasis, the results for Test 8 are isolated in Figure 35:

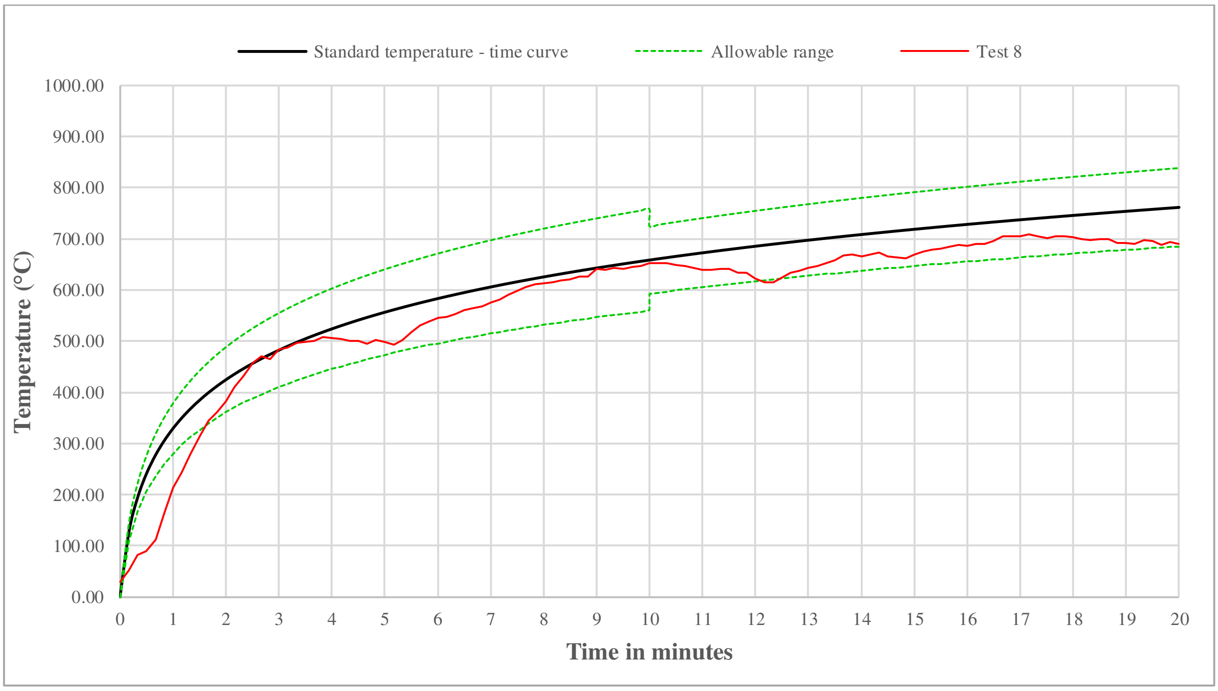

Figure 35: Test 8 results

After approximately the first 1.5 minutes the furnace temperatures begin to enter the required temperature range and remain mostly within the limits for the remainder of the test. After 15 minutes the furnace temperature is seen to stabilize and remain constant at a temperature between 650 and 700 degrees Celsius.

The furnace temperature never exceeded the temperature reached at 20 minutes. This indicates that if a longer fire test were to be required with the use of the presented diesel burner, a secondary and even a tertiary burner would be required that would be activated at the 10 minute mark. This would allow the furnace temperatures to continue increasing at the SANS 10177 standard time - temperature rate.
In order to construct a full size testing furnace, the size of the diesel burner would need to be scaled. Alternatively, more burners would be required.

7.2.3.2. Comparison with Firelab fire test curve

Figure 36 shows a 20 minute extract of the results of a fire test conducted by Firelab on a fire door, recorded by multiple thermocouples set up inside a vertical furnace. Results from Test 8 are superimposed for comparison.

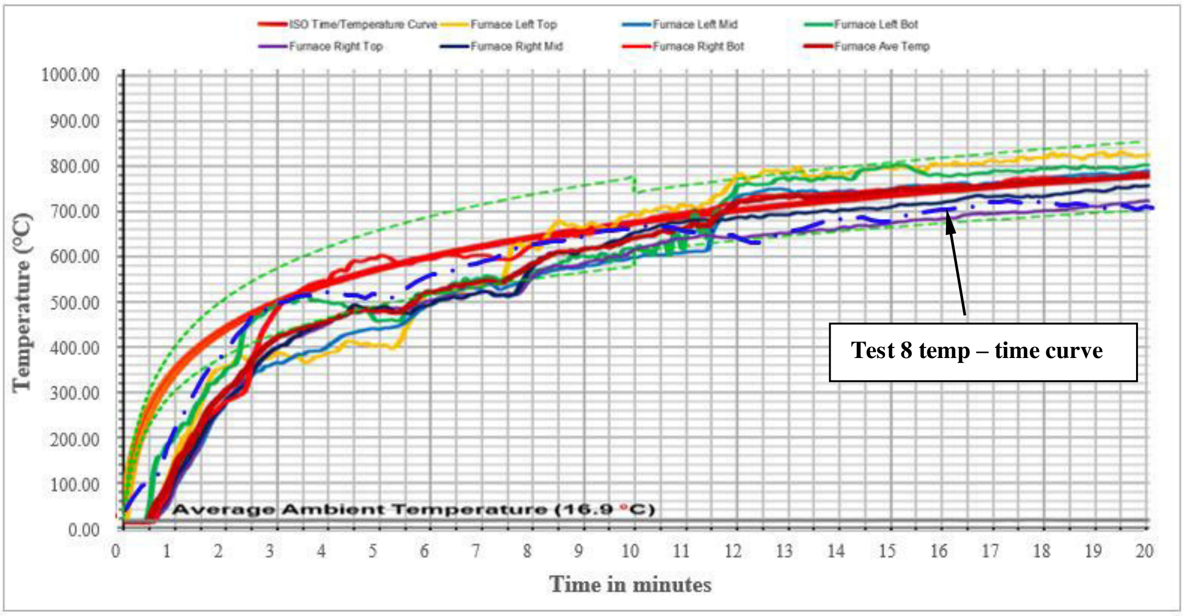

Figure 36: Comparison of Firelab fire curve with that of Test 8

The results from the Firelab test are seen to fall outside of the allowable range for the first 5 minutes. However, the furnace temperature then begins to stabilize and meet the requirements of the SANS temperature tolerances. The furnace temperatures within the Firelab furnace do not begin to level out after 10 minutes as was seen in Tests 1 to 8. This is due to the fact that the vertical furnace within which this particular test was conducted contains a total of 16 burners.

The burners are activated at different times during each test to provide the required heat necessary to achieve the required temperature for the full test.

Both the Firelab test and Test 8 were conducted with the use of forced air and a diesel burner and thus the results from Test 8 are seen to follow a very similar pattern as those from the Firelab test.

7.2.3.3. Correlation with the ASTM E119 fire curve

Figure 37 shows the ASTM E119 Standard time - temperature curve from 0 to 20 minutes. The results from Test 8 are compared with the data from the ASTM standard. The standard requires that the total area under the test time - temperature curve for a test of one hour or less is within 10 percent of the total area under the standard time - temperature curve for the same period.

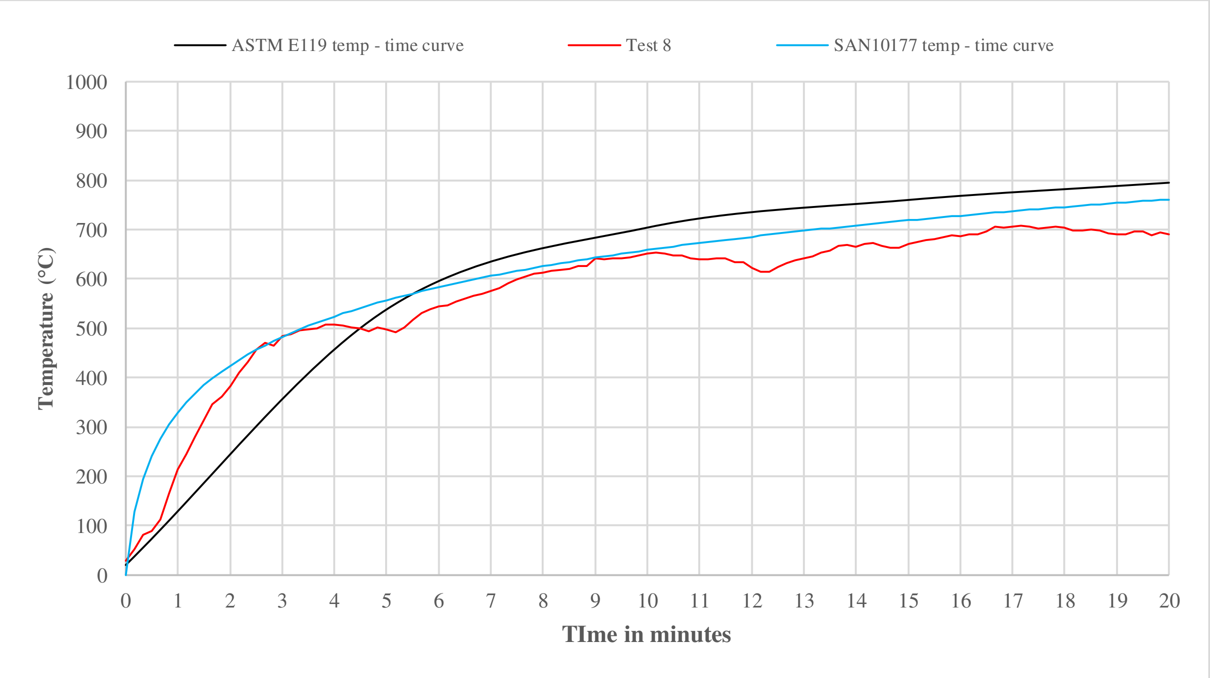

Figure 37: Test 8 results in comparison with the ASTM E119 Standard time - temperature curve

The most notable difference between the ASTM E119 and SANS 10177 time - temperature curves is the gradient of the curve in the first 5 minutes. The gradient of the SANS curve between 0 and 1.5 minutes is 1.8 times that of the gradient of the ASTM curve between 0 and 1.5 minutes.

The linear correlation between Test 8 results and the ASTM E119 curve is 0.976 whereas the correlation with the SANS 10177 curve is 0.982.

In order to assess if Test 8 results comply with the temperature tolerance requirements of ASTM E119, the areas under the ASTM standard time - temperature curve and Test 8 curve were determined. Table 6 shows a comparison of the area under the two curves:

Table 6: Area under time - temperature curve comparison

Temperature – time curve	Area under curve (°C – min)	Difference (%)
ASTM E119	12047.5	4.5
Test 8	11500.9	

Overall, the difference between the area under Test 8, and the standard time – temperature curve is 4.5 %. This is below the required difference of 10 percent, implying that the furnace temperatures recorded during Test 8 are within an acceptable range for ASTM E119 standards.

8. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDIES

8.1. SUMMARY OF FINDINGS

The objectives of this study were to obtain a fundamental understanding of the various methods used in order to conduct a fire test, understand the necessary requirements of various structural elements in order to comply with the requirements of stability, integrity and insulation in a fire, develop a method of conducting a fire test by experimenting with different burning apparatus and to conduct multiple tests in order to determine the repeatability of the fire testing method decided upon.

This was done by conducting multiple preliminary experiments in order to decide on a method that can be used repeatedly to conduct fire tests that comply with the requirements of SANS. Final tests were then conducted with the use of an innovative burner that functioned to atomize liquid diesel enabling a steady and controllable fire to be created within the testing furnace.

Preliminary tests performed highlighted certain shortfalls of the standard time - temperature curves seen in multiple international standards. It was found that the furnace temperatures required by these standards were not realistic and do not represent the temperatures observed in a natural fire. The maximum furnace temperature that could be achieved in the natural fire tests was 762 °C. The maximum temperatures required by SANS 10177 for 30 minute, 60 minute and 120 minute fire tests are 822 °C, 925 °C and 1030 °C respectively. It was therefore concluded that it would only be possible to achieve such high temperatures with the use of flammable liquids as the fuel type.

Preliminary tests with the use of two flammable liquids (petroleum and diesel) were then conducted. A maximum furnace temperature of 689 °C was achieved during the petrol test. Petrol proved to be too volatile to be used in fire tests and no additional tests were conducted with this fuel.
A maximum furnace temperature of 727 °C was achieved during the preliminary diesel test and the lower self-ignition temperature of diesel, in comparison with petrol, produced a far more rapid increase in furnace temperature in the first few minutes of the test. The flame produced by the diesel could be controlled and it was therefore used as the fuel type for all subsequent tests.

Final tests were then conducted with the use of a diesel burner. The diesel burner vaporized the liquid diesel using a sealed chamber and rapidly flowing forced air. An average correlation of 0.944 was achieved with respect to SANS 10177 data for the eight diesel blower tests conducted. It became clear that results improved significantly with experience and data correlated closer to the SANS requirements in the latter tests. Test 8 temperatures fell within the allowable tolerances for 91 percent of the time and were within the allowable range with respect to ASTM E119 requirements.

The diesel burner used in the final tests is therefore a suitable burner to be used when conducting fire tests according to SANS 10177, BS 476, and ASTM E119. A high level of repeatability was achieved throughout all 8 tests as all results followed the same trend within a narrow band.

The size of the furnace used in this study does not meet the minimum dimensional requirements of any of the standards mentioned here. In order to conduct fire tests according to an international standard such as SANS 10177, a full sized furnace will need to be constructed. Multiple burners will be required that can be controlled when necessary in order to maintain furnace temperatures within the allowable ranges.

8.2. FURTHER RESEARCH TO BE PERFORMED

Future research on the topic of fire testing of structural elements can be conducted on the following:

- The results that are obtained by conducting a standard fire test on a structural element do not necessarily represent the performance of the element in a real fire situation. The expression of fire resistance of an element is simply a measure of its relative performance in comparison with other specimens. Further research can be conducted on the feasibility of conducting fire tests in such a way that allow an element to be subjected to specific conditions that will resemble those of what it may encounter in its intended environment. By conducting fire tests in this manner, the relative performance of the element will no longer be assessed but it will allow one to make safe assumptions about the possible performance of the element in a real fire.
- The natural fire curve as presented in Eurocode 1 is one method of conducting a fire test specific to a particular compartment; however the natural / compartment fire model from Eurocode 1 (Figure 13) does not accurately resemble a typical natural compartment fire curve such as the one in Figure 5. Further research could be conducted into alternative methods of obtaining realistic fire curves that can be followed during a fire test.

- The furnace used for testing did not meet the minimum dimensional requirements according to any international standard. Conducting similar tests with the use of a full sized furnace could provide further insight into the practicality of the standard time - temperature curve. Appendix B shows a proposed horizontal furnace design based on the furnace requirements gathered from literature. This furnace may be built and tested for the purpose of conducting future research. It may be used for the testing of a wide range of elements such as beams, roofs and roof assemblies, and different types of horizontal room dividing elements.
- The tests conducted during this study did not look at the behaviour of any particular building elements. Future research may be conducted on the fire resistance capabilities of non - standard elements such as composite elements.
- The furnace used in this study was made of metal which is inherently a good conductor and therefore a poor insulator. Future tests can be conducted using a furnace constructed using materials with better insulating capabilities in order to achieve a higher furnace temperature.
- All tests were conducted on the roof of a three storey building. Although the interlocking earth brick wall was constructed as a wind barrier, it is probable that some of the furnace heat was lost due to wind passing over the top of the furnace. Future research can be conducted on ground level or indoors in order to prevent this heat loss.
- Fire testing according to the methods seen in international standards is limited in that the tests are conducted on single isolated elements. In reality, the elements form part of a structure and the boundary conditions can have a large influence on the behaviour of the element in a fire. Further research can be conducted into fire testing of scaled down replicas of structures using the same materials and support conditions in order to test how the particular element will behave when part of a larger structure.

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APPENDIX A

NATURAL / PARAMETRIC COMPARTMENT FIRE MODEL CALCULATIONS

A. Eurocode 1: Part 1-2 (2002) - Natural / Parametric compartment

fire model calculations

A natural / parametric compartment time - temperature curve can be used as the heating curve in a fire test as an alternative to the standard time - temperature curve. Eurocode 1: Part 1-2 (2002) contains formulas that can be used to determine a time - temperature curve for the heating and cooling phase of a natural compartment fire based on physical parameters specific to the compartment. In order to demonstrate the Eurocode 1 natural / parametric compartment fire model, an arbitrary compartment size was selected with dimensions as seen in Figure 38. A single opening resembling a door was assumed on the front face. All dimensions are given in metres.

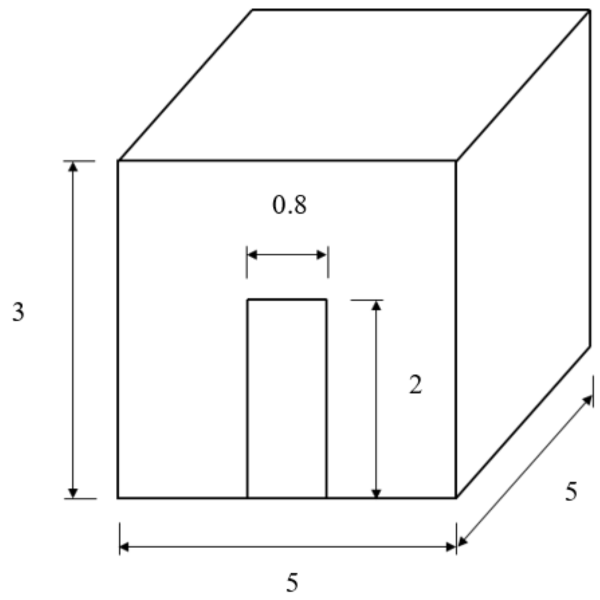


Figure 38: Arbitrary compartment size selected to determine Eurocode natural time - temperature curve

A summary of the calculations used to determine the time - temperature curves in both the heating and cooling phases is presented below.

(a) Heating Phase

The temperature curve during the heating phase is given by (Eurocode 1, 2002):

$$\theta_g = 20 + 1325\left(1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*}\right) \qquad \text{(A. 1)}$$

Where:

- θ_g = gas temperature in the fire compartment
- t^* = $t \cdot \Gamma$
- t = Time in seconds at any given point during fire test
- Γ = $[O / b]^2 / (0.04 / 1160)^2$
    - O = Opening factor = $A_v\sqrt{h_{eq}} / A_t$
        - A_v = Vertical opening area
        - h_{eq} = Weighted average of window heights on all walls / height of window if enclosure only has one
        - A_t = Total area of enclosure
    - b = $\sqrt{\rho c \lambda}$
        - ρ is the density of the boundary enclosure
        - c is the specific heat of the boundary enclosure
        - λ is the thermal conductivity of the boundary enclosure

The maximum temperature (θ_{max}) in the heating phase occurs at $t^* = t^*_{max}$, where

- $t^*_{max} = t_{max} \cdot \Gamma$, and
- $t_{max} = \max [(0.2 \cdot 10^{-3} \cdot q_{t,d} / O) ; t_{lim}]$, where,
    - $q_{t,d}$ is the design value of the fire load density related to the total surface area (A_t) of the enclosure
    - $q_{t,d}$ = $q_{f,d} \cdot A_f / A_t$
    - $q_{f,d}$ is the design value of the fire load density related to the surface area (A_f) of the floor
    - t_{lim} = 25 minutes in case of slow fire growth rate; 20 minutes in case of medium fire growth rate and 15 minutes in case of fast fire growth rate

Calculations

- A_v = 1.6 m^2
- h_{eq} = 2 m
- A_t = 110 m^2

- ρ = 2300 kg/m^3
- c = 1230 J/kgK
- λ = 1.3 W/mK

(ρ and c: Values for heavy concrete)

- b = 1917.7
- Γ = 0.0915

The time - temperature curve in the heating phase can now be found with the use of equation A.1 and the above values.

(b) Cooling Phase

The time - temperature curves in the cooling phase are given by (Eurocode 1, 2002):

$$\theta_g = \theta_{max} - 625(t^* - t^*_{max} \cdot x) \quad \text{for} \quad t^*_{max} \leq 0.5$$

$$\theta_g = \theta_{max} - 250(3 - t^*_{max})(t^* - t^*_{max} \cdot x) \quad \text{for} \quad 0.5 < t^*_{max} < 2$$

$$\theta_g = \theta_{max} - 250(t^* - t^*_{max} \cdot x) \quad \text{for} \quad t^*_{max} \geq 2$$

Where:

- X = 1.0 if $t_{max} > t_{lim}$ or,
- X = $t_{lim} \cdot \Gamma / t^*_{max}$

(c) Time - Temperature Curve Comparison

A comparison of the Eurocode natural fire curve with the SANS 10177, BS 476 and ASTM E119 standard time - temperature curves can be seen in Figure 39.

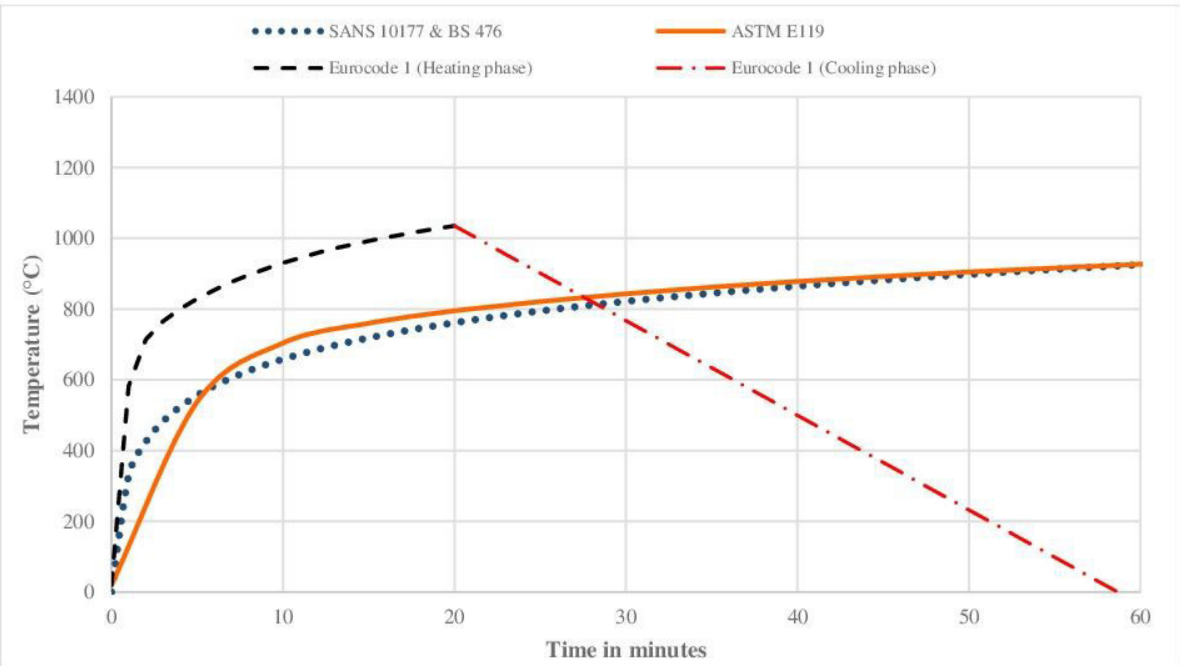


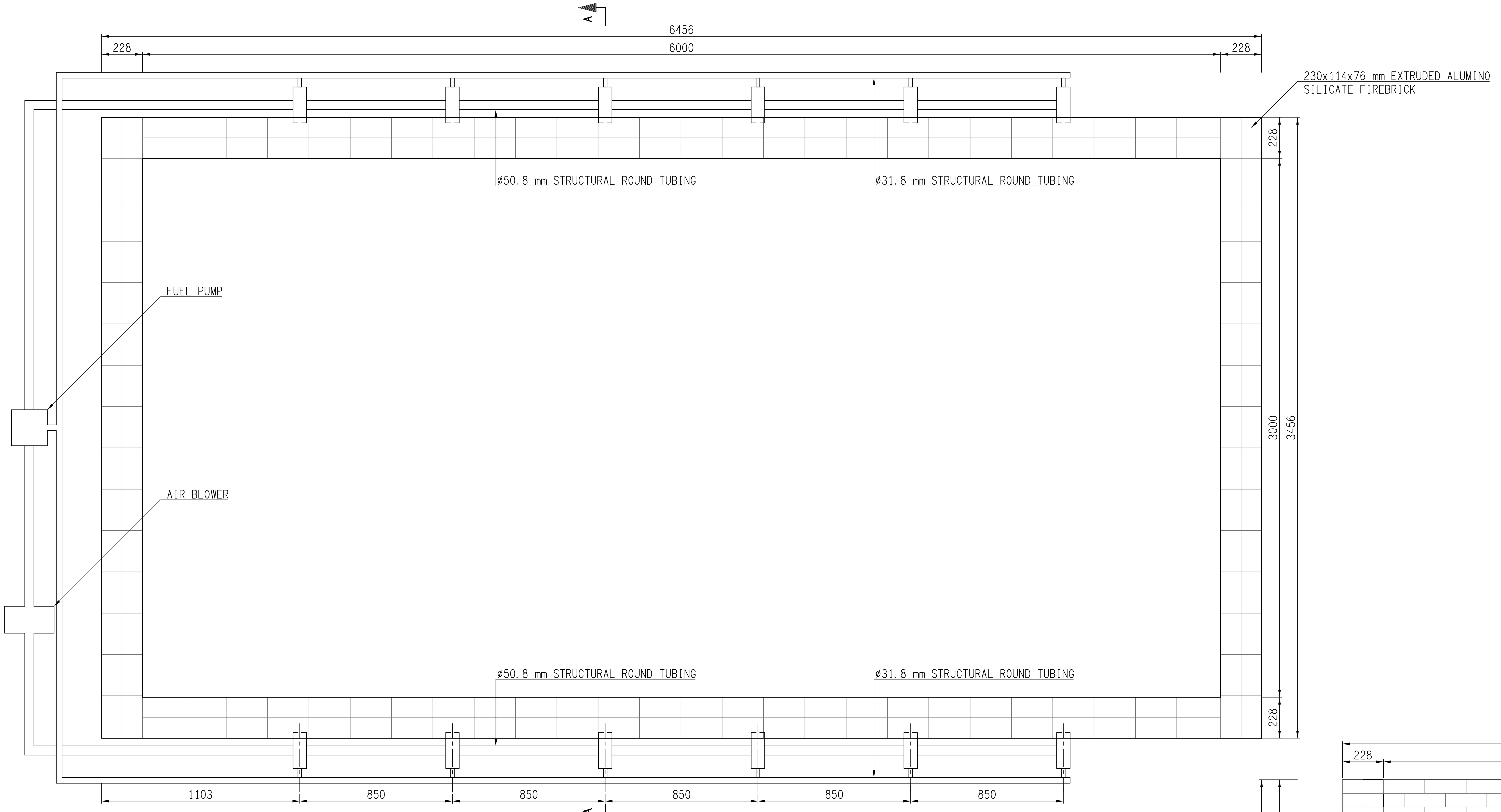
Figure 39: Comparison of Eurocode 1 natural fire curve with various standard time - temperature curves

APPENDIX B

PROPOSED HORIZONTAL FIRE TESTING FURNACE

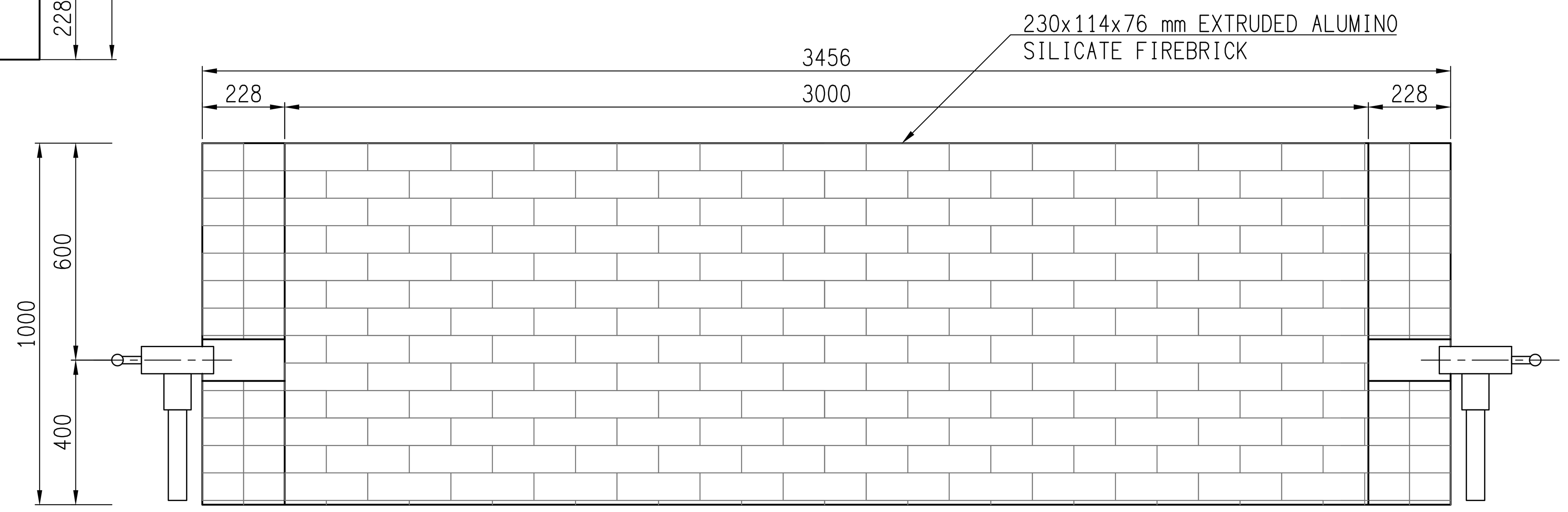
NOTES:

1. BRICK TO BE USED IN CONSTRUCTION : 230x114x76 mm EXTRUDED ALUMINO SILICATE FIREBRICK
2. VENTILATION HOLES MUST BE PROVIDED IN THE SIDES OF THE FURNACE. THE TOTAL AREA OF OPENINGS MUST NOT EXCEED 33% OF THE FLOOR AREA
3. ADDITIONAL AREA BETWEEN THE SPECIMEN AND FURNACE APERTURE MUST BE FILLED PRIOR TO TESTING



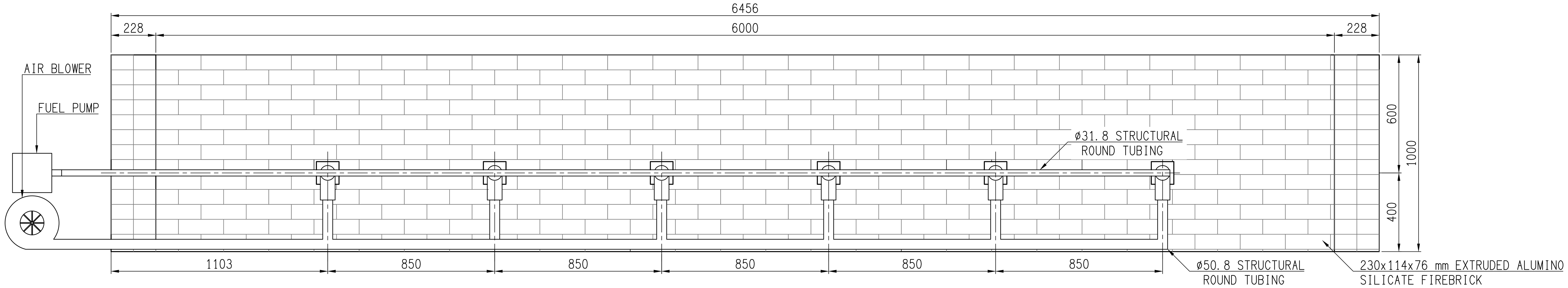
PLAN VIEW: HORIZONTAL FURNACE

SCALE 1:10



SECTION A–A: HORIZONTAL FURNACE

SCALE 1:10



ELEVATION: HORIZONTAL FURNACE

SCALE 1:10

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UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG	UNIVERSITY OF THE WITWATERSRAND SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING	FIRE TESTING METHODS OF BUILDING ELEMENTS	HORIZONTAL FURNACE	CRAIG BLACK STUDENT NUMBER: 608884