# Comparative analysis of fire test standards applicable to building materials

By

Marisse Anchen Whitehead

Pectora roborant cultus recti

Thesis presented in partial fulfilment of the requirements for the degree of Master of Engineering in Civil Engineering in the Faculty of Engineering at Stellenbosch University

Supervisor: Prof. Richard S. Walls

Co-supervisor: Mr Dirk Streicher

April 2022

# Declaration

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or part submitted it for obtaining any qualification.

April 2022

# Abstract

Research in fire behaviour started centuries ago following large-scale urban fires. The focus moved to establish material and construction rules during the past 150 years of fire engineering development. These rules eventually turned into standards and design codes of practice, and globally a plethora of standards and codes with the same objectives are now available. Unfortunately, although current standards and codes might have the same objectives, differences in test methodologies significantly influence the results and the results' applicability.

This thesis aims to provide a detailed comparison of fire testing standards to provide a safe testing environment for South Africa and other developing world countries. Available codes are reviewed and compared to provide a list of test standards used where material safety in a building is of concern. Reaction-to-fire and fire resistance tests are specifically compared and contrasted. Aspects such as the nature of samples tested, sample orientation, heat sources and properties measured are considered. It is shown that to obtain a fire-safe building, a variety of material properties must be controlled, such as heat release rates, smoke emissions, structural resistance, flame spread rate, calorific values and critical heat flux. A single test cannot address all these properties, and hence a suite of test standards is required.

Ultimately, the author’s opinion is that adopting the Eurocode classification and associated test standards would be beneficial and pragmatic based on the analysis conducted below. However, from a scientific and engineering perspective, there are still shortcomings in the Eurocode guidelines, which are discussed, and recommendations for addressing these are provided. Recommendations include adopting the Cone Calorimeter instead of current identified European tests. It is shown that the South African suite of standards should be thoroughly revised, and there are severe limitations to the current suite of standards.

# Uittreksel

Navorsing oor brandgedrag het eeue gelede reeds weens grootskaalse stedelike brande ontstaan. In die afgelope 150 jaar het die fokus geskuif na die vasstel van materiaal- en konstruksiereëls in die ingenieursontwikkeling van brande. Dié reëls het mettertyd standaarde en ontwerpkodes in die praktyk geword. Daar is tans wêreldwyd 'n menigte standaarde en kodes met dieselfde doel beskikbaar. Hoewel dié huidige standaarde en kodes dieselfde doel dien, het die verskille in toetsmetodologieë 'n beduidende invloed op die resultate en gevolglik ook die toepassing daarvan.

Hierdie tesis het ten doel om 'n gedetailleerde vergelyking tussen brandtoetsstandaarde daar te stel sodat 'n veilige toetsomgewing vir Suid-Afrika en ander ontwikkelende lande verskaf kan word.Beskikbare kodes word bestudeer en met mekaar vergelyk om 'n lys van toetsstandaarde te verskaf wat gebruik is in geboue waar die veiligheid van materiale van belang is. Reaksie-op-brand en brandweerstandtoetse word spesifiek vergelyk en teenoor mekaar gestel. Aspekte soos die aard van getoetste monsters, monster-oriëntasie, hittebronne en getoetste eienskappe is in berekening gebring. Dit toon dat 'n verskeidenheid materiaal-eienskappe beheer moet word om te verseker dat 'n gebou brandveilig is, onder meer die koers van hittevrylating, rook-uitlatings, strukturele weerstand, die koers van vlamverspreiding, kaloriese waardes en kritieke hittevloei. 'n Enkele toets is nie voldoende vir al die eienskappe nie; 'n reeks toetskodes is nodig.

Die skrywer is gevolglik van mening dat, gegrond op die analises hieronder, die Eurokode-klassifikasie en geassosieerde toetsstandaarde die voordeligste en mees pragmatiese sal wees. Uit 'n wetenskaplike en ingenieursperspektief is daar egter steeds tekortkominge in die Eurokode-riglyne. Dié aspekte word hier bespreek en aanbevelings word gemaak om die probleme te ondervang. Van die aanbevelings sluit in die gebruik van die 'cone calorimeter' pleks van sommige Europese toetse. Dit toon dat die huidige kodereeks ernstige beperkings het en die Suid-Afrikaanse reeks van standaarde deeglik hersien moet word.

# Acknowledgements

I would like to express my sincere gratitude to the following people and organisations:

- My supervisor, Dr Richard Walls, for introducing me to the interesting field of structural fire engineering and his guidance throughout this project's execution. Truly the best supervisor one could ask for.
- My co-supervisor, Mr Dirk Streicher, for his suggestion of this topic and his undivining assistance and employment offering. I hope together we can make a positive impact in the fire testing industry going forward.
- My fellow students in the structures department at Stellenbosch University, for their friendliness and support around the office.
- To my second family in Stellenbosch, the Sondays. Thank you for every laugh, every smile and every meal you never hesitated to offer.
- Finally, to my parents for their unending support in every aspect of my life and financial support throughout my years at university. With dad working $\pm 35$ years in the fire industry, my passion for fire started young, and I hope to continue with the legacy in the industry and make you both proud.


“But seek first the kingdom of God and His righteousness, and all these things shall be added to you. Therefore, do not worry about tomorrow, for tomorrow will worry about its own things.”

- Matthew 6:33-34

# Table of Contents

# List of Figures

# List of Tables

# Nomenclature

### Latin variables

| | |
|---|---|
| $A_f$ | Floor area |
| $c_p$ | Specific heat |
| $C$ | Orifice plate coefficient |
| $d$ | Distance |
| $dT$ | Temperature difference over a distance |
| $dx$ | Change in the distance in the direction of heat flow |
| $D$ | Extinction coefficient in smoke measuring system |
| $e_f$ | Fire load density |
| $E$ | Energy |
| $F$ | Surface Fire Index |
| $F_s$ | Flame spread |
| $h_c$ | Convection heat transfer coefficient |
| $i_{1/2/3}$ | Fire Propagation Index at different times |
| $I$ | The overall index of performance |
| $I_f$ | Flame spread of the surface |
| $I_h$ | Overall heat contributed |
| $I_s$ | Smoke density |
| $k$ | Thermal conductivity |
| $k\rho c_p$ | Thermal inertia |
| $L$ | Span of specimen |
| $\dot{m}$ | Mass flow rate |
| $m_w$ | Moisture content |
| $M$ | Mass |
| $r_o$ | Stoichiometric oxygen/fuel mass ratio |
| $t$ | Time in minutes |
| $T$ | Temperature |
| $T_c$ | Temperature rise recorded for the non-combustible standard at time $t$ |
| $T_e$ | Absolute temperature of the emitting surface |
| $T_e$ | Gas temperature at the orifice plate |

| | |
|---|---|
| $T_g$ | Gas temperature |
| $T_m$ | Temperature rise recorded for the material at time $t$ |
| $T_r$ | Absolute temperature of the receiving surface |
| $T_s$ | Surface temperature |
| $\dot{q}$ | Heat release rate |
| $\dot{q}''$ | Heat flux per unit area |
| $\dot{Q}$ | Average heat release rate |
| $xp$ | Flame distance |
| $X_{O_2}$ | Measured mole fraction of $O_2$ in the exhaust air |
| $y_s$ | Smoke yield |
| $Y_H$ | Mass fraction of hydrogen in the fuel |
| $Y_W$ | Moisture content of the fuel |

**Greek variables**

| | |
|---|---|
| $\Delta h_v$ | Latent heat of vaporization of water @ $25℃$ |
| $\Delta H$ or $\Delta h$ | Calorific value (heat of combustion) |
| $\Delta P$ | Change in pressure |
| $\Delta T$ | Change in temperature |
| $\varepsilon$ | Emissivity factor |
| $\rho$ | Density |
| $\delta f$ | Flame length |
| $\sigma$ | Stefan-Boltzmann constant |
| $\varphi$ | Configuration factor |
| $\infty$ | Ambient conditions |

**Acronyms**

| | |
|---|---|
| A.D. | Anno Domini |
| ASTM | American Society for Testing and Materials |
| B.C. | Before Christ |
| BS | British Standard |
| CE | Conformitè Europëenne |
| CEN | European Committee for Standardisation |

| | |
|---|---|
| CFE | Critical flux at extinguishment |
| CHF | Critical Heat Flux |
| CPD | Commission Products Directive |
| CPR | Construction Product Regulation |
| DIAP | Direct field of application |
| EC | European Commission |
| EHC | Effective heat of combustion |
| EN | European Norm (European Standard) |
| EU | European Union |
| EXAP | Extended field of application |
| FIGRA | Fire Growth Rate |
| FM | Federal Mutual (FM Global standards) |
| FPI | Fire Propagation Index |
| FPA | Fire Propagation Apparatus |
| H-TRIS | Heat-Transfer Rate Inducing System |
| HRR | Heat Release Rate |
| ICC | International Code Council |
| ISO | International Standards Organisation |
| LFS | Lateral Flame Spread |
| LIFT | Lateral Ignition and Flame Transport |
| LOI | Limiting Oxygen index |
| NFPA | National Fire Protection Association |
| NIST | National Institute of Standards and Technology |
| NBR | National Building Regulation |
| PBD | Performance-Based Design |
| SA | South Africa |
| SABS | South African Bureau of Standards |
| SANS | South African National Standards |
| SBI | Single Burning Item |
| SFPE | Society for Fire Protection Engineers |
| SMORGA | Smoke growth rate |
| SPR | Smoke production rate |
| THR | Total Heat Released |

| | |
|---|---|
| THP | Total Heat Production |
| TRP | Thermal response parameter |
| TSP | Total smoke production |
| UL | Underwriters Laboratories |

**Abbreviations**

| | |
|---|---|
| Cal | Calorific Value |
| E | Integrity resistance |
| EI | Integrity and insulation resistance |
| EW | Integrity and radiation reduction |
| FlameSR | Flame spread rate |
| I | Insulation resistance |
| IgTemp | Ignition temperature |
| R | Structural (stability) resistance |
| Smoke | Smoke production rate |
| Toxicity | Toxicity of smoke |
| W | Radiation reduction |

**Subscripts**

| | |
|---|---|
| $0$ | Ambient conditions |
| $0_2$ | Oxygen |
| $600s$ | In 600 seconds |
| $av$ | Average |
| $c$ | Convective |
| $eff$ | Effective |
| $ext$ | Applied |
| $h$ | Hours |
| $ig$ | At ignition |
| $chem$ | Chemical |
| $c, gross$ | Gross |
| $c, net$ | Net |
| $p$ | Peak |
| $sb$ | Sustained burning |
| $t$ | Total |

# Glossary

| | |
|---|---|
| Code | An example, a model or a set of rules that knowledgeable people advise others to follow. The guideline is not law but could be incorporated into law |
| Fire Parameters | Measured test properties quantify them. Examples are flame spread and fire resistance |
| Material Test Properties | These properties can be directly measured from tests performed. They are relevant to the sample material and the resultant effects of their combustion. Examples are critical heat flux and heat release rate |
| Standard | A more detailed elaboration, covering what it takes to comply with codes |

# 1 Introduction

## 1.1 Background

Fire has been studied for thousands of years, but the development of technically sound fire tests for the protection of buildings for the first time appears to have taken place only in the past 300 years. A primitive understanding of fire dynamics coupled with increasingly sophisticated mathematics laid the foundation for the revolution leading to fire tests (Lawson, 2009). Also, numerous large fires destroying vast portions of major cities such as The New York City and San Francisco fires triggered the development of fire test methods and were further specified by law (Bankoff *et al.*, 2012).

The earliest building codes known were developed between 1913 B.C. and 1955 B.C. (NFPA, 2021). These early codes stated only the consequences if buildings were not built well and did not follow a set of building procedures. The first consensus fire standard developed was issued in 1917 by the American Society for Testing and Materials (ASTM E119, 1917) for the fire resistance of building construction and assemblies. It specified that the performance of walls, columns, floors, and other building members under fire exposure conditions are items of significant importance in securing that building constructions are safe.

Specific standards were implemented, be it voluntary or compulsory, to form the basis for consumer protection, health, safety, and environmental issues. In all developed countries, standards, codes, and regulations exist that affect and control fire safety. These may be highly prescriptive or performance-based (i.e., they allow for specific performance criteria to be achieved, rather than only specifying specific rules to be followed), or somewhere between this prescriptive versus performance-based spectrum. Most standards demonstrate only a pass or fail criteria, leading to modern codes and standards becoming far more detailed. *Standards* are typically defined as published documents containing technical specifications or other precise criteria used consistently, as a rule, guideline, or definition (SABS, 2021). In this document, it should be noted that reference to a *test method* will be referred to as the fire testing standard that it applies to, and this requires reference to the codes of practice.

According to Hurley & Rosenbaum (2015), fire testing was initially designed to classify a material or assembly's fire resistance, flame spread, or heat release rate. These methods often provide limited information concerning actual fire scenarios. However, the proposed testing methods still provide valuable information that may be used in computer simulations. During the past two decades, standardised testing methods have become more accommodating to the need for data input and facilitated the development of new fire model simulations.

In recent years, the focus has shifted to ensuring that the structural safety of buildings is as high as possible to minimize the risk of death, injury, property loss, and environmental damage (Wang *et al.*,2012). Protecting the structure, fabric, and contents of a building is the first step in protecting property. The fire engineer must ensure that the building materials have been tested according to the appropriate standard; however, a deemed-to-satisfy approach is often taken to apply the regulation to a building in a prescriptive manner.

Over decades, different regulatory and testing agencies have developed a myriad of fire testing standards (e.g., BS, NFPA, ASTM, EN, ISO, SANS, UL). It can be challenging for developing nations, who do not develop their test-own set of standards, to know which codes to adopt or adapt. Many guidelines have overlapping principles or focus on specific aspects (e.g., flame spread) but may classify products differently. Limited studies have been conducted to compare and contrast such standards to identify their scope, applicability, limitations and benefits.

## 1.2 Problem Statement

This thesis aims to provide a detailed comparison of fire testing standards to provide a safe testing environment for South Africa. However, the work will typically apply to other countries. For this to be done, there is a need to understand the fundamental fire properties of building materials and identify how fire tests can quantify these properties. Emphasis is also placed upon developing an analysis procedure regarding fire testing standards. This thesis will focus on a selection of standards specific to fire safety pertaining to a range of construction materials. Testing regimes required to analyse these materials for safety purposes will be developed and evaluated. Available standards will be reviewed and compared to provide a list of test standards used where material safety in a building is of concern. Many nations already have a suite of standards especially relating to fire testing of building materials. However, most of these standards are somehow either full or partial copies of one another. Hopefully, this thesis can assist in reducing the plethora of tests to a core of more manageable standards.

This study aims not to rewrite any South African fire testing standards as it would be impractical and costly. However, it cannot be dismissed that there is a rising concern in the industry regarding fire testing codes and standards concerning their application and overall outcome. This study will hopefully aid in providing valuable knowledge and proven research of the standards and testing methods to provide an appropriate guideline for safer buildings. In-depth investigations will be made on whether some aspects of local tests can be compared to international fire testing standards or not.

## 1.3 Research Objectives

The following research objectives that will be considered for this study are to:

1. Identify the inherent requirements of products in terms of fire safety
2. Obtain insight into the results of the fire tests and how this relates to fire safety by identifying fundamental properties and fire parameters (e.g., heat release rate, energy content, oxygen consumption)
3. Evaluate the application of the fire test results and the various classification systems and processes that exist
4. Compare available international fire testing standards concerning construction materials by providing in-depth knowledge of the standards
5. Compare and contrast fire testing standards, consider the various options available, provide details on which fire test standards can and cannot be used
6. Identify shortcomings in existing South African fire test standards
7. Propose a way forward to develop a comprehensive fire testing regime that focuses on construction materials and products broadly applicable to developing nations such as South Africa.

## 1.4 Scope of Work

This work offers novel insight regarding fire safety requirements of construction materials by comparing current fire testing standards and identifying the fundamental aspect of those most suitable to provide some form of standardised testing. This research thesis provides a fundamental perspective on whether the outcomes of specific testing standards are relevant and valuable. The purpose of testing standards is identified, stating if it contributes towards safer buildings. The work discusses the engineering approach of performance-based design and its influence on testing standards and the relating testing methodologies.

It is impossible to discuss all available fire test standards, and this work focuses on those most commonly utilised. Furthermore, it is acknowledged that numerous factors influence what test procedures are used in countries, including regulatory requirements, historical developments, test costs, level of technical competency, availability of facilities and similar factors. It is impossible to consider all of these factors, and this work focuses primarily on technical fire engineering considerations.

## 1.5 Report Synopsis

To achieve the objectives mentioned in Section 1.3, the structure of this thesis is as follows:

I. Introduction (Chapter 1): A background to fire testing and related concepts are presented. The problem statement, objectives and scope of work are provided
II. Literature review (Chapter 2): A literature review is performed focussing on the fundamentals of fire dynamics and fire parameters, followed by a study into code development and its relationship with performance-based design
III. Application of Fire Testing for the Built Environment (Chapter 3): The focus of this chapter will be placed on identifying the requirements of building fire safety. An introduction to the application of a test result to classification systems internationally and locally is provided. A short discussion of an element design and the two methods linked to it, namely prescriptive and performance-based designs, will be examined.
IV. Methodology to Compare Fire Test Standards (Chapter 4): The specific procedures and analysis followed in this study to distinguish between the specific tests regarding similarities and differences are discussed in the chapter. An outline of the methodology needed to perform a comparative analysis is provided, encapsulating the essential sections that require investigation
V. Fire Test Standards Overview (Chapter 5): This chapter discusses the need for fire tests and describes fire tests in general. Specific fire tests are discussed regarding the two main categories of *reaction-to-fire* tests and *fire resistance* tests. A discussion is provided around the fundamental properties that these fire tests require either as inputs or provide as outputs from their respective results. Various other fire tests are mentioned to provide an overview of the available tests and standards and their correlation with quantifiable parameters. General remarks concerning challenges in fire testing and uncertainty in fire testing are provided. A summary of the different measurable parameters and their corresponding fire tests standards are given
VI. Comparative Analysis of Fire Test Standards (Chapter 6): This chapter relates the comparable fire tests of the SA standards to the international standards. The respective limitations and several recommendations are discussed. The primary focus will be the *reaction-to-fire* and *fire resistance* test standards. A suite of suitable fire testing standards for South Africa are identified
VII. Conclusions and Recommendations (Chapter 7): This final chapter encapsulates the essential findings of this thesis. Future recommendations for fire testing and developments are made

Figure 1-1 describes the structure in detail, emphasising essential aspects.

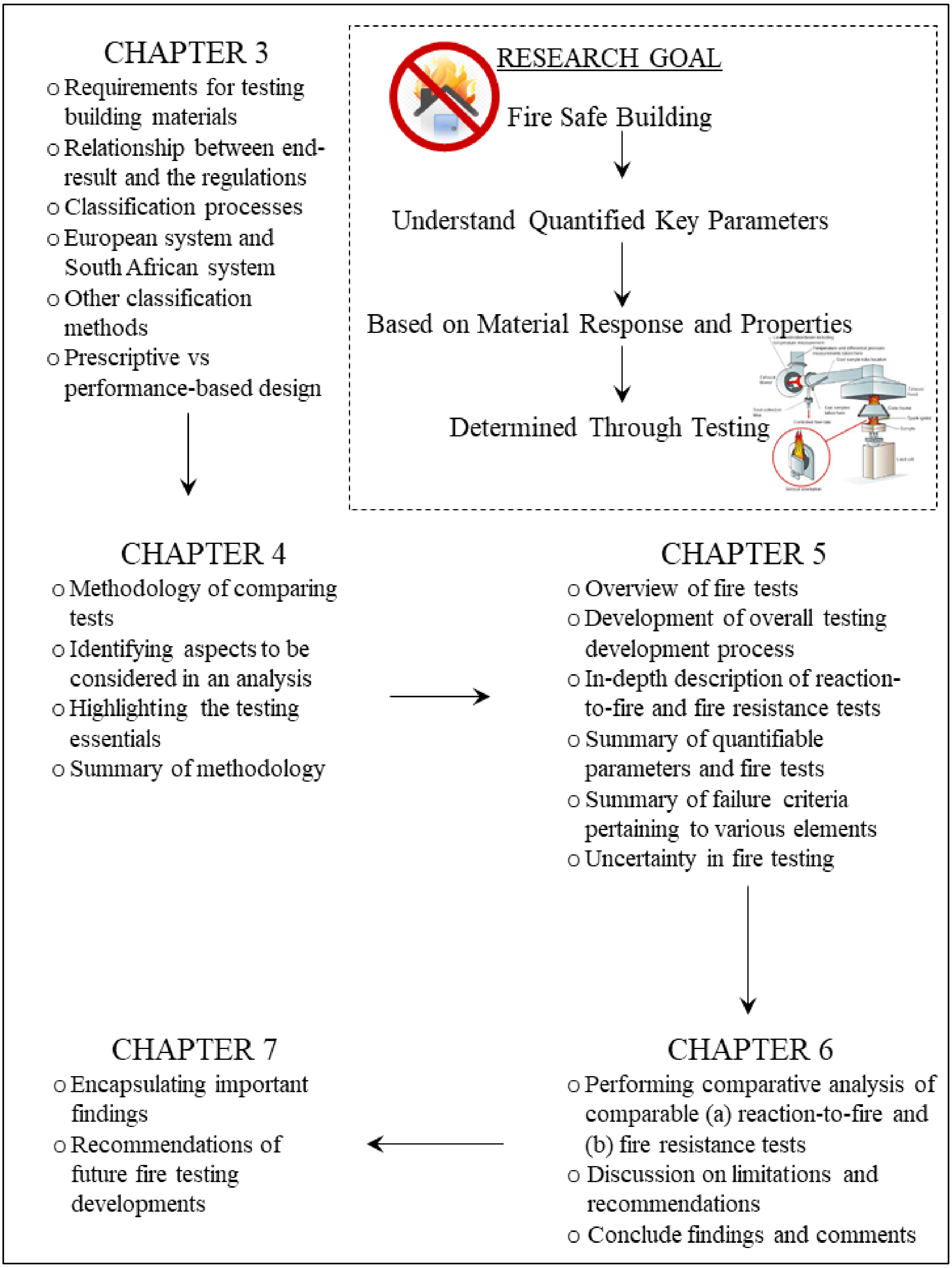



*Figure 1-1: Detailed structure adopted for the thesis*

Figure 1-2 illustrates the topics of discussion of each chapter. Thus, the most critical content of each chapter is provided. This figure can also be seen as the developmental process of performing a fire test. The client will have inherent requirements that should abide by the national building regulations or act. The client will proceed to the designing stage of either a prescriptive or performance-based design. After which, the chosen element will require to be classified. This classification is reached through material properties that quantify specific fire parameters, and these properties are tested for during the chosen fire test. The classification and said requirements would provide the necessary information on which fire test standard should be utilised to provide a result. This outcome can either be accepted or re-assessed, in which case changes can be made towards the design of the element, or the client's requirement should be altered, and the entire process will be repeated.

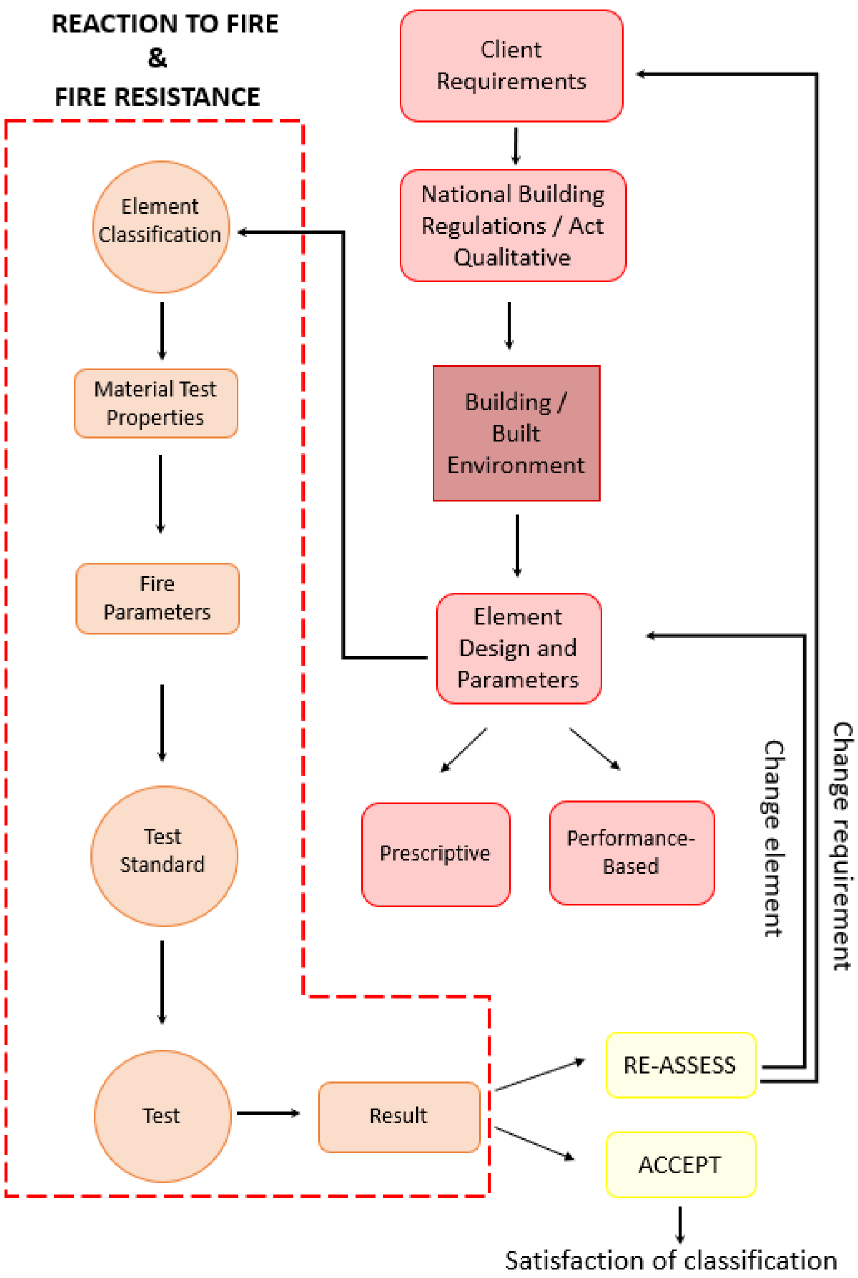



*Figure 1-2: Topics of discussion for each chapter to address overall objectives*

# 2 Literature Review

## 2.1 Introduction

This chapter presents a brief overview of the basic concepts of fire engineering necessary to understand the subsequent chapters. The field of fire dynamics is extensive, consisting of various speciality fields, some of which have been appropriately discussed in works such as Drysdale (2011) and Buchanan and Abu (2017). The heat energy flow from hot bodies to cooler bodies will be discussed first. After that, discussions follow regarding measurable fire parameters that define the basic terminology used in fire engineering. Section 2.4 concludes the theoretical concepts by describing flammability and flame spread characteristics. Lastly, the chapter focuses on code development, the conflagrations that motivated fire testing standards, and codes change. Finally, the chapter concludes by providing insight into performance-based fire safety designs.

## 2.2 Heat Transfer

The analysis of fire behaviour demands a sound understanding of thermal engineering, including the area of heat transfer. The three mechanisms of heat transfer, conduction, convection, and radiation will be discussed. The following subsections will present the fundamental physics associated with these mechanisms and the parameters associated with each.

### 2.2.1 Conduction

Conduction is most clearly present in solids, where heat energy is transmitted from each molecule to its nearest neighbour through the interactions of free electrons. The flow of thermal energy away from the high-temperature regions towards low-temperature regions is known as heat flux.

Heat flux in a steady-state one-dimensional situation can be expressed by:

$$\dot{q}" = -k\frac{dT}{dx} \tag{2.1}$$

where:

| | | |
|---|---|---|
| $\dot{q}"$ | = | Heat flux [W/m$^2$] |
| $k$ | = | Thermal conductivity [W/m·K] |
| $dT$ | = | Temperature difference over a distance [℃ $or$ $K$] |
| $dx$ | = | Change in the distance in the direction of heat flow [m] |

Buchanan and Abu (2017) define thermal conductivity as the amount of heat transferred through a unit of thickness of material per unit temperature difference. In general, good conductors of heat presents a high $k$ value and, in turn, are good conductors of electricity such as steel. Thermal conductivity is vital at most stages of a fire, especially during the latter stage when the fire is fully developed and the spread of the fire is a risk. An example might be a steel girder passing through a firewall that may conduct sufficient heat to start a fire in the neighbouring room.

Therefore, the relative thermal conductivity of building materials may be an essential factor in the fire-resisting ability of a structure. The density of material likewise plays a vital role in defining the thermal resistance, and materials with higher densities will generally have a higher thermal resistance. Common thermal properties of some materials required to perform heat transfer calculations in solid materials at ambient temperature are given in Table 2-1.

*Table 2-1: Thermal properties of some common materials (Buchanan and Abu, 2017)*

| Material | Thermal conductivity, $k$ (W/mK) | Specific heat, $c_p$ (J/kgK) | Density, $\rho$ (kg/m$^3$) |
|---|---|---|---|
| Copper | 387 | 380 | 8940 |
| Steel (mild) | 45.8 | 460 | 7850 |
| Brick (common) | 0.69 | 840 | 1600 |
| Concrete | 0.8–1.4 | 880 | 1900–2300 |
| Glass (plate) | 0.76 | 840 | 2700 |
| Gypsum plaster | 0.48 | 840 | 1440 |
| PMMA[b] | 0.19 | 1420 | 1190 |
| Oak[c] | 0.17 | 2380 | 800 |
| Yellow pine[c] | 0.14 | 2850 | 640 |
| Asbestos | 0.15 | 1050 | 577 |
| Fibre insulating board | 0.041 | 2090 | 229 |
| Polyurethane foam[d] | 0.034 | 1400 | 20 |
| Air | 0.026 | 1040 | 1.1 |

The material's specific heat, density, and conductivity are required to execute heat transfer calculations involving conduction. An amount of heat required to be applied to a unit mass of material to lift its temperature by one degree is called specific heat. For a constant fuel load, lining materials with low thermal inertia will result in higher temperatures experienced.

In a fire test scenario, the rise in temperature experienced by the exposed face of the specimen will result in a temperature gradient in the structural member; this, in turn, will cause a rise in temperature on the unexposed face through the conduction of heat. In other fire testing scenarios, the fire resistance of different materials has to more than often be determined; thus, the knowledge of heat transfer into a structure and through a material's boundary is required (Drysdale, 2011)

### 2.2.2 Convection

Convection occurs in liquids and gases. It is the movement of the fluids' molecules through fluid mass, which spreads the heat energy. This movement convective heat transfer is responsible for flame spread and the upward flow of hot gases in buildings, allowing cool air to enter the lower level of a building to replace the hot gases. The movement also in addition help to maintain the burning of building materials and other combustible equipment.

Convective heat transfer occurs when heat is transferred from a solid's surface to a fluid's surroundings, heating or cooling the solid. The heat transfer is directly proportional to the temperature difference between the two materials; therefore, the heat flux per unit area $\dot{q}"$[W/m$^2$] is expressed as:

$$\dot{q}" = h_c \Delta T \quad (2.2)$$

where:

| | | |
|---|---|---|
| $h_c$ | = | Convection heat transfer coefficient [W/$m^2$·K] |
| $\Delta T$ | = | Temperature difference between the solid surface and the surrounding fluid [°C or K] |

The convection heat transfer coefficient $h_c$ depends on the system's characteristics and may vary due to factors such as the geometry of the surface, the nature of the flow, and the thickness of the boundary layer (Buchanan and Abu, 2017). Convection is present during the full fire development but is especially important during the early stages when the radiation levels are minimal (Drysdale, 2011). A recommended heat transfer coefficient for surfaces exposed to standard fire curves (ISO, 1999) and for surfaces exposed to more extreme fire curves is 25 W/$m^2$·K and 50 W/$m^2$·K, respectively. Natural fires and the Eurocode parametric fire have a recommended coefficient of 35 W/$m^2$·K (EN 1991-1-2:2002).

### 2.2.3 Radiation

The transfer of energy through a transparent solid or liquid, or vacuum is known as radiation. Thermal radiation encompasses the same method of transmission as electromagnetic radiation, which means electromagnetic wave propagation (Incropera *et al.*, 2005). Radiation does not require any material or medium to transfer its energy. Radiation is most notably responsible for the heat transfer from hot flames to adjacent surfaces, which can cause building materials to ignite a structure and radiate heat to adjacent structures.

The radiative heat flux $\dot{q}"$ *(W/m²)* at a point on a surface is given by:

$$\dot{q}" = \varphi \varepsilon \sigma \left( {T_e}^4 - {T_r}^4 \right) \tag{2.3}$$

where:

| | | |
|---|---|---|
| $\varphi$ | = | Configuration factor |
| $\varepsilon$ | = | Emissivity of the surface |
| $\sigma$ | = | Stefan-Boltzmann constant ($5.67 \times 10^{-8}$ W/$m^2$·K⁴) |
| $T_e$ | = | Absolute temperature of the emitting surface ($K$) |
| $T_r$ | = | Absolute temperature of the receiving surface ($K$) |

The configuration factor $\varphi$, otherwise known as the ‘view factor, measures how much of the emitter is “seen” by the receiving surface. The emissivity, however, is the efficiency of the emitter ranging from zero to 1.0. A black body radiator has the highest value of 1.0 though most hot surfaces or luminous flames in fire situations have an emissivity between 0.7 and 1.0. In fire testing equipment such as the cone calorimeter, this heat flux is referred to as irradiance, the radiant flux incident on an infinitesimal element.

## 2.3 Quantifiable Material Test Properties

The following section introduces concepts necessary for understanding the products from combustion and other fire testing experiments that can be utilised for several purposes. Such as in fire models for up-scaling experiments, ranking products by their fire performance and in fire testing when developing new materials.

### 2.3.1 Heat of Combustion

The heat of combustion (calorific value) is the amount of heat released during the complete combustion of a unit mass of fuel and is expressed in kJ/g or MJ/kg. The higher the calorific value, the higher the heat release rate during combustion. The calorific value ($\Delta H_c$) can typically range between 15 MJ/kg to 50 MJ/kg for solid, liquid, and gaseous combustible materials, as depicted in Table 2-2.

*Table 2-2: Net calorific value for ordinary combustible materials [MJ/kg] (Buchanan and Abu, 2017)*

| | |
|---|---|
| **Solids** | |
| Wood | 17.5 |
| Other cellulosic materials | 20.0 |
| Clothes, Cork, Cotton, Paper, Cardboard, Silk, Straw, Wool | |
| Carbon | 30.0 |
| Anthracite, Charcoal, Coal | |
| **Chemicals** | |
| Alcohols | 30.0 |
| Methanol, Ethanol, Ethyl alcohol | |
| Fuels | 45.0 |
| Gasoline, Petroleum, Diesel | |
| Pure hydrocarbon plastics | 40.0 |
| Polyethylene, Polystyrene, Polypropylene | |
| **Other products** | |
| Polyester (plastic) | 30.0 |
| Polyisocyanurate and polyurethane (plastics) | 25.0 |
| Polyvinylchloride, PVC (plastic) | 20.0 |
| Rubber tyre | 30.0 |

The burning characteristics of individual components have presented information to predict the fire behaviour of materials. The characteristics can be measured utilising a cone calorimeter. The oxygen consumption principle states that the amount of oxygen required for combustion determines the net heat of combustion at bench-scale. Most combustibles release approximately 13.1 MJ of heat for each kilogram of oxygen consumed (ISO, 2015a).

Buchanan and Abu (2017) also described a value, namely the effective heat of combustion, which is valid for combustible materials containing moisture under normal conditions and is calculated by the following equation:

$$\Delta H_{eff} = \Delta H_c(1 - 0.01\mathrm{m}_w) - 0.025\mathrm{m}_w \qquad 2.4$$

where $\mathrm{m}_w$ is the moisture content as a percentage of the weight of the material.

### 2.3.2 Fire Load Density

Suppose the calorific value is known for a specific fuel. In that case, it is then possible to calculate the maximum amount of energy, *E (MJ)*, that the specific fuel can release during combustion and is given by the following equation:

$$E = M\Delta H_{eff} \qquad 2.5$$

where M is the initial mass of the fuel, measured in kilograms. By dividing the maximum amount of energy contained in the fuel by the floor area of the enclosure, a fire load density, $e_f$ *(MJ/m²)*, can be calculated (Buchanan and Abu, 2017).

### 2.3.3 Heat Release Rate

The critical question in a fire is: ‘how big is the fire’? Heat release rate (HRR) is vital for fire safety engineering in describing fires. Babrauskas and Peacock (1992) describe the heat release rate as the single most crucial variable in characterizing products' flammability and fire hazard. The HRR is distinct as it usually increases to a peak value and declines after an adequate amount of fuel has been consumed. To design a particular real-life fire scenario, the size of the fire in terms of kW or MW must be known. An average heat release rate $\dot{Q}$ (MW) can be calculated as stipulated in Equation 2.6:

$$\dot{Q} = E/t \tag{2.6}$$

where *E* is the total energy contained in the fuel (MJ), and *t* is the burning duration (s).

The heat release rate is calculated by measuring the oxygen and flue gas concentration changes in a cone calorimeter made as part of the oxygen consumption principle used, as previously mentioned. The fundamental theoretical HRR calculated as described in Equation 2.7:

$$\dot{q} = \left(\frac{\Delta h_c}{r_o}\right)\left(\dot{m}_{O_2},\infty - \dot{m}_{O_2}\right) \tag{2.7}$$

where:

| | | |
|---|---|---|
| $\dot{q}$ | = | Rate of heat released (kW) |
| $\Delta h_c$ | = | Net heat of combustion (kJ/kg) |
| $r_o$ | = | Stoichiometric oxygen/fuel mass ratio |
| $\dot{m}_{O_2}$ | = | Oxygen mass flow rate (kg/s) |
| $\infty$ | = | Ambient conditions |

A more straightforward analysis consisting of trapping out the $H_2O$ and $CO_2$ in the sample line because of the use of the $O_2$ analyser and using a heat of combustion value of 13.1 MJ can be calculated as described by (Babrauskas 1982):

$$\dot{q} = (13.1 \times 10^3)(1.10)C\sqrt{\frac{\Delta P}{T_e}}\frac{[0.2095 - X_{O_2}]}{[1.105 - 1.5X_{O_2}]} \tag{2.8}$$

where:

| | | |
|---|---|---|
| $\dot{q}$ | = | Rate of heat released (kW) |
| $C$ | = | Orifice plate coefficient ($m^{1/2}kg^{1/2}K^{1/2}$) |
| $\Delta P$ | = | Pressure drop across the orifice plate (Pa) |
| $T_e$ | = | Gas temperature at the orifice plate (K) |
| $X_{O_2}$ | = | Measured mole fraction of $O_2$ in the exhaust air |

In 1982, the first contribution of a method to qualitatively measure the heat release in a room fire was standardised as the ASTM E2257 (ASTM, 2017). During this decade, the pioneering work of Parker (1984) was established. The author presented measuring techniques for the prediction of large-scale heat release rates, utilising bench-scale methods. Bench-scale fire tests can accurately determine a fire risk by calculating the heat release rate as it best predicts the fire hazard.

### 2.3.4 Ignitability

Ignition is accepted to be an exothermic reaction, and this stage can be identified by a chemical change of the material involved and temperatures significantly more than ambient being produced (Buchanan and Abu, 2017). There are primarily two forms of ignition: piloted-ignition and auto-ignition. One occurs in the presence of a spark, and the other occurs from the volatile gases of a fuel source known as spontaneous ignition.

A set amount of heat input and temperatures from an external source are required to initiate a pilot ignition. This occurrence of ignition is dependable on various properties of the fuel source, such as the material properties, the size and shape, and the heat exposure time (Buchanan and Abu, 2017).

Thermal inertia ($k\rho c$) of the material influences the time to ignition of materials. It is defined as the product of thermal conductivity ($k$), density ($\rho$) and specific heat ($c_p$). Surfaces with low thermal inertia will increase in temperature and ignite rapidly. Materials like low-density plastic foams will experience additional repercussions such as rapid flame spread and fire propagation. Materials with higher thermal inertia, such as wood, will not encounter these effects. The effective time to ignition ($t_{ig}$) is an important parameter to quantify and is often used in fire testing standards. Babrauskas (2004) suggested that the measured ignition delay time curve may be utilised to calculate this parameter. These figures, however, do not represent true material qualities and are heavily influenced by external factors such as airflow velocity and oxygen content. Babrauskas (2004), Quintiere and Harkleroad (1984) and Dietenberger, (1996) performed fundamental analysis regarding ignition, which the reader can refer to if more information is required.

In some testing apparatus, an electric pilot ignition such as an electric spark is deemed more accurate than the use of a gas pilot ignition. No additional localized heat flux is imposed on the sample by the piloted electric ignitor. It is most beneficial for a specimen to contain a low ignitability limit since it is the only protection aid if the element does not ignite.

Ignitability forms part of essential fire properties established from bench-scale flammability tests. The Cone Calorimeter (ISO, 2015a), LIFT apparatus (ASTM, 2018), and FM Flammability Apparatus or Fire Propagation Apparatus (FPA) (ASTM, 2019) are examples of standardised radiative heat transfer tests that include the ignitability criteria.

### 2.3.5 Published Temperature - Time Curves

Edwin Sachs, in 1903 was the first man to act and lay down criteria on how fire resistance in a building should be approached (Law and Bisby, 2020). Fire resistance is referred to as the capability of a structure or building element to withstand a fire. It is quantified as a time parameter to assign a building element a specific fire rating. Three classes of endurance were originally proposed relating the fire resistance of the structure to a provided temperature. Initially, full, partial, and temporary protection were used; however, that changed to a time-based criterion of one two or four-hour protection. Fully protected structures were interpreted as elements that can resist a compartment's complete burnout and contents when subject to a fire. The structure must do so with no fire rescue services Babrauskas and Williamson, (1978).

The standard fire curve defined in 1917 by the ASTM (ASTM E119, 1917) was adopted by many countries internationally, but not in Britain. The British eventually adopted the proposed standard; however, they suggested additional criteria to the fire resistance test: insulation, integrity, and stability. These failure criteria formed the basis for the International Standard ISO 834 (ISO, 1999) standard. Figure 2-1 describes the temperature recorded from tests performed to establish this curve and compares the two published curves. Two other published curves are also depicted.

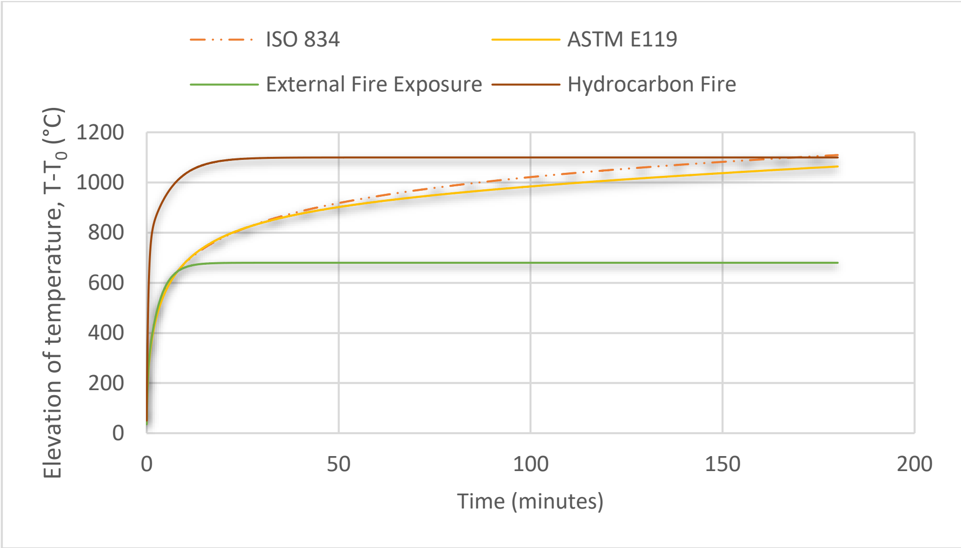



*Figure 2-1: Published Curves (recreated from Buchanan and Abu, 2017)*

According to ISO (1999), the standard fire curve used in fire resistance tests and is a time-temperature curve described by Equation 2.9 :

$$T_g = 345\log(8t + 1) + 20 \qquad 2.9$$

where $T_g$ is the gas temperature in °C, and $t$ is the time in minutes.

Equation 2.10 depicts the formula used to calculate the temperature based on ASTM E119 (1917):

$$T_g = 750\left(1 - e^{-3.79553\sqrt{t_h}}\right) + 170.41\sqrt{t_h} + 20 \qquad 2.10$$

where $T_g$ is the gas temperature in °C, and $t_h$ is the time in hours.

From the ISO 834 curve, it is possible to establish that a 60-minute rated element does not mean it can provide double with the fire resistance of a 30-minute rated element due to the curve being non-linear. A heating phase is established within the first few minutes as the structure is heating up; however, it remains somewhat unaffected with low temperature and less radiation entering the structure.

Two other published curves are described by Buchanan and Abu (2017), which consist of the external fire curve given by:

$$T_g = 660(1 - 0.686e^{-0.32t} - 0.313e^{-3.8t}) + 20 \qquad 2.11$$

and the hydrocarbon fire curve:

$$T_g = 1080(1 - 0.325e^{-0.167t} - 0.675e^{-2.5t}) + 20 \qquad 2.12$$

where, $T_g$ is the gas temperature in °C, and $t$ is the time in minutes.

Equation 2.11 is a time-temperature relationship that can be used to estimate the fire resistance of exterior non-loadbearing walls under both internal and external exposure situations. The external fire exposure curve is described in BS EN 1363-Part 2 in the latter instance (BS EN, 1999) that stipulates alternative heating conditions is used. The hydrocarbon fire curve is the most severe design scenario and replicates fires in buildings that store petrochemical products.

These tests are preferred to be executed as full-scale rather than small-scale tests due to the potential effects caused by deflections and connections in elements of a building construction only being assessable in this arrangement.

More than a century in use, the standard fire resistance test has been globally applied and standardised by various countries. The advantage of this measurement system is the simplicity of use and repeatability of the experiments (Gales *et al.*, 2020). Historically, however, the standard fire resistance test has not been favourable amongst all practitioners and researchers. Many question the applicability of the test results as the only criteria to classify structural fire resistance designs (Bisby *et al.*, 2013).

Between 1970 and 2002, an incident involving the collapse of a multi-storey building was investigated by Beitel and Iwankiw (2008). A multitude of collapses, 22 to be precise, were induced by fire in concrete, steel and masonry buildings. The investigation concluded that the standard fire test could not predict the failure mechanism that occurred.

Limitations include unrealistic representation of a real fire, high expense of full-scale testing, inadequate prediction of specific failure mechanisms, and ill consideration of cooling phases in other design curves.

## 2.4 Flammability and Flame Spread

This section will discuss the flammability and surface flame spread parameters that occur during a fire's growth. Additionally, various modes of flame spread will be defined. Fire safety engineers will better understand the influence flame spread has on the results of a fire once dealt with this section.

### 2.4.1 Flammability Defined

The concept of flammability was born out of a need to quantify the burning behaviour of a specific fire situation using a single measure. However, flammability is generally difficult to define due to the various responses of a material in different fire settings. Various material characteristics define flammability. These are the burning intensity, ease of ignitability, flame spread tendency, heat release rate, and the substance's smoke and toxicity production rates (Lautenberger *et al.*, 2006). A material's overall flammability may require a thorough assessment of information from several laboratory research tests, aided with some form of analysis or modelling to interpret the results accurately.

The research test involves bench-scale flammability testing, which results in data for material classifications or predictions of large-scale fire phenomena. Small-sized test methods are preferred as they are more time and cost-effective than their large-scale counterpart. This preference is primarily due to the requirements of small amounts of specimens and shorter setup and breakdown time.

Bench-scale tests inherently test for material parameters and properties, placing a substantial interest in the predictions of large-scale fire behaviour. The data obtained can be combined with dynamic fire models to achieve the relevant predictions (Lautenberger *et al.*, 2006).

It should be noted that several fire properties influence a material's flammability. The propensity of flame spread, ignitability, heat release rate, smoke production and toxicity, and mass burning rate are the most important influencers. Moreover, the inherent resistance that material possesses towards a fire may also be a measure of flammability. No fire risk will occur if the material has not ignited or does not support flame spread resulting in a lower heat release rate and smaller burning area (Lautenberger *et al.*, 2006). In most fire situations, non-thermal hazards such as reduced visibility and asphyxiation are humans' primary causes of death. Products of incomplete combustion, $H_2O$ and $CO_2$

are the most common products from burning. Developing flame conditions is a large room home to two significant toxicants: carbon monoxide (CO) and hydrogen cyanide (HCN).

### 2.4.2 Flame Spread

Ignition acts as the controlling mechanism of flame spread and fire growth. In order to measure a material's fire behaviour, only a few fire tests are used in industry.

The limiting oxygen index (LOI) (ISO, 2017) and the Underwriters' Laboratory UL 94 test (UL, 2013) are both preliminary indicative tests of a material's flammability potential. The Cone Calorimeter may also be utilised; although it inherently does not measure flame spread rate, it measures the time to ignition and rate of heat release, which will be discussed in detail in Section 5.3.2.

Drysdale (2011) describes flame spread as a continuous series of piloted ignitions occurring at the flame's leading edge. It is a process whereby the surface of a solid or liquid creates a pyrolysing region for a flame to move along. Flame spread is not to be confused with flame propagation in a premixed fuel system. Due to the increasing temperature of the burning surface by the direct or remote heating of the generated flame, flame spread occurs (Hasemi, 2016). The surface flame spread is a critical fire behaviour parameter in modern-day built environments, and several reviews of this parameter have been dealt with by Williams (1976), Fernández-Pello and Williams (1977) and Hurley (1995). (Fernández-Pello and Williams, 1977)

### 2.4.3 Flame Spread Process

The overall flame spread process occurring on a flat surface may involve different modes. These modes are dependable on the orientation of the material and the direction of the airflow. These factors may influence whether the fire growth involves one or multiple modes of transport. Lateral, horizontal (upward or downward), opposed flow (self-inducing buoyancy effects), and wind-aided flame spread are examples of the various modes. Each mode of flame spread will be discussed further.

The development of surface flame spread is described by the SFPE Handbook of fire, Hurley (1995) as a result of the following cycled process:

1. The heat from the flame over the fuel surface causes vaporisation of the material.
2. Pyrolysed gas and oxygen mixing in the surrounding area of the fuel surface.
3. Diffusion flame formation due to pyrolysed gas combustion.
4. Diffusion flame causes unburnt fuel surface to reach ignition.

The heat transfer involving the flame (gas phase), solid, and oxygen and fuel concentrations strongly affect the abovementioned process. The flame spread rate across the surface can be viewed as consecutive ignitions over a combustible material. However, to ensure its sustainability, the increasing flame temperature equilibrium must be regulated along with the rise in the surface temperature

Figures 2-2 and 2-3 illustrate two forms of flame spread. The inhibition of wind flow is termed opposed flow flame spread. In contrast, the wind-aided flame spread is a result of the buoyancy effect of the flame itself.

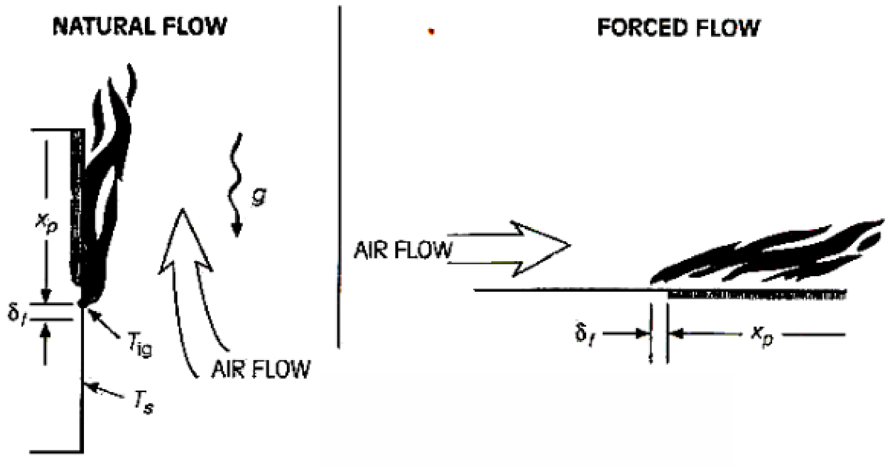



*Figure 2-2: Opposed-flow flame spread (Quintiere, 1998)*

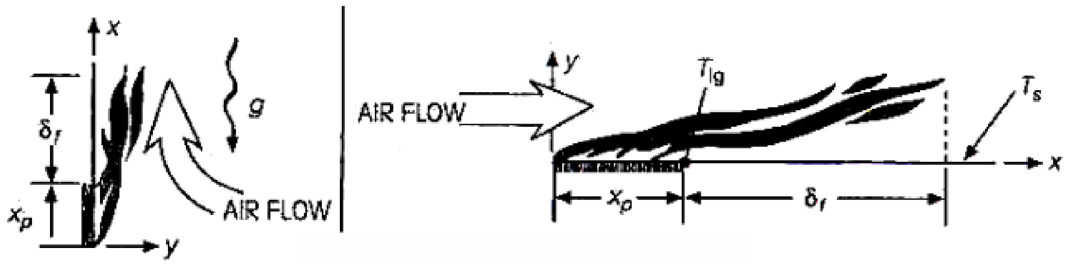



*Figure 2-3: Wind-aided flame spread (Quintiere, 1998)*

In the figures above, the flame is seen to be measured through a distance termed $xp$. This position marks the rate of motion, otherwise known as the flame spread velocity and the extent of the pyrolysis region. This region is regulated by the temperature and composition of the material, i.e., the burning rate. The advancing face of the flame spread is the region denoted by $\delta f$, indicating the flame length and $T_{ig}$ *and* $T_s$, denoting the ignition and surface temperatures.

### 2.4.4 Flame Spread Tests

#### *2.4.4.1 Bench-scale tests*

As mentioned, bench-scale apparatuses are mainly used to establish rankings and classifications in the relevant standards or create input parameters for large-scale fire behaviour scenarios and models. In the following subsection, standardized flame spread tests will be explained in detail.

The Lateral Ignition Flame Transport (LIFT) apparatus was standardized as the ASTM E1321- 18 test (ASTM, 2018), designed to measure lateral flame spread rates. As mentioned above, the locally induced airflow is opposite the flame spread; therefore, the apparatus experiences opposed flame spread. This flame spread method is a function of external heat fluxes. The lateral flame spread is measured using the LIFT apparatus over various fluxes and temperatures equivalent to a fire scenario.

Initially developed in the 1980s, the Flame Propagation Apparatus or Fire Propagation Apparatus (FPA) was standardised as the ASTM E2058 (ASTM, 2019) and ISO 12136 (ISO, 2011). This method essentially acts as a heat release calorimeter; however, the flame spread and fire propagation index is determined during testing.

The instrument is utilised primarily in the insurance industry by FM Global and in clean room and cable products (FM Global, 1989).

The Single Flame Source, otherwise known as the Ignitability Test standardised as ISO 11925-Part 2 (ISO, 2010), forms part of the European suite of standards for reaction-to-fire performance of products. Flame spread measurements, although not the primary objective of the test method, can be utilised to assess the ignitability of materials. The test method is examined in detail in Section 5.3.7. The tiny flame application for a set period will address the ignitability by measuring the spread of the application.

In South Africa, the national standard to determine the burning properties of building materials is set out in SANS 10177-9 (SANS, 2006). The burning characteristics measurable is ignition, flame spread, and heat contribution. This standard uses a small ignition source of a Bunsen burner under controlled conditions to observe insulation materials' relevant basic fire properties. The ease of ignition, spread of flame, and the heat contribution of each substance are all seen and measured (SANS, 2006).

The Radiant Panel Flame Spread Apparatus ASTM E162 (ASTM, 2021a) or ASTM D3675 (ASTM, 2021b) is a test that will not be further detailed in the following chapters but is worth mentioning in the broader aspects of flame spread testing. The apparatus utilises a radiant gas-fired panel to measure the surface flammability of building products and cellular plastics. The outcome of the test is formatted to provide an index calculated from the flame spread measured. This index is necessary for various industries, particularly mass transit, such as buses and trains.

#### *2.4.4.2 Large-scale tests*

The first large-scale test that will be discussed is the UL 723 (UL, 2018). Also adopted as the ASTM E84 (ASTM, 2021c), the standards describe the testing of surface burning characteristics of building materials. It is used to determine the surface flame spread and flammability parameters. These standards utilize the 'Steiner tunnel' test developed in the 1940s.

A specimen sized 0.5 m x 7.5 m forming the tests' tunnel ceiling is ignited at one end. In the presence of a forced airflow, the flame propagation distance is measured as a function of time. This testing method introduced the ranking of materials by an arbitrary flame spread index compared to the new age of fire tests which yields data that assists in assessing the dangers associated with combustible materials. Literature, however, indicates that a material's performance in the test cannot be correlated to its behaviour in a real fire (Lautenberger *et al.*, 2006).

Another example is the ISO 9705 (ISO, 2015b) used to classify all lining materials by applying the Room Corner Test. The testing specifications are outlined in Section 5.3.4. The corner configuration measures the HRR by using oxygen consumption calorimetry developed by Parker (1982). This design is preferred because the flame length is hotter and more extended in a corner design than a flat wall due to the radiation interaction between surfaces and reduced air entrainment.

A testing method for determining the reaction-to-fire behaviour of building products, excluding flooring elements, is described in the Single Burning Item (SBI). Standardised as the BS EN 13823 (BS EN, 2010a), the material is exposed to a thermal attack by a propane burner, and the flame spread is consequently measured. In South Africa, building materials' surface burning characteristics are determined through the standardised test method described in SANS 10177-10 (SANS, 2007). The test apparatus is an inverted channel tunnel test discussed in Section 5.3.12. The burning behaviour and potential for self-propagation of fire spread of building envelope materials are determined by measuring the maximum flame spread. The test can produce a combined heat flux associated with any building material's conductive, convective, and radiative properties.

## 2.5 Overview of Code and Standard Development

Fire plays a vital role in the existence and survival of humankind. It took decades of horrific fire incidents, many lost properties and the most tragic of them all, loss of lives, but humans have developed to be better equipped to manage and prevent fire scenarios. Safer buildings can be designed by enforcing codes and standards that limit the destructive effects of a fire outbreak. Agencies such as the NFPA, ISO, UL, EN, ASTM, and many others have contributed to writing and formulating the fire test standards that aim to provide safer structures.

### 2.5.1 System for Developing Codes and Standards

Even though fire safety has been studied for a number of years, the development of scientifically based fire test standards for buildings seems to be less than 300 years old. Fire test methods were primarily developed in Europe and Asia, and even still to this day, these two continents are the front runners in code development. However, the USA is also extensively involved.

The legal framework must enable stakeholders to achieve a life and property fire safety benchmark acceptable to society. Roman Law Communities created a fire and health risk, for which orderly settlement planning was a requirement. Specific responsibilities and civil rights are allocated to neighbouring properties. Various approaches to formulate building standards may be considered, such as the performance-based approach or the prescriptive-based approach, which takes on a deemed-to-satisfy system.

A building regulation offers a standard viewed as an approved technical point of reference that standardises building and construction processes. It can be described as the minimum standard providing measurement criteria employed during the building development (Laubscher, 2011).

In South Africa, in the 19th Century, the lawmakers tried to ensure proper sanitation and minimise conflagrations by establishing The South African Bureau of Standards (SABS) (SABS, 1945). However, in the 20th Century, the protection of public health and safety took preference. Consequently, minimum standards were developed for building construction and protection, which led to the National Building Regulations being implemented in 1985. South Africa National Standards (SANS) forms part of a division of the SABS. The perception exists that the SABS and SANS are the same and cannot be used without the other. However, this is not the case. The SABS is a certification body that SANS accredits.

SABS's two business ventures consist of the certification and test laboratories divisions (SABS, 2005). SABS cannot be referred to as a standard that is solely reserved for the SANS entity. According to a specific SANS testing or certification standard, products can be sampled, tested, and certified by a testing and certification body.

The question might now be, so what is SANS standard? A specific SANS standard is defined as a standard that specifies the performance requirements of a specific product. It can either be written locally or formulated by adopting an international, e.g., ISO standard. The criteria laid out in a specific SANS standard certify the tested product. An accreditation body may only award certification if the product complies with the specific requirements.

In America, the development of their national standards known as the NFPA standards is dealt with differently. Although all national standards, even in South Africa, can be written through the participation of public individuals, this process is encouraged in the USA (NFPA, 2021a).

Every three to five years, revisions and updates of all NFPA standards take place. This revision cycle runs approximately two years to complete. The revision is done carefully by following a published schedule, including estimated deadlines for each stage in the standards' development process. Figure 2-4 outlines the four fundamental steps in the NFPA standards development process.

The NFPA suite of documents now consists of more than 250 technical committees, each involving up to 30 voting members of balanced representation, reaching consensus regarding aspects to reduce the risk of harm and provide fire safety.

The most well-known worldwide federation of national standards bodies, a non-governmental organisation, The International Organisation of Standardisation (ISO), was established in 1947. ISO deals with international borders and facilitates the exchange of goods and services. As an organisation, it aims to encourage the development of standardisation to assist in scientific, intellectual and technological processes. These objectives are reached through the 120 standards bodies, each country, including 86 member bodies, 25 corresponding members, and nine subscriber members. The technical committees carried out the scientific work, which established their subcommittees and working groups. A report with a three-year validation is constructed to which it can be converted into an international standard or withdrawn. An important aspect of standardisation within Europe is that the European Committee for Standardization (CEN) standards are mandatory within the member states of the Trade Union.

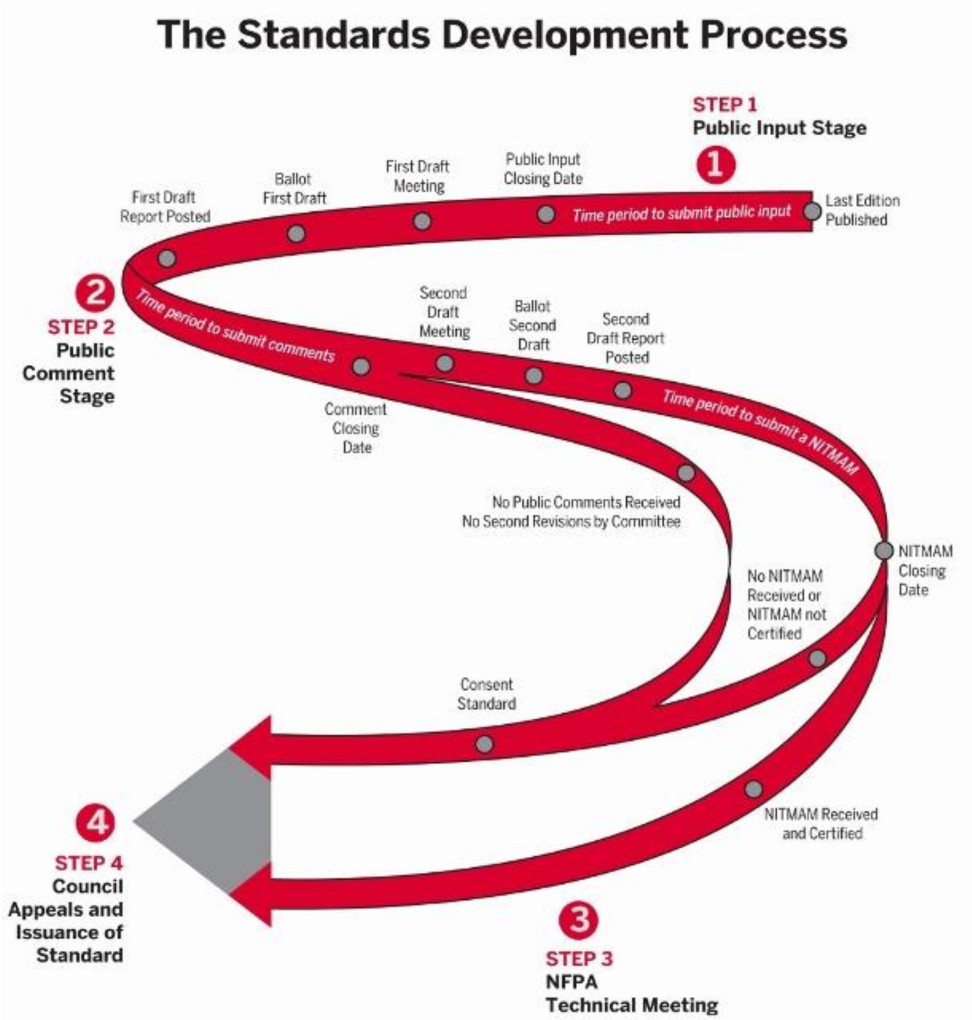



*Figure 2-4: Development process of NFPA standards (NFPA, 2021)*

### 2.5.2 Fires that Inspired Change of Standards

Details about the fire tragedies are drawn from History Editors (2009) unless noted otherwise.

The systematic process mentioned above is not always followed when developing fire safety legislation, codes, and standards. Significant fire incidents resulting in considerable property damage and loss of life are all too often responsible for this development.

The history of fire code advancement goes back to the Great Fire of Rome in 64 A.D. that destroyed nearly 70 % of the city. The Great New York Fire of 1835 (Shoub, 1961) was the catalyst for the first documented legal test procedure in North America. The NFPA later accepted this fire test method for the classification of roof coverings. It is now known as ASTM E108, Standard Test Methods for Fire Tests of Roof Coverings (ASTM, 2020), and has been in use for nearly 100 years. Around 300 individuals were killed in the Great Chicago Fire of 1871. A year later, the local City Council outlawed wood in construction and mandated flame-resistant materials.

Chicago would again suffer a devastating fire in 1903, when the Iroquois Theatre burned full-bore, trapping 602 people inside. Several fire safety standards were violated in the theatre's construction, and when the fire broke out, many of the exits were concealed behind thick black curtains or locked. Following the Iroquois Theatre fire, a fire curtain became mandatory for large theatres after the stage fire spread to the auditorium. As a result of this fire, "crash bars" began to be used on doors, and doors in public buildings were required to leave in an egress-only direction. Both of these safety requirements were developed around 20 years ago and prevented countless deaths.

In 1911, the Triangle Shirtwaist Factory also suffered a tragic fate. One hundred forty-seven workers survived the fire trapped in the 10-story building, whose top three floors were occupied by the company, as shown in Figure 2-5. The company's preventative measures, such as closed entrances to limit theft and prohibiting workers from taking illegal breaks, effectively prevented the imprisoned persons from fleeing. Many people jumped from the windows to escape the fire, but others died from inhaling flames and smoke. NFPA created the Committee on Safety to Life as a result of this fire. As a result of the committee's work, a comprehensive guide to exits and life safety features was created, which we can see in the modern NFPA 101-Life Safety Code (NFPA, 2021b)

*Figure 2-5: Triangle Shirtwaist Company occupied the top three floors of the Asch building (Zalosh, 2003)*

Within the twenty-first century, in 2017, to be precise, the world witnessed the destructive fire at Grenfell Tower, which claimed the lives of 71 people and hundreds more were left with both physical and psychological injuries. Various reports and revisions were submitted regarding the incident, one of which was the report of Dr Lane (Lane, 2018), in which she delivered an in-depth fire safety investigation. In her report, it is stated that 'the rain screen cladding assembly installed during the refurbishment in 2012 till 2016, together with the insulation fitted to the existing external wall and the missing or defective barriers became part of successful combustion processes'. In the case of an internal fire, cavity fire, or exterior fire, the external cladding produced a condition that connected every flat on a floor; and every storey from level three to the roof. It allowed the external fire to spread via the building's windows, resulting in a series of internal fires. The external cladding system used on Grenfell Tower did not meet the Building Regulations' functional requirements, contributing to the observed failure of the fire protection measures supplied within the premises. The 24-storey building can be seen ablaze in Figure 2-6.

*Figure 2-6: The 24-storey Grenfell Tower block on fire (Selwyn, 2018)*

A report by Torero (2019) stated that a fire of the sort of the original kitchen fire at the heart of the Grenfell Tower disaster is an entirely foreseeable event in structures of that nature, following the initiation of a Phase One Public Inquiry. Many predictable factors could result in similar localized fires. He also stated that the Grenfell Tower building envelope was altered so that the fire developed in such a way that the building's ability to protect the people and the fire brigades' ability to handle the event was utterly crippled. The Grenfell Tower disaster further demonstrated that the concept of a "sufficient amount of vertical fire spread" does not exist in today's design, compliance, or competency paradigms. A lack of unmistakable technical foundation in techniques can be easily overcome by employing equally non-rigorous reasoning, resulting in widespread confusion.

As was evident during the Phase One process, there is currently some uncertainty in the field, and it is a critical component that contributed to the Grenfell Tower fire's conclusion. According to the recommendations, the most significant attention should be given to compartmentalization integrity since it provides the most significant and robust protection. It is also essential to develop a thorough grasp of the dangers of fire in towering buildings. Because the types of buildings that potentially allow vertical fire spread are so diverse, present efforts to re-evaluate building risk are insufficient and limited by a lack of understanding of façade systems' intricacies.

It was further suggested that the apparent positive measures recommended by various reports would most likely not improve safety in the long term. The more profound underlying issues will be ignored due to the suggestions acting as justifications. The examples mentioned above indicate how tragic fires helped shape the advancements of modern fire safety regulations and standards.

Insurance firms have also contributed to code revisions in order to manage risk better and prevent fire-related losses. Changes in building materials and processes have increased our awareness of risk throughout the years, and the advent of new technologies has supported the advancement of modern fire-fighting practices.

## 2.6 Performance-Based Fire Safety Design

When designing fire safety systems, there are deemed-to-satisfy approaches or performance-based fire engineering design (PBD) approaches. This section aims to introduce the concept of performance-based design, provide a holistic overview of the requirements and focus on what performance-based design is and what it entails.

### 2.6.1 Definition

Performance-based fire design uses science and engineering to create fire protection and life safety systems in buildings that take into account the unique qualities of the structure (Hurley and Rosenbaum, 2015). It is founded on three key characteristics: (1) ensuring that a building has the necessary level of fire safety in the case of a fire. (2) The design foundation, also known as design fire scenarios, is used to determine the sorts of fires, occupant characteristics, and architectural attributes for which the building's fire safety systems are designed to provide protection. (3) An engineering analysis of design options against fire safety goals and objectives utilizing recommended methodology and performance criteria can be created (Hurley and Rosenbaum, 2015).

Buchanan and Abu (2017) depict in Figure 2-7 a multi-level hierarchical format that many countries have adopted during the development of new codes that are inclusive of PBD.

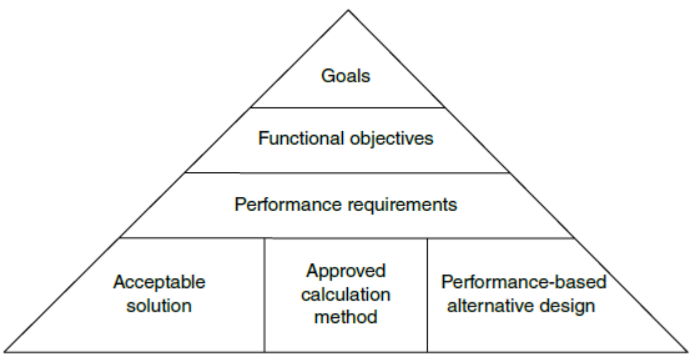



*Figure 2-7: Hierarchical relationship for performance-based design (Buchanan and Abu, 2017)*

It is quick and simple to implement a prescriptive design strategy. It does, however, have limitations; however, the primary goal of preserving life and property from the consequences of fire is met (ACBC, 2005). To assure fire resistance for structures, most prescriptive methods rely on conventional fire curves. Unfortunately, because of the shortcomings of the standard fire curve, as discussed in earlier sections, manufacturers tend to follow the standard fire test standards without considering the impacts of a real fire, which might lead to uneconomical solutions (Bailey, 2004).

Applying a PBD approach to a simple building may be time-consuming and applying and reviewing designs requires additional knowledge. It may also be more sensitive to change compared to a standardized code. Many structures do not need a fire engineering strategy, and as a result, both prescriptive and performance-based designs may need to co-exist. Sound codes must be developed for more superficial structures to ensure that fire safety can be implemented in diverse structures (EPDB, 2018).

The SFPE Engineering Guide provides a framework for PBD (Hurley *et al.*, 2016). Figure 2-8 illustrates this approach. The goal of the process is to identify the phases involved in PBD without specifying which methodologies should be used to create a design.

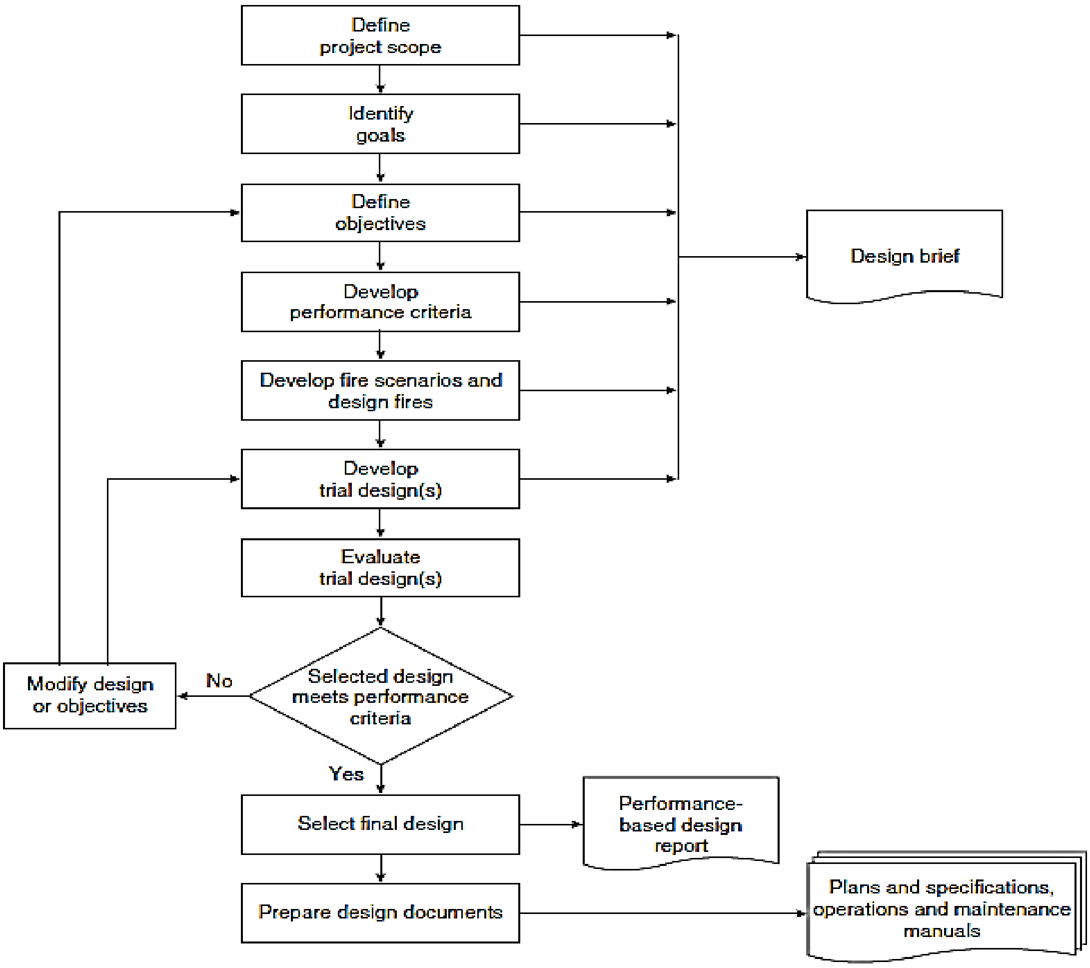



*Figure 2-8: Performance-based design framework (Hurley, 1995)*

### 2.6.2 Human Movement and Evacuation

Human response includes individuals' consciousness, principles, mindsets, behaviours and expectations. These responses, including people's survival skills and strategies, are studied as human behaviour when exposed to a fire. This topic will only be briefly mentioned in this work.

Research on the movement of people dates back to the early 1900s, with the most detailed investigations occurring in the 1980s and 1990s. Human behaviour research has revealed that any action taken in a scenario results from a behavioural or decision-making process, rather than random chance or acts triggered by environmental changes. Unfortunately, researchers realised that many aspects of human behaviour could not be reduced to a simple formula that can be applied, unlike in other cases of fire safety engineering. It was often restricted to simple assumptions that were not always suitable; research by Canter (1980), Wood (1972) and Proulx (1993) indicates the faults in having these expectations. The responses of people in a fire situation were not integrated into fire safety designs.

### 2.6.3 Smoke Control

The spread of fire and smoke to neighbouring rooms is a significant cause of fire mortality. Incomplete combustion results in carbon monoxide gas (CO) or solid carbon (C) as soot particles in many fire settings. The layout of the building has a significant impact on the passage of fire and smoke. Scenario analysis, which examines numerous plausible worst-case situations, is one approach for showing fire safety (ABCB, 2005; Spearpoint, 2008). A comparison in each scenario evaluates the projected growth and spread of fire and smoke with detection and occupant movement, taking into account all active and passive fire prevention measures and structural behaviour to determine if the performance standards have been reached (Buchanan and Abu, 2017).

Several different approaches and design concerns are taken into account while designing smoke control systems. When designing smoke control in PBD, the potential impact of wind, stack effect (i.e. chimney effect in atria over multiple stories), the position of openings, the buoyancy of fire gases, ambient temperatures, and building materials on smoke flow are all considered (Spearpoint, 2008).

### 2.6.4 Materials and Fire Spread

The combustibility or flame spread characteristics, the calorific value and restrictions on the heat release rate in structures are all regulated in most nations. As more sophisticated performance-based codes have been developed, designers have more leeway to devise inventive solutions to fire safety challenges. They must, however, be able to meet the required levels of safety and performance, as determined by the approving authorities.

Actual fire behaviour, which is a function of the compartment's area and height, ventilation provision, type, configuration, and quantity of combustible material in the compartment, is considered in performance-based design (Drysdale, 2011). The fire spread can ultimately be controlled through construction; it must control its movement and provide structural stability to ensure adequate protection against fire severity.

In a performance-based code setting, the design fire severity is typically a total burnout fire or the equivalent time of a complete burnout fire (Lane, 2000). To improve simple prescriptive fire resistance criteria, several performance-based regulations allow the use of similar equations (Buchanan and Abu, 2017).

### 2.6.5 Structural Resistance

Three requirements must be met for a structure to be fire-resistant: stability, integrity, and insulation. In the event of a fire, structural stability refers to the ability of a structure to sustain its load-bearing capability. Designers must also consider material structural qualities, including yield strength, ultimate strength, and modulus of elasticity. These qualities are altered to account for the temperature rise. For an element to satisfy the integrity requirement, it should not allow hot gasses or smoke to pass through it. To meet insulation requirements, the unexposed side of the member should not exceed a specific temperature limit (Buchanan and Abu, 2017). The criteria are depicted in Figure 2-9, along with a visual aid. The detail regarding the requirements will be discussed in Section 3.3.


*Figure 2-9: Criteria for fire resistance according to European standards (Structural Timber Association, 2014)*

The practice of designing for structural resistance dates back to the 1920s (Ingberg, 1928). The basic premise is that the product of time and temperature throughout the exposure period yields a measure of fire intensity. There are various drawbacks to the traditional way of designing structural fire resistance:

- All of the elements that influence the temperature and duration of compartment fires are disregarded.
- The performance of structural parts at high temperatures is often disregarded, and structural elements are examined separately.
- When the temperature is raised to the fourth power, the radiation changes; as a result, the common practice of using the product of time and temperature to depict heat transport is inadequate
- The rate at which a substance burn is influenced by the degree of fire exposure.
- The fire load does not represent the fire hazard of combustible materials in and of itself.

Performance-based design of structural fire resistance should define the following aspects: firstly, the structural fire exposure. Secondly, considering the material properties and strains induced by the raised temperatures, the structural response at elevated temperatures should be determined.

### 2.6.6 Detection and Suppression

As mentioned in the previous sections, fire suppression and detection systems are essential in providing life and property safety. These fire detection systems compensate for the variations amongst the standards for structural protection and means of escape (Hurley and Rosenbaum, 2015).

In the broader application of performance-based design, detection is the first element that needs to be addressed, as it should take place before suppression systems are activated. The most important aspect of a PBD analysis is estimating the activation of both these systems. Various detection systems exist, such as heat and smoke and other types. The principle operation of a heat detector is more straightforward than a smoke detector due to the various methods and associated shortcomings linked to the employment of these detectors. The suppression systems' effect on the heat release rate must be determined only once the activation time is defined.

However, most of these systems are very costly to implement. It is thus essential that the operation of detection and suppression systems be evaluated to provide the associated activation times and the effect they will have on fire. Hurley and Rosenbaum (2015) presented information on evaluation methods, which the reader can consult.

## 2.7 Overview of Literature Review

This chapter has provided an overview of fire behaviour phenomena, fire engineering standards and performance-based safety design. These concepts are fundamental for being able to carry out and evaluate fire tests on materials. Hence, these concepts will now be applied in the following chapters when assessing how building standards ensure fire safety.

# 3 Application of Fire Testing for the Built Environment

## 3.1 Introduction

The chapter will follow the structure illustrated in Figure 3-1. The sections greyed out are not to be discussed in this chapter. This chapter will be centred around the application of a result from a fire test and fitting it into the broader aim of fire-safe buildings and the built environment.

A brief overview of the requirements needed for fire protection will be provided in Section 3.2. As shown in Figure 3-1, the process will be explained below and in the following sections. The process of achieving these requirements will be supported by establishing a relationship between quantifiable fire parameters and the requirements, as illustrated by the red outline shown in Figure 3-1. These parameters are attained through fire testing, which will be further discussed in Chapter 5. However, information regarding the fire test results and their application is essential before an in-depth discussion of the fire tests can be obtained. Therefore, this chapter will further discuss the application of the outcome of a fire test. The various classification systems internationally across various countries will be examined according to the different standards discussed. This knowledge will allow the reader to have a broader understanding of the methodology employed by individual fire tests. A short discussion of an element design and the two methods linked to it, namely prescriptive and performance-based designs, will be examined, as provided in Section 3.5.

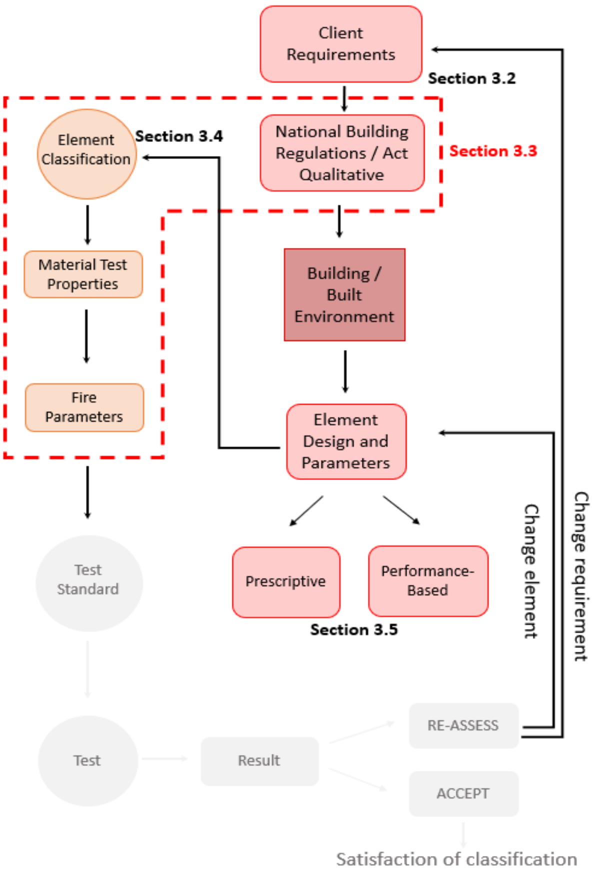



*Figure 3-1: Structure adopted for Chapter 3*

## 3.2 Requirements for Fire-Safe Buildings

Building requirements typically stem from the needs of a client, which inherently leads to performance criteria. Even if a client cannot articulate these in fire engineering terms, he/she has certain qualitative expectations in terms of safety, business continuity and environmental protection. Figure 3-1 indicates the process required to achieve the requirements first stipulated by the client. Before any design or test is commenced, the most critical question is, what performance of the element, material or product being tested is required by the client? This performance directly refers to a classification rating or criteria.

The client can also define one, or more end-user scenarios, referring to a building or a large or small room with different ignition sources and openings. The requirement by the client may also refer to a construction element such as lining materials, doors, flooring, cladding. These requirements must satisfy the building regulations as stipulated by a specific country, and client requirements may be more stringent or less stringent than national regulations.

A building regulation can be described as the minimum standard providing measurement criteria employed during building development and is typically enforced by law. The principal purpose of the building code is to achieve reasonable safety for the building's occupants and thus reasonable structural safety. The South African National Building Regulations (NBR) provide the general building fire protection requirements listed below. These requirements present a limited scope depending on the category of the building (Government of the Republic of South Africa, 1977) :

*(1) Any building shall be so designed, constructed and equipped that in case of fire:*

- *(a) the protection of occupants or users, including persons with disabilities, therein is ensured, and that provision is made for the safe evacuation of such occupants or users*
- *(b) the spread and intensity of such fire within such building and the spread of fire to any other building will be minimized*
- *(c) sufficient stability will be retained to ensure that such building will not endanger any other building: Provided that in the case of any multi-storey building, no major failure of the structural system shall occur*
- *(d) the generation and spread of smoke will be minimized or controlled to the greatest extent reasonably practicable; and*
- *(e) adequate means of access, and detecting equipment, fighting, controlling, and extinguishing such fire, is provided.*

[Note: In the sections that follow points (a) to (e) will be discussed in terms of specific requirements for safe buildings and how these can be achieved.]

*(2) The requirements of sub-regulation (1) shall be deemed to be satisfied where the design, construction and equipment of any building comply with SANS 10400-T:*

*Provided that where any local authority is of the opinion that such compliance would not comply with all the requirements of sub-regulation (1), such local authority shall, in writing, notify the owner of the building of its reasons for its opinion and may require the owner to submit for approval a rational design prepared by an approved competent person.*

In summary, the building process of safe buildings should be constructed and executed in such a manner as to provide reasonable safety for occupants of the building in the case of a fire. Materials, location and the end-use condition of the building should be taken into consideration. The structure should also provide emergency facilities and housing for fire protection equipment. Adequate protection to adjacent buildings from fire hazards should be provided through active response systems, separation distances and similar aspects (Bøhm, 1978).

To satisfy the above requirements of an ordinary building, as seen in Figure 3-2, the following questions arise; (a) how the material lining, i.e., cladding on the outside of the building wall will behave, (b) how the door, the roof, the floor, electrical cables and compartmentation functions are going to react, and (c) how the penetration of ducting or windows are going to affect the building behaviour in the event of a fire.

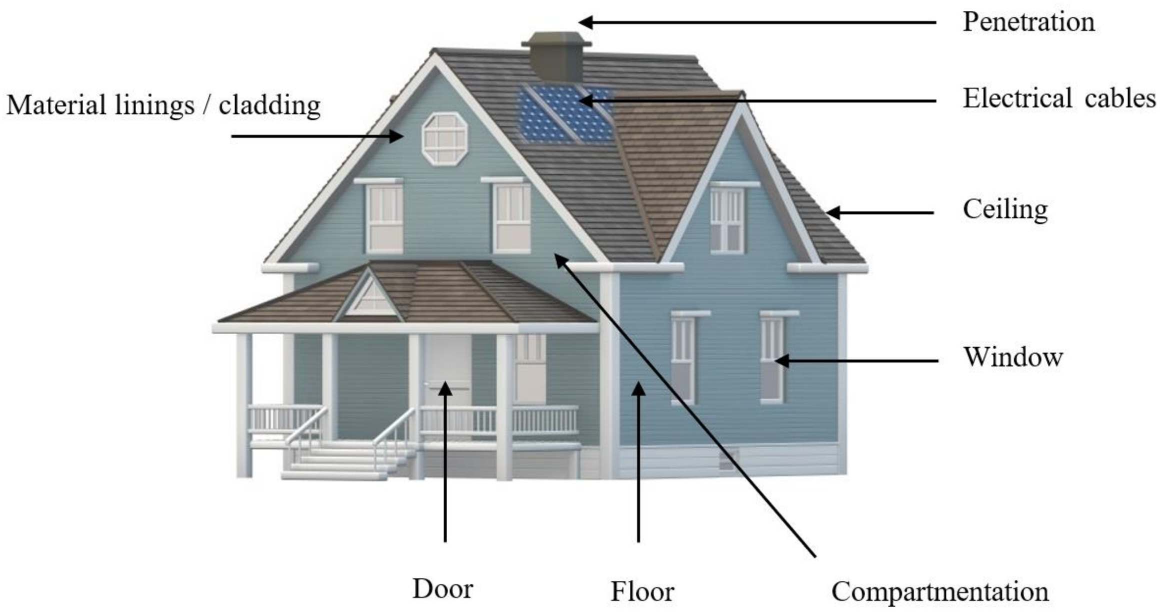



*Figure 3-2: Schematic of building elements (figure by author)*

The requirements can be summarized into three main parts relating to fire safety:

I. Means of escape – Provision of an acceptable evacuation method for individuals in the event of a fire breakout within a building.
II. Internal fire spread – In the event of a fire, the following aspects must be ensured within a building: structural stability, sufficient compartmental separation, prevention of smoke and fire spread in concealed areas and inhibiting flashover.
III. External fire spread – Exterior structural parts such as the walls and roof should provide sufficient fire resistance to prevent external fire spread.

As discussed in Section 2.3.5, referring to the time-temperature curve, the purpose is to prevent the rapid increase in heat release rate to prevent flashover and ensure the escape of the occupants. Therefore, the flame spread across the surface needs to be reduced and minimise the heat release rate from the surface. The development of specific fire tests will provide the means to understand these properties and how they can be measured to be controlled adequately (Sundström, 2007). In this work point (I) above will not be an explicit focus. However, it will be implicitly addressed by providing fire-safe construction products.

## 3.3 Relationship between Fire Parameters and Building Requirements

The section will consider obtaining a fire-safe building by assessing individual fire performance parameters and achieving the NBR requirements. This consideration forms the basis for comparing standards and test apparatuses in this work and serves as a theoretical basis for material classification, as discussed in the following section.

Considering the requirements outlined in the NBR above, the following are specific objectives that should be achieved, along with the clause on page 27 from which these details are derived, and fire parameters directly influence these:

1. Provision for safe evacuation - 1(a)
2. Limit spread of fire - 1(b)
3. Limit the intensity of the fire – 1(b)
4. Sufficient stability retained – 1(c)
5. Limit generation and spread of smoke – 1(d)

Other requirements presented in the NBR do not directly apply to construction material products such as fire detection, suppression and support for people with disabilities. Hence, they will not be explicitly considered.

The following are material or product parameters, as discussed in Chapter 2, which should be assessed and controlled to determine the extent to which they are fire safe, and whether the specific objectives listed above (1-5) can be achieved:

a. Material ignitability
b. Surface flame spread
c. Fire intensity
d. Smoke production
e. Structural resistance
f. Integrity resistance
g. Insulation resistance

The relationship between the NBR requirements and fundamental fire parameters can now be mapped in the following way, showing their interrelationship, as provided in Table 3-1. The properties within the table represent physical phenomena (e.g., critical heat flux (CHF)) or test results that can be measured. Based on the measured value of the property, the fire parameter can be assessed (e.g., ignitability). If the parameter requirements are satisfied, it will lead to various aspects of the NBR requirements being satisfied. This process is illustrated in Figure 3-3.

*Table 3-1: Relationship between NBR requirements for a fire-safe building and fundamental fire parameters*

| Fire Parameter | 1. Safe evacuation | 2. Spread of fire | 3. Intensity of fire | 4. Sufficient stability | 5. Smoke spread |
|---|---|---|---|---|---|
| **a. Material ignitability** | | CHF, IgTemp | CHF, IgTemp, Cal, FlameSR | | |
| **b. Surface flame spread** | | CHF, IgTemp, FlameSR | FlameSR | | |
| **c. Fire intensity** | | HRR, Cal, FlameSR | HRR, Cal, FlameSR | | |
| **d. Smoke production** | Smoke, Toxicity | Smoke | | | Smoke, Toxicity |
| **e. Structural stability** | R | | | R | |
| **f. Integrity** | E | E | E | | E |
| **g. Insulation** | I | I | I | | |

*CHF – Critical heat flux; IgTemp – Ignition temperature (spontaneous or piloted); Cal – Calorific value; HRR- Heat release rate; FlameSR – Flame spread rate; R – Structural resistance; E – Integrity resistance of systems; I – Insulation; Smoke – Smoke production rate; Toxicity – Toxicity of smoke*


*Figure 3-3: Process of establishing a fire-safe building*

In Table 3-1, it can be seen that one property can be a component of various parameters. A parameter can consist of multiple properties that influence or describes the parameter. For instance, the requirement of safe evacuation is influenced by smoke production, structural stability, integrity, and insulation. These are then described by properties that are measured or observed in fire tests. The properties have been given abbreviations and are listed below the table.

For instance, to prevent the spread of fire, (a) material ignitability, (b) surface flame spread and (c) fire intensity should be controlled. These are satisfied by measuring (a) critical heat flux and ignition temperature, (b) as per (a) along with flame spread rates, and (c) as per (b). Fire spread is additionally affected by (d) the production of smoke. The smoke can spread the fire if it contains embers or brands of incomplete combustion causing ignition of combustible materials. (f) Penetrations by flames through a material or sample can cause the unburnt areas of the material to lose their integrity and aid the flame spread process. If the (g) insulation parameter is violated, it may subject the material to spontaneous combustion and spread the fire.

The parameters of (e) structural resistance, (f) integrity resistance and (g) insulation resistance are all quantified by indices referred to as R, E and I. These are not explicitly measured as they are just an index based on standard fire exposure time, assigned to each respective parameter. The actual properties that are measured will be explained in Section 3.4.2.2 (e.g., a load-bearing resistance of 30 minutes) as they are too intricate based on the material tested and other factors to be mentioned in Table 3-1.

Based on the discussions above, it can be observed that several parameters and properties need to have suitable performance or values for a building to achieve an acceptable level of fire safety. However, this necessitates carrying out multiple tests and compiling the results into a single classification system. Engineers can then use specific products suitable for different risk scenarios, which will now be discussed for the European, South African, and the Fire Propagation Index (primarily British based).

## 3.4 Classification Process

### 3.4.1 Introduction

This section will discuss the need to develop a sound engineering philosophy for testing construction products. This philosophy will be based on various classification processes implemented as per Figure 3-4. One route can be the classification of the material properties within Table 3-1 and measured through testing. The other route is the classification of the material fire parameters, which pertains explicitly to fire-resistance criteria.


*Figure 3-4: Classification process*

Furthermore, this section will provide a background and overview of the classification process as implemented by the European Union countries. The discussion will include classification systems for reaction-to-fire and fire resistance of building products (EN, 2009).

As per the objectives of this thesis and the established regulations and requirements in Section 3.2, the South African classification process will also be examined. Lastly, additional classification methods implemented in other parts of the world will be briefly considered.

### 3.4.2 European Classification System

In the past, pan-European standardisation of construction products was inadequate. Manufacturers, designers and engineers had to deal with this lack of uniform assessment of the fire performance of the products they manufactured, designed or utilised.

The national standards for each country were developed in-house, causing many standards across Europe. In the 1970s, six national laboratories surveyed numerous European test methodologies used to rank the flammability of 24 different lining materials used in buildings, according to each country's test and classification procedure (Emmons, 1974). The results shown in Figure 3-5 illustrate the alarming distribution and variation in the results between countries. Problems identified included new products continuously arriving on the market and the complication of the range of applications.

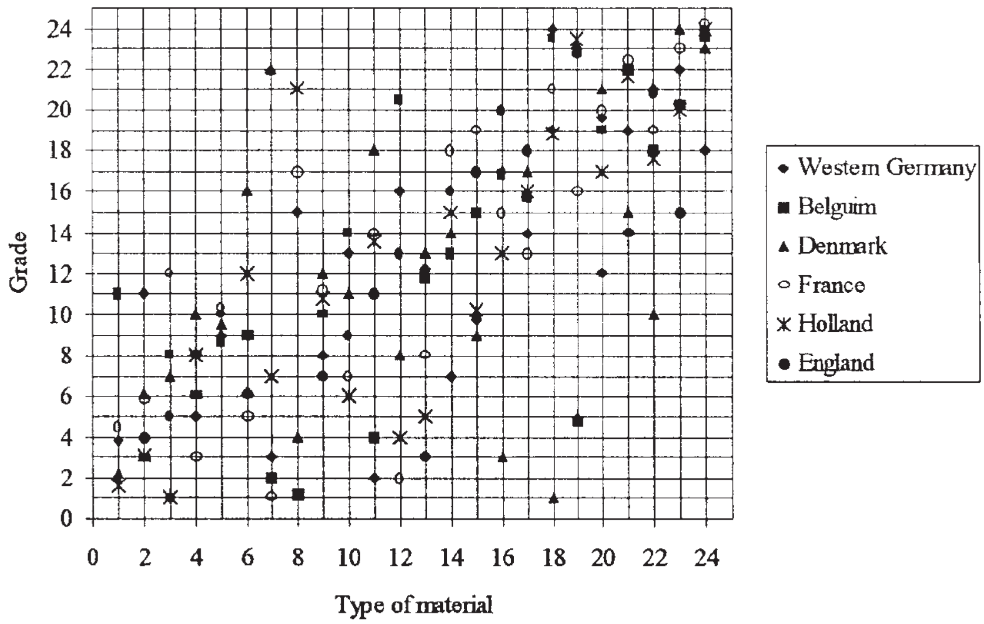



*Figure 3-5: The ranking of 24 lining materials based on fire tests conducted in various European countries (Emmons, 1974)*

The European reaction-to-fire classification system was established to harmonise and replace the different national standardized tests and classifications. At the end of 1988, the European Commission published the Construction Products Directive (CPD), and the classification system was in support hereof.

In 1994 a Commission Decision first presented the different classes of reaction-to-fire performance. These classes were linked to specific test standards that will be discussed in the following sections. However, this decision did not provide the limits for the defined classes; thus, a new test method, the SBI, was developed (Messerschmidt, 2008). The European Commission published the Euroclasses in 2000. However, this Commission Decision was not operational until the SBI test was published as a European Standard and later adopted as a British Standard (BS EN, 2010a). The SBI standard describes various end-use conditions represented by standard substrates to reduce the number of tests performed and produce a more generalised result. Product samples can be attached to these substrates before testing is commenced.

Seven Euroclasses and elements now exist in the classification standards with several correlations between them. Five European test methods are in place and will be discussed in Section 5.3.

These test methods, as mentioned earlier, all test various properties that describe specific parameters. The parameters satisfy the list of requirements set out in the regulation by the specific nation. The Construction Product Regulation (CPR), in 2011, replaced the CPD. Six interpretative documents were published to link the essential requirements that were stipulated in the CPR. The second essential requirement listed is safety in case of fire. The CPR also includes the mandates for preparing harmonized standards and guidelines for European technical approvals. The interpretative document encompassing safety in case of fire defines several measures to satisfy the essential requirement (European Union, 2011).

As previously discussed, these measures can be referred to as parameters. One of these parameters is inhibiting the generation and spread of smoke and fire within a room. The contribution of building products to the development of a fire should be limited. The document further states that the different classes of reaction-to-fire performances of the products in their end-use conditions are the only way to express the limitation (Sundström, 2007).

Therefore, to assign a particular classification to a material, test results must be interpreted and assessed, and the boundary conditions must be included in this analysis. Currently, this classification method is a direct field of application (DIAP) (DIN EN, 2010). The DIAP is mainly based on data from fire resistances tests. Additionally, if a product is of different dimensions and cannot be tested, a vast field of application (EXAP) standard is applied to confirm its performance (BS EN, 2010b).

The harmonisation of fire test standards within the European Union (EU) proved to be meaningful in providing simplification and standardisation as aimed. Essentially, the harmonised tests and standards are in place. However, the philosophy regarding what level of classification for fire safety of construction products is acceptable is still the responsibility of each Member State (European Union, 2020).

In the field of fire, the essential specifications are published by two different entities. The definitions of Euroclasses and the regulations for declaration of conformity are published by the European Commission as stated. However, the CEN European Standardization body and ISO are responsible for publishing the harmonised test and product standards.

A classified product can be CE marked (i.e., shows compliance to EN regulations) if the harmonised technical properties have been verified and compliance was reached. However, since these building fire safety regulations have been established, there has been some concern for legislators and authorities. These concerns pertain explicitly to the reaction-to-fire of building products. An intense ongoing process is underway to develop other reaction-to-fire test methods and ranking systems (Horrocks and Price, 2001).

#### *3.4.2.1 Reaction-to-fire classification*

The reaction-to-fire classification system for building products mainly considers surface covering, insulation and pipe insulation materials. Floor coverings and cables are also considered. Each classification means that specific parameters are tested and achieved for product testing within a particular end-use application. The European classification system procedure for the reaction-to-fire test results are provided in EN 13501-Part 1 (EN, 2009). This European Standard aims to establish a standardized method for classifying building goods' fire resistance. This classification is based on the methods provided for testing and the procedures for the appropriate field of application. The classification standard lays out broad requirements, a reporting model, and background information on the entire testing and classification system. As specified in Appendix A, Table A- 1, this classification system allows for additional tests to increase the accuracy of a specific classification class.

The building product groups are all treated similarly. However, the contributions of the Swedish work to the broader field of harmonisation led to certain class boundaries (Thureson *et al.*, 2008). The boundary conditions for surface coverings, pipe insulations and cables are all based on this work.

The European test standards used to determine the Euroclasses is described in Table 3-2.

*Table 3-2: European reaction-to-fire tests standards defined*

| Test | Definition |
| --- | --- |
| EN 13501 | Fire classification |
| EN 13238 | Standard substrates for product samples |
| EN ISO 1182 | Non-combustibility furnace test |
| EN ISO 1716 | Bomb calorimeter |
| EN ISO 13823 | Single Burning Item (SBI) |
| EN ISO 11925-2 | Small flame test |
| EN 14390 (ISO 9705) | Room corner test |
| EN ISO 9239-1 | Radiant panel floor test |

As will be explained in Section 4.2, the SBI holds importance in the classification system. The CPR of the European Commission has stipulated that they, instead of the traditional regulatory methods used in each country, classify most building products. It will be required that all European Member States tests and classify building products sold in Europe using the Single Burning Item test method. (European Commission, 2003).

All construction products, excluding floor coverings, are allocated into seven main classes, A1, A2, B, C, D, E and F. The classes are accompanied by additional classifications relating to smoke production and the number of flaming droplets and particles. The smoke generated by a product during a fire can be classified as s1 (little or no smoke), s2 (visible smoke) and s3 (substantial smoke). Burning droplets or particles can be either a d0 (nothing), d1 (some) and d2 (plenty).

**Euroclass F:** The lowest class, F, is for products that have not been tested or have failed the EN reaction-to-fire tests.

**Euroclass E:** Products are only tested for 15 seconds with the application of a small flame. Measurable results are ignitability and flame spread.

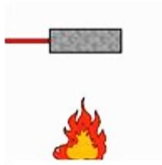
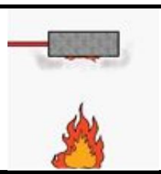
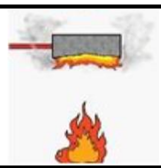
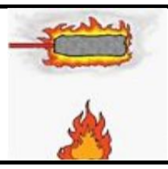
**Euroclass D, C, B:** The first SBI-test, wherein a total sample is tested. A small flame test is also used with a 30 second flame application period. The criteria of the products will be based on the flame spread rate, the extent of damaged and if flaming droplets is produced.

**Euroclass A2:** The Non-combustibility test is performed, and there is also a test for the calorific content of the product, namely the bomb calorimeter test. The parameters used in these tests are similar to those used for Euroclass A1 classification; however, they consist of different numerical values. The SBI test is also utilised in which the parameters, HRR, flame spread, smoke production and the generation of flaming particles are tested.

**Euroclass A1:** Only the calorific content, which should be of a negligible value, is tested.

Classes A1 and A2 are non-combustible, where materials from these classes do not contribute significantly to a fire. These classifications are summarised in Table 3-3. This classification method is based on a compounding level of testing where every class must abide by stricter rules set out.

*Table 3-3: Euroclass classification identification* (Mercor Tecresa, 2018)

| Class | Performance description | Illustration |
|---|---|---|
| A1<br>Non- combustible | No contribution to fire |  |
| A2<br>Non- combustible | No significant contribution to fire |  |
| B<br>Combustible | Minimal contribution to fire |  |
| C<br>Combustible | Limited contribution to fire |  |
| D<br>Combustible | Contribution to fire |  |
| E<br>Combustible | A significant contribution to fire |  |
| F<br>Combustible | Non tested materials | |

According to the EN 13501-1 standard, Table 3-4 provides the relevant tests required to achieve the specific Euroclass criteria. Details of the tests will be discussed in Chapter 5.

*Table 3-4: European reaction-to-fire tests with the class requirement* (recreated from EN, 2009)

| Euroclass | EN ISO 1716<br>Bomb calorimeter | EN ISO 1182<br>Non-combustibility | EN 13823<br>SBI | EN 11925-2<br>Ignitability |
|---|---|---|---|---|
| **A1** | ✓ | ✓ | | |
| **A2** | ✓ | | ✓ | |
| **B** | | | ✓ | ✓ |
| **C** | | | ✓ | ✓ |
| **D** | | | ✓ | ✓ |
| **E** | | | | ✓ |
| **F** | | | | |

Linings are categorised using classes B through E, which may reduce or delay flashover in a room for specific periods, as shown in Figure 3-6. Floor coverings are classified separately; however, only seven classes define floor coverings, as shown in Table 3-5.

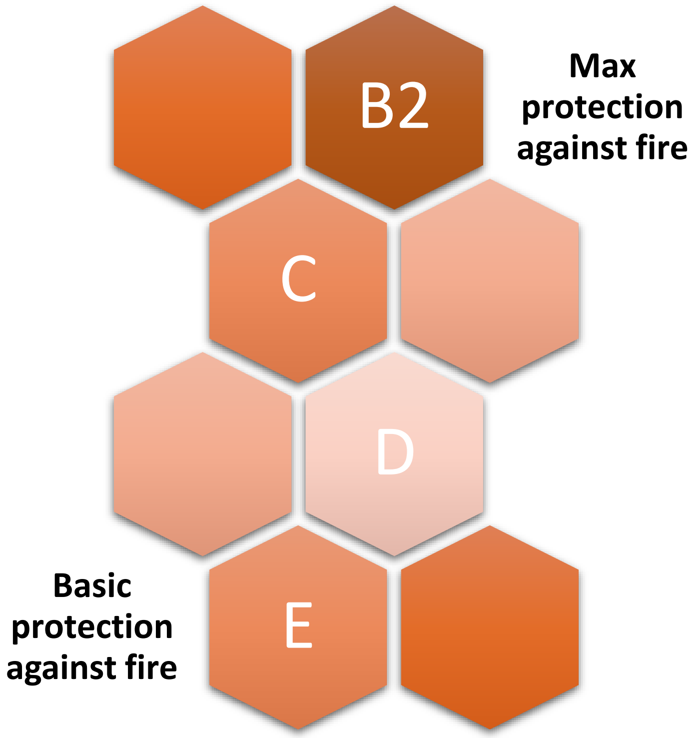



*Figure 3-6: Lining categorisation according to the Euroclasses (figure by author)*

*Table 3-5: Euroclass classification of floor coverings identification*[1] (recreated from EN, 2009)

| Class | Performance description | |
|---|---|---|
| $A1_{fl}$ | Only achievable by non-flammable floor coverings which do not present any risk in terms of smoke formation | Non-Combustible |
| $A2_{fl}$ | Only achievable by non-flammable floor coverings with low levels of organic binding agents | |
| $B_{fl}$ | Radiation intensity of 8 kW/m$^2$ = flame retardant construction products | Combustible |
| $C_{fl}$ | Radiation intensity of 4.5 kW/m$^2$ = flame retardant construction products | |
| $D_{fl}$ | Radiation intensity of 3 kW/m$^2$ = flame retardant construction products | |
| $E_{fl}$ | Small burner test = normally flammable construction products | |
| $F_{fl}$ | No requirements made<br>No test = easily flammable construction products | |

[1] *fl refers to floor covering*

As illustrated in Table A- 4, this classification system offers approximately 40 different combination classes of lining materials, and 11-floor covering material combinations are also provided. Only a small number of the possible combinations are expected to be used by each European country. Table 3-6 provides the relevant tests required to achieve the specific Euroclass criteria for floor coverings. The reader can refer to the EN 13501-1 (EN, 2009) for information regarding the classification of linear pipe thermal insulation products as they are not within the scope of this paper and will thus not be discussed.

*Table 3-6: European reaction-to-fire tests with the class requirement for floor coverings* (recreated from EN, 2009)

| **Euroclass** | **EN ISO 1716 Bomb calorimeter** | **EN ISO 1182 Non-combustibility** | **EN 13823 SBI** | **EN 11925-2 Ignitability** | **EN ISO 9239-1 Floor radiant panel** |
|---|---|---|---|---|---|
| $\mathbf{A1}_{fl}$ | ✓ | ✓ | | | |
| $\mathbf{A2}_{fl}$ | ✓ | ✓ | | | ✓ |
| $\mathbf{B}_{fl}$ | | | | ✓ | ✓ |
| $\mathbf{C}_{fl}$ | | | | ✓ | ✓ |
| $\mathbf{D}_{fl}$ | | | | ✓ | ✓ |
| $\mathbf{E}_{fl}$ | | | | ✓ | |
| $\mathbf{F}_{fl}$ | | | | | |

The smoke emission is measured using two parameters, the smoke growth rate and the total smoke production in 10 minutes. Tables 3-7 and 3-8 provide the classification definitions for the above-mentioned required measurements.

*Table 3-7: Classification of smoke emission* (recreated from EN 2007)

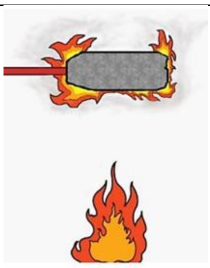
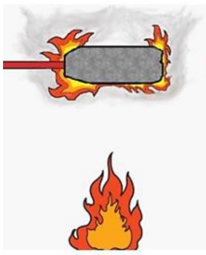
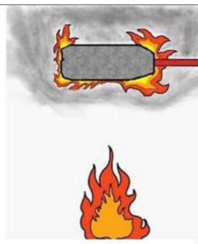
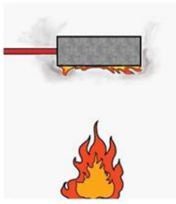
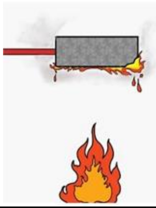
| **S1** | **S2** | **S3** |
|---|---|---|
| Smoke growth rate $\leq 30$ m$^2$/s$^2$ | Smoke growth rate $\leq 180$ m$^2$/s$^2$ | Smoke growth rate $> 180$ m$^2$/s$^2$ |
| Total smoke production in 10 min $\leq 50$ m$^2$ | Total smoke production in 10 min $\leq 200$ m$^2$ | Total smoke production in 10 min $> 200$ m$^2$ |
|  |  |  |

*Table 3-8: Classification of flaming droplets* (recreated from EN 2007*)*

| d1 | d2 | d3 |
|---|---|---|
| No flaming droplets | Flaming droplets falling during < 10 s over a 600 s timeframe | Flaming droplets falling during < 10 s over a 600 s timeframe |
|  |  |  |

The degree of combustibility during a standard reaction-to-fire test is measured by considering several concepts that need to distinguish between the different Euroclasses, as provided in Appendix A, Table A-2. The required numerical limitations and requirements for these concepts to describe a specific class is provided in Table A- 3. The FIre Growth RAte (FIGRA) index was developed by Sundström (2007) during the development process of the SBI. The index was a manner in which test data for fire classification could be interpreted. The values attached to the FIGRA index is calculated from SBI data.

#### *3.4.2.2 Fire resistance classification*

Building materials tested and classified for fire safety and fire resistance of buildings will be discussed here. The European classifications are provided in EN 13501-2 (BS EN, 2016), and the document provides procedures for dividing the fire resistance test results into classes.

The test results of the building elements and structures for loadbearing capacity (R), integrity (E), and insulation (I) are converted into a list of predetermined classes. Load bearing elements, such as columns, need to satisfy the stability criteria by maintaining sufficient resistance to prevent failure and ultimately the global collapse of a structure during the event of a fire.

Separating members such as walls and partitions must prevent flames and hot gases from penetrating adjacent compartments to minimise fire spread and satisfy the integrity criteria. The temperature on the unexposed surface of separating members needs to be kept low enough to satisfy the insulation requirement. Most standards specify an average and maximum temperature rise of 140℃ and 180℃ respectively to prevent spontaneous ignition of members in close contact with the separating member, as illustrated in Figure 2-9.

Moreover, an index indicating the time, rounded down to the nearest 15 or 30 minutes, for the property or class is maintained and assigned as illustrated below in Figure 3-7. For example, a loadbearing wall with a capacity of 155 minutes, the integrity of 80 minutes and insulation of 42 minutes would be classified as R120, RE60 and REI30.

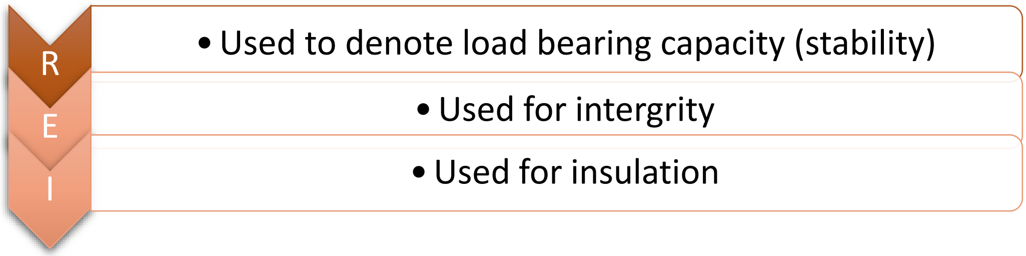



*Figure 3-7: Fire resistance index (figure by author)*

### 3.4.3 South African Classification System

As a brief explanation of how the South African process to fire safety has been developed, reference will be made to the 5-level hierarchy applied in the South African context (De Villiers and Boshoff, 2012). The objective is described in the National Building Regulations (Government of the Republic of South Africa, 1977) and Building Standards, SANS 10400. The regulation is divided into 23 chapters. SANS 10400-T (SANS, 2020) discusses fire protection. A normative reference is made to the SANS 10177 suite of testing standards to satisfy the individual requirements, and when satisfied, it shall be classified against a different standards protocol.

Therefore, in South Africa, no harmonised classification system exists but rather individual tests. Instead, the SANS 10177 suite describes “Fire testing of materials, components and elements used in buildings”, consisting of 12 different parts, Table 3-9. Each part, however, makes a normative reference to a different standard to classify the respective member that was tested according to SANS 10177. Thus, depending on what type of product is used, a specific test will be carried out to obtain a classification against a single standard.

*Table 3-9: SANS 10177 description of standards* (recreated from SANS, 2005a)

| Supplier | No. | Part | Description or member tested |
|---|---|---|---|
| **SANS** | 10177 | 1 | General introduction to the methods of test |
| **SANS** | 10177 | 2 | Wall / Partition / Floor / Ceiling / Beam / Column |
| **SANS** | 10177 | 3 | Surface fire index of finishing material |
| **SANS** | 10177 | 4 | Surface fire index of floor coverings |
| **SANS** | 10177 | 5 | Non-combustibility at 750 °C of building materials |
| **SANS** | 10177 | 6 | Non-combustibility at 300 °C of electrical insulation materials |
| **SANS** | 10177 | 7 | Fire test for fire-check properties of building elements |
| **SANS** | 10177 | 8 | Surface burning characteristics of building materials |
| **SANS** | 10177 | 9 | Small-scale burning characteristics of building materials: ignition, flame spread and heat contribution |
| **SANS** | 10177 | 10 | Surface burning characteristics of building materials using the inverted channel tunnel test |
| **SANS** | 10177 | 11 | Large-scale fire performance evaluation of building envelope thermal insulation systems (with or without sprinklers) |
| **SANS** | 10177 | 12 | Test methods for fire tests of roof coverings |

This thesis will only focus on the standards of construction materials and testing methods comparable to the European standards. As indicated in Table 3-9 parts 3 (SANS, 2005b) and 4 (SANS, 2005c) of the SANS 10177 suite explain the surface fire index of finishing materials and floor coverings. The classification method provides five different classes. The Surface Fire Index is a method of classification based on the extent of flame spread of the surface ($I_f$), the smoke density ($I_s$) and the overall heat contributed ($I_h$) by the sample. As indicated in Table 3-10, these three contributions provide an overall Surface Fire Index (F). The relevant calculations for each index are described in the applicable testing standards. The classification for floor coverings follows a similar suite, although the calculations are vastly different. The fire resistance furnace test is utilised as a testing method for both standards.

*Table 3-10: Classification of finishing materials* (SANS, 2005b)

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| Class | Maximum value | | | |
| | Spread of flame index $I_f$ | Heat contribution index $I_h$ | Smoke emission index $I_s$ | Surface fire index F |
| 1 | 0.1 | 0.1 | 0.2 | 0.1 |
| 2 | 0.7 | 0.8 | 1.0 | 0.6 |
| 3 | 1.5 | 1.7 | 2.0 | 1.2 |
| 4 | 3.5 | 3.8 | 4.0 | 2.9 |
| 5 | 5.5 | 5.8 | 6.0 | 4.5 |

Table 3-11 indicates the standards that will undergo further analysis and the classification standard that evaluates the respective tests. These testing standards will be discussed and described in Chapter 5.

*Table 3-11: Evaluation protocol of material classification*

| Testing standard | Classification standard | Testing regime |
|---|---|---|
| SANS 10177-2 | SANS 1253 | Fire doors and fire shutters |
| SANS 10177-5 & SANS 10177-10 | SANS 428 | Non-combustible products |
| SANS 10177-5 & SANS 10177-10 | SANS 428 | Combustible products |

As determined by SANS 10177-5, combustibility relates to materials used to construct and finish buildings. According to their behaviour in the non-combustibility test, they are classed as non-combustible or combustible, as shown in Table 3-12.

*Table 3-12: Combustibility as per SANS 10177-5*

| Class | Combustibility |
|---|---|
| A | Non-combustible |
| B | Combustible |

The surface properties classification process utilises the testing methods of SANS 10177-10. The symbolic classification of non-combustible materials as determined with SANS 10177-10 will be provided in Table 3-13. In contrast, the combustible materials symbolic classification as determined with the same testing methods is given in Table 3-14. The products shall then be used following the Occupancy Classifications in the building regulations (TIPSASA, 2019).

*Table 3-13: Symbolic classification of non-combustible materials* (TIPSASA, 2012)

| Small-scale application<br>Flame spread from back wall (mm) | Behaviour of material | Classification |
|---|---|---|
| ≤ 2000 | No flame spread | A1 |
| ≤ 3000 | Low flame spread (no flaming droplets included) | A2 |
| | Low flame spread (flaming droplets included) | A3 |
| ≤ 4000 | Average flame spread (no flaming droplets included) | A4 |
| | Average flame spread (flaming droplets included) | A5 |
| > 4000 | Rapid-fire spread | A6 |

*Table 3-14: Symbolic classification of combustible materials* (TIPSASA, 2012)

| Surface fire properties | | Classification |
|---|---|---|
| Small-scale application<br>Flame height from fire source (mm) | Behaviour of material | |
| ≤ 2000 | No flame spread | B1 |
| ≤ 3000 | Low flame spread (no flaming droplets included) | B2 |
| | Low flame spread (flaming droplets included) | B3 |
| ≤ 4000 | Average flame spread (no flaming droplets included) | B4 |
| | Average flame spread (flaming droplets included) | B5 |
| > 4000 | Rapid-fire spread | B6 |

Recent developments in South Africa have led to discussions regarding an amendment to SANS 10400-Part T to align with European practices. Further discussions will follow in Chapter 6 concerning the adoption process South Africa has followed and the shortfalls regarding this process.

### 3.4.4 Fire Propagation Index Classification System

Initially proposed in the 1960s alongside the Fire Propagation Test (FPA) (NFPA, 2022), the Fire Propagation Index (FPI) will be discussed in Section 5.3.8 and is now used in Britain within BS 476 Parts 6 and 7 (BS, 1989). It is an alternative classification system for materials.

The FPI describes the results of the FPA. A comparative analysis is provided of the performance contribution of lining material to the growth of a fire. However, Azhakesan *et al.* (1994) recognised that a burning lining material risks releasing an amount of hearing early. Weightings were suggested to be applied to the indices to highlight the temperature rises. An ‘I’ and sub-indices $i_1$, $i_2$ and $i_3$ were assigned to the values. The higher the fire propagation index ($i_1$ $highest$), the greater the effect that the product has on speeding up the fire growth.

The fire propagation index is thus calculated by summating the three-time based subindices using the following equation:

$$I = \sum_{1/2}^{3} \left(\frac{T_m - T_c}{10t}\right)_{i1} + \sum_{4}^{10} \left(\frac{T_m - T_c}{10t}\right)_{i2} + \sum_{12}^{20} \left(\frac{T_m - T_c}{10t}\right)_{i3} \qquad 3.1$$

where:

| | | |
|---|---|---|
| $I$ | = | The overall index of performance |
| $i_1$ | = | Calculated at $\frac{1}{2}$ minute intervals over 1 min - 3 min period |
| $i_2$ | = | Calculated at 1-minute intervals over 4 min – 10 min period |
| $i_3$ | = | Calculated at 1-minute intervals over 12 min – 20 min period |
| $t$ | = | Time in minutes from the start of the test |
| $T_m$ | = | Temperature rise recorded for the material at time $t$ |
| $T_c$ | = | Temperature rise recorded for the non-combustible standard at time $t$ |

Therefore, a material that would satisfy the Building Regulations Class 0 satisfied the condition of $i_1 \leq 6$ *and* $I \leq 12$ (HM Government, 2010).

Various literature studies have been performed on the FPI. In the mid-1970s, FM Global applied calorimetry methodologies to assess heat release rate due to convection and radiation (Tewarson, 1977). Khan and Chaos (2016) also provide an in-depth discussion regarding the FPI and its description of the fire behaviour of materials in large-scale fires under radiating flame conditions.

## 3.5 Prescriptive versus Performance-Based Design (PBD)

### 3.5.1 Background and Overview

Extensive background and introductory aspects on the topic of prescriptive and PBD were discussed in Section 2.6. Regarding this section, reference will be made to Figure 3-1. The process to meet the requirements and provide input to the built environment in terms of a prescriptive or performance-based design strategy will be examined.

After the client requirements, a design process is required, and the NBR has been formulated to create the built environment. The procedure is to design an element that is either prescriptive or performance-based. The construction element still requires a form of classification, as discussed in Section 3.3.

According to the required classification, a fire test standard will be assigned to test the element for a prescriptive design. A set of parameters will emerge from the test performed that will be deemed acceptable in satisfying the classification condition or require reassessment. A performance-based design may acquire evaluation on whether the element matches up to the requirements of the building. Either the element may need to be redesigned, or the client requirements may need to be updated. To reiterate, the design process specifies what classification or result is required. Building on the understanding of the relationship of the requirements, the parameters and material properties, in Section 3.3, the classification condition indicates what testing standard will be used to perform the test that will comply with the classification need.

### 3.5.2 Prescriptive versus Performance-Based Design Standards Comparison

Introducing the concepts of performance versus prescriptive based testing and comparisons, a simple case study is provided below to illustrate this topic. Figure 3-8 shows a walling system developed for a hospital requiring a specific fire-resistance rating. An initial question to be posed is: would results from bench-scale testing provide comparable fire resistance to that of the full-scale test shown in the picture? Also, what fire scenario should be used for the design?


*Figure 3-8: Drywall sandwich panel large-scale furnace test* (Gerhard Gous, 2021)

For the case study, the rating was based upon building regulations. Safety is a high priority since this is for public health infrastructure, so obtaining reduced fire ratings on products is less advisable. The consequence of failure would be high. Hence, standard fire testing was selected to be consistent with NBR requirements. However, the walling system was not a conventional configuration due to client requirements. Hence, to ensure safety, (a) performance-based geometric and material specification was carried out, with (b) a prescriptive testing approach.

- Since the walling system is not combustible, reaction-to-fire testing is not required.
- Since the walls must serve to provide compartmentation, integrity and insulation resistance are essential. However, load-bearing resistance was not required, as the system was within a load-bearing concrete frame.
- The wall can crack during testing, and large deflections would be problematic and affect performance. Hence, bench-scale tests are not suitable.

The discussion above highlights how NBR, client, prescriptive and performance-based requirements can come together and lead to a specific test to obtain material properties and fire resistance ratings. Such a simple example serves as an introduction to highlight aspects that can be considered and contrasted when comparing the many fire tests described in Chapter 5 and compared below.

From the discussions above, an important question can be highlighted: could a performance-based design using a client-defined fire scenario be directly compared with the standard fire test regime carried out as described above? As introduced in Section 3.4.3, this is impossible since the different failure criteria are not linearly related to the fire exposure times and temperatures. Hence, it would have been possible for this hospital to use a different fire scenario, but the results would have been primarily applicable to that fire scenario.

## 3.6 Conclusion

The objective of providing a fire-safe building was discussed in this section. The national building regulations of South Africa were presented as the requirements to achieve this objective. It was determined that the regulations could be satisfied by quantifiable fire parameters. These may consist of one or multiple material test properties measured, calculated, observed or evaluated by performing fire tests. A relationship was described between the parameters and the regulations that form the basis of the classification process.

The process was introduced to conclude how the fire parameters or material test properties are used after being evaluated. The European and South African classification process were discussed. Comparing and contrasting these two processes leads to the following conclusions:

- The European approach provides seven classes for flammability of materials compared to SA’s five classes.
- Harmonised European classification system as opposed to standalone tests.
- European system leads to a more significant number of tests (5) potentially required per product.
- SA only provides two tests that give comparable results to the European tests.
- Classifications are not relatable between the SA and European approaches.
- Fire resistance classifications are similar but with different annotations.

These conclusions force us to understand the requirements and influences on testing methods that lead to classification methods. Fire tests also need to be understood to establish the limitations and the reasons for the differences between these two classifications systems. The fire tests will be examined in Chapter 5. The influences, however, will become important in a comparative analysis between fire test standards that will be discussed in Chapter 6.

# 4 Methodology to Compare Fire Test Standards

## 4.1 Introduction

This chapter will focus on the methodology required and the aspects to consider when comparing fire test standards. The objective is to provide a framework and background for the comparative analysis in Chapter 6. This chapter is structured as follows: Section 4.2 provides a comparative reference scenario that has been used in the development of the Eurocodes for contrasting test procedures and the data they provide. It is mentioned as an example of how fire test standards can be compared.

A brief discussion on what aspects need to be considered when comparing fire test standards will be provided in Section 4.3. The main aspects discussed include the essentials required for testing and how these influence testing standards, such as whether samples are tested horizontally or vertically and what heat source is used. An indication of how different elements can be tested and their overall effect on fire testing standards will be presented in Sections 4.3.1 and 4.3.2.

Finally, Section 4.3.3 presents observations and measurements made during tests to outline the unique data that tests can obtain. This section is essential to provide accurate information on whether or not the obtained data can be compared across different test methods and fire testing standards in Chapter 6. A summary of the methodology required to execute a comparison will be established.

## 4.2 Eurocode Reference Scenario for Test Method Comparison

Before discussing how to test standards will be compared in this work, a procedure that the European regulators have carried out is presented in this section. In the literature, it is referred to as the reference scenario (European Commission, 2003). The reference scenario can be considered an investigation into how a single methodology can be used to assess fire safety and the extent to which it compares to results from other test methods. The scenario was meant to assist the development of the European classification system. The entire Euroclass system was directly linked to perceived hazards in a reference scenario, leading to a comparative testing methodology. A fire in a room was defined as the single reference fire scenario for the Euroclass system. The Room Corner test was developed to define this room fire as the single large-scale reference scenario test to make it a centralized assessment system (European Commission, 2003). Ultimately, the philosophy that was obtained was that the single burning item (SBI) test as described in Section 5.3.6 was developed to assess the performance of building materials in a room corner scenario.

The SBI results were compared to full-scale tests based on the ISO 9705 Room Corner Test, as discussed in Section 5.3.4. Firstly, the product ranking in the SBI test had to provide a high correlation to the room corner test as a primary objective. Secondly, the characteristics required by the room corner test had to be measured in a repeatable and reproducible manner by the SBI test methods. This philosophy of the European testing and classification system for building materials and their reaction to fire is illustrated in Figure 4-1.

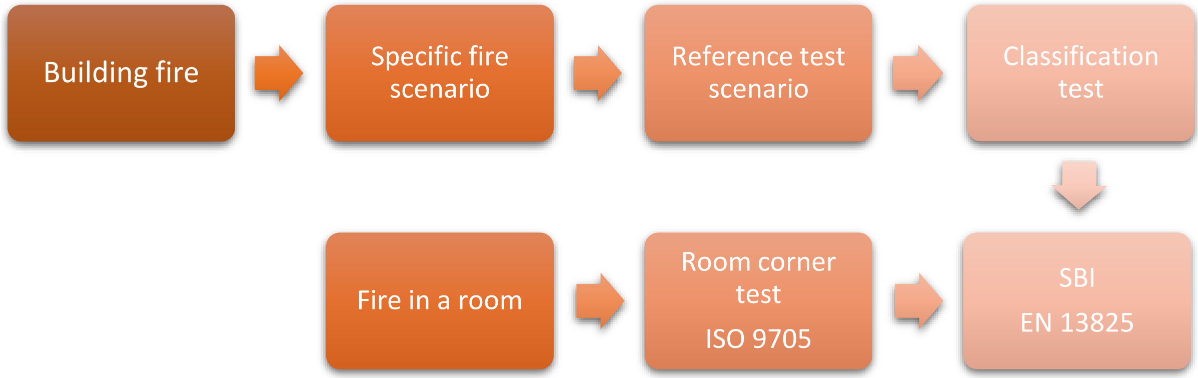



*Figure 4-1: Harmonised European testing and classification system (recreated from Messerschmidt, 2016)*

Concerning the SBI test, in 1997, a round-robin test including 20 laboratories and 30 different construction products were tested using the SBI to define the performance of the products in an intermediate-scale test when exposed to one single fire (Van Mierlo and Sette, 2005).

The same 30 products were also tested in the reference test apparatus (i.e., large-scale room corner test). Those results yielded four main clusters of products regarding time to flashover as it was regarded as the most critical parameter. The four categories were: (a) flashover reached within 2 minutes, (b) flashover occurring between 2 and 10 minutes, (c) flashover between 10 and 20 minutes, and (d) flashover never reached. Only when the products' behaviour in the SBI test correlated with their behaviour in the Room Corner Test can class limits be set using this technique. Hence, the properties of flame spread rate, heat release rate, ignition temperature, critical heat flux and calorific value are inherently assessed by considering overall fire behaviour in relation to flashover.

It was necessary to develop a method for quantifying fire spread to create the four categories. The Fire Growth Rate (FIGRA) was thus produced, as discussed by Sundström (2007), and is now one of the leading classification parameters introduced. The FIGRA, as will be discussed in Section 5.3.6, can be used to provide a measure that leads to material categorization. In work, Sundström noted that the SBI test and the utilisation of the FIGRA parameter as the primary classification parameter could predict the risk correctly for almost 90% of the construction products. FIGRA is a classification criterion first proposed in 1998 to classify the fire qualities of building items for the CPD. For two reasons, the parameter FIGRA is unique.

1. It uses reference situations to forecast the burning behaviour of a wide range of building materials. These reference situations, in turn, are linked to actual fires.
2. It is a part of the CPD harmonised instructions.

As a result, FIGRA can be used on a wide variety of objects. The increased rate of burning intensity and HRR during a test utilizing the SBI is characterized as FIGRA. FIGRA is determined as the function's greatest value (heat release rate)/ (elapsed test time), where Watts/second is the unit.

In addition, before FIGRA can be determined, certain HRR and total heat release rate thresholds must be met. Threshold settings are required to avoid including minimal and early HRR values, which would result in unrealistic FIGRA levels. EN 13823 contains a full definition of FIGRA (BS EN, 2010a).

However, using the SBI as a single criteria method for quantifying fire resistance has significant limitations, as will be discussed in Section 6.4.2**.** It has been identified that a more comprehensive assessment of products is required, and a single parameter (FIGRA) is insufficient for considering the wide-ranging and complex response of materials to fire. Hence, various authors have criticized this and highlighted the need for multiple tests and parameters to be obtained for each material (Messerschmidt, 2008). Hence, it was necessary to develop classification systems (European Commission, 2003), as discussed in Section 3.4.2.

## 4.3 Aspects to Consider when Comparing Fire Test Standards

### 4.3.1 Testing Essentials

The essential testing inputs form a fundamental step in the methodology process. The inputs must be analysed in order to equate and compare two test methods with one another. The inputs examined in this section are the sample preparation, composition, size and mounting, end-use function, specimen orientation, and material variation. Each fire test standard, which relates to a specific test that is performed, considers all of the inputs mentioned above, as discussed in Section 5.

#### *4.3.1.1 Sample preparation*

The samples selected for the suitable testing method need to be representative of the end-use conditions. Other factors that require consideration will also be discussed.

#### *4.3.1.2 Sample composition*

Samples tested can consist of a single homogenous material or a multi-layered composite system, where each layer has significantly different properties. A sample of uniform multilayer materials such as plywood in Figure 4-2 may include all layers when determining the gross heat of combustion. Conversely, in the case of multilayer materials or composites containing substantial non-homogeneous material, separate tests are necessary for each component.

*Figure 4-2: Plywood multilayer material sample* (Homenish, 2020)

The surface properties play an essential role in how materials react to different types of thermal exposure. It is recommended that a test sample be coated or have varnish of any kind applied to it prior to testing, such as paint, intumescent insulation or any other type of fire retardant.

#### *4.3.1.3 Sample size and mounting*

As mentioned, each testing standard specifies the sample size relevant to the testing method's dimensions. Regarding the thickness of the material, the sample must closely mimic the end-use conditions since this material can either be described as thermally thin or thick. Thermally thin materials are assumed to experience a negligible temperature gradient throughout their bulk and be influenced by backing conditions. In contrast, thermally thick materials are assumed to act as semi-infinite solids. In some instances, specimen mounting techniques can significantly affect test results. If the specimen is orientated incorrectly, it will considerably affect its tendency for flame spread, affecting the test outcome.

#### *4.3.1.4 End-use function*

As a more extensive system component, the material or product needs to be evaluated regarding its function. A component can be part of a ceiling, floor, wall or door assembly.

A visible section of the exposed material must be present in the sample to evaluate the material that forms part of an assembly, such as a floor, ceiling, or wall. For instance, if a fire door is to be evaluated, the outer sections and parts most likely to fail due to fire should be included in the sample, with the caveat that the door should be tested as a whole.

#### *4.3.1.5 Specimen orientation*

The time to ignition at a specified heat flux is affected by the orientation of the specimen being tested. Research at the University of Edinburgh showed that for a 6 mm thick slab of PMMA (Perspex) inclined at $0°, 30°, 45°, 60°$ and $90°,$ and regardless of the incident heat flux, an inclination of $30°$ was measured to have the shortest time to ignition (Horrocks and Price, 2008). The test was performed perpendicular to the surface at various radiant heat fluxes, as illustrated in Figure 4-3. This figure also indicates how the heat flux onto samples also influenced measured HRR. Corresponding temperatures and time to piloted ignition were recorded. Thus, the test orientation is not necessarily the same as the orientation of use, and fluxes will vary with time in a fire. In small-scale testing, the most practical orientation is horizontal facing upward.

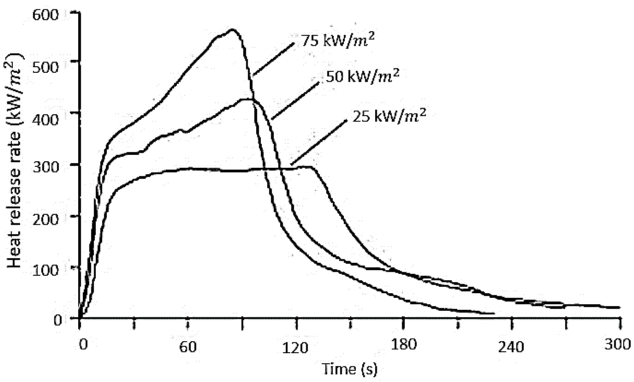



*Figure 4-3: Heat release rate versus time of PMMA at different heat fluxes (Horrocks and Price, 2008)*

#### *4.3.1.6 Material variation*

According to their production conditions, moisture and organic content materials or products to be evaluated for reaction-to-fire exhibit variances in their physical and chemical composition and structure. Nonetheless, samples acquired from a single source tend to have fewer variances. As a result, if the repeatability of the fire tests is a concern, the samples must come from the same source. Similarly, if a commercial product requires testing, a specific amount of material is often generated in a single batch.

If the repeatability of the fire tests is a problem, the samples must come from the same source and the same batch.

### 4.3.2 Heat Source Effects

#### *4.3.2.1 Radiant heat source*

Previously, European countries' reaction-to-fire testing was mandated by rules. However, they differed in approach, scale, and exposure settings, leading to questions about how they relate to full-scale fire conditions and comparing results. This section discusses reaction-to-fire testing and the methodology for assessing the impact of different heat sources. The parameters evaluated by these tests must be at heat fluxes that remain constant throughout the test and are somewhat uniform across the surface of the specimen in order to be significant.

The most appropriate heat source is a radiant panel, and a radiant panel can either consist of porous gas panels or electrical heating elements. Because these tests are designed to quantify precise flammability characteristics, heat transfer control is critical.

When the regulating mechanism can be compared, it is easy to compare test methodologies. Convective heat transmission becomes considerable when the heater is too close to the specimen. As a result, modifying the radiant heat flux by increasing the heater's power or changing the distance between the heater and the specimen ensures that the heat transfer is primarily radiative. During testing, operating at a constant power level affects the incident radiant heat flux. A cold specimen is introduced before the test begins. The specimen works as a heat sink, lowering the heater's temperature and, as a result, lowering the incident radiant heat flux.

After ignition, the heater temperature and incidence radiant heat flux rise due to the heat generated by the specimen. To maintain the incidence of radiant heat flux during a test, the heater's temperature must remain constant, which is relatively simple to achieve with electrical heating components (Hull, 2008; Janssens, 2008).

#### *4.3.2.2 Piloted ignition*

In most cases, piloted ignition is used in testing because it indicates most real fires and is conservative in other situations. Using a pilot spark or flame lowers the variability in time to sustained burning between numerous tests carried out under the same conditions. Because the preheating interval before ignition impacts the burning rate after ignition, a pilot boosts the repeatability of heat release rate measurements. The ignition pilot could be a tiny flame from a gas burner or an electric spark. A potential issue with pilot flames is that fire retardants in the fuel volatiles can extinguish them, but an electric spark remains stable when fire retardants are present (Janssens, 2015).

At least under some circumstances, the precise position of a pilot flame may be crucial for ensuring consistency in the monitored ignition times (Babrauskas, 2004).

#### *4.3.2.3 Fire resistance tests*

Most fire resistance tests specify a heating curve to which the sample or assembly must be tested in a fire-resistance furnace, and this provides the environment for the test setup. As discussed in Section 2.3.5, the heating curves vary and may significantly influence the test outcomes, seeing as its sample is essentially tested at a higher temperature depending on the curve being used. Parametric curves are not used in most fire resistance test instances; however, this will provide a decay phase and a more relatable fire scenario to real fires.

### 4.3.3 Observation and Measurements

As illustrated in Table 5-30, various parameters are evaluated using different testing standards and their respective tests. To perform a comparative analysis between two different testing methods, one must evaluate the parameter or measurement that result from the respective test. The results are usually stated in the fire test report.

Regarding fire resistance tests, if the observations and outcomes measured are desired to be compared, one must examine the fire test report to identify the heating curve used to perform the test. Different testing standards from different countries may refer to the same testing method, e.g., a full-scale furnace, but not necessarily the same heating curve. If the test was performed using the same curve, the results could be accepted as similar. If not, the tests cannot be equated to one another.

## 4.4 Summary of Methodology for a Comparison

The sections mentioned above-provided information regarding the necessary inputs, effects of heat sources, measurements, and observation when performing a comparative analysis. The main sections of fire tests that ought to be investigated once a comparative analysis plans to be performed are listed in Table 4-1 below.

The first step and probably the most obvious is to read the standards thoroughly and to take note of the publication date. There is no purpose in assessing the standard if it is outdated, obsolete, or due for revision.

## 4.5 Conclusion

This chapter has provided an overview of the methodology that can be utilised to compare fire test standards. An example of a comparative method employed by European regulators was presented. This method highlighted the various aspects that can be compared and those that cannot and the limitations attached.

Secondly, aspects or characteristics to consider when performing a comparative study were discussed. Characteristics relating to the specimen and energy input to the test was examined. The aspects highlight the requirements and influences on fire testing and their related standards.

These concepts are fundamental for being able to carry out and evaluate fire tests on materials. Hence, these concepts will now be applied in the following chapters when assessing how building standards ensure fire safety.

*Table 4-1: Aspects to consider when performing a comparative analysis*

**Apparatus**
- Large, small or intermediate scale

**Suitability of product**
- Surface characteristics
- Dimensions
- Composition of materials

**Specimen construction**
- Size
- Condition
- Preparation

**Heat sources**
- Radiant , pilot or burners
- Gas, liquid fuel, electric
- Heating curves

**Testing requirements**
- Fire parameters specified to be monitored
- Physical properties
- Chemical properties
- Heat source output

**Testing environment**
- Specimen orientation
- Testing configuration

**Observations and measurements**
- Measured material properties
- Fire parameters as test results
- Units connected to the result
- Uncertainty in measurements
- Smoke and toxicity

**Classification systems**
- Normative references
- Criterion
- Requirements to be satisfied
- Classification of:
  - Reaction-to-fire tests
  - Fire resistance tests
  - Smoke and toxicity

# 5 Fire Test Standards Overview

## 5.1 Introduction

After explaining what is needed for classification and the requirements for a safe building in Chapter 3, this chapter discusses several specific fire tests for building materials. A detailed understanding of the behaviour of the tests is required to conduct a comparative analysis. A comparative methodology was set up in Chapter 4, and the comparative analysis is done in Chapter 6. A summary of the tests will be discussed to provide insight, along with aspects highlighted and discussed. Multiple tables and figures have been added to this chapter to summarise the tests and understand the results. This discussion adds a significant number of pages to this chapter. However, the reader is encouraged to focus on general setups and results from the data provided. Such understanding is crucial for appreciating the inner workings of the tests and the fire parameters they assess, such that a comparative analysis of the tests can be carried out.

A host of standards worldwide address fire testing methods and apparatuses used for testing building or construction products. However, the most widely used standards such as the ASTM International, European Standards, British Standards and the South African National Standards 10177 suite of tests will be examined in this chapter.

Primarily (a) reaction-to-fire tests and (b) fire resistance tests will be our focus, describing the development of the tests and what results can be obtained. Lastly, the fire parameters in terms of heat release rate, combustion reaction, flame spread, time to ignition, heat flux, smoke production, and toxicity related to the overall development of fire are summarised. The chapter will follow the structure illustrated in Figure 5-1. The focus will be on examining the tests standards and their relevant test apparatus, as highlighted in the figure.

Note that if the reader is interested in how the tests are carried out, reference should be made to Appendix C, where this will be discussed. In many instances, tests are operated influence results obtained, but such details are excluded for brevity.

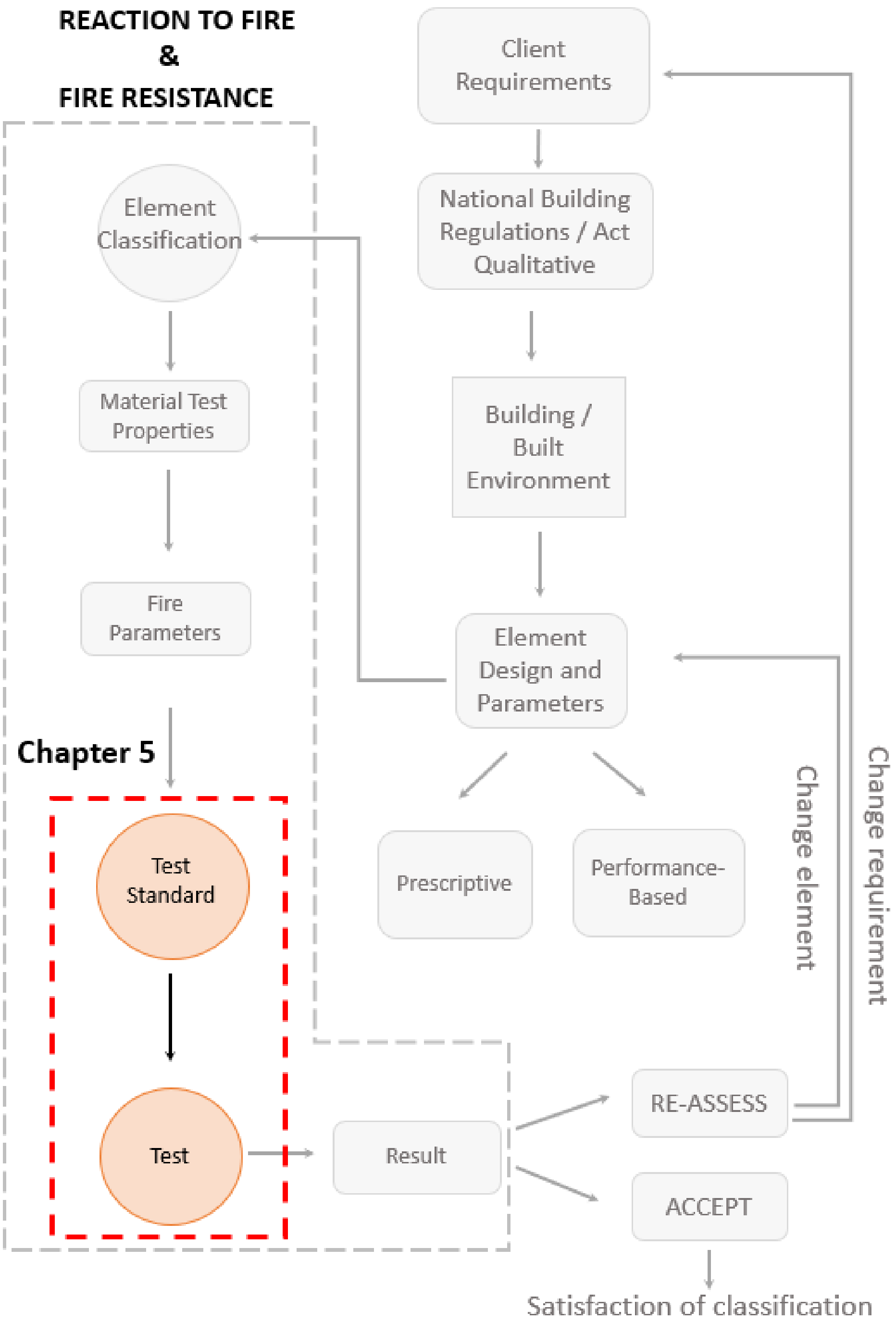



*Figure 5-1: Structure adopted for Chapter 5*

## 5.2 Understanding and Categorizing Fire Tests

Fire tests may be subdivided into two distinct categories, (a) structure-related tests intended to determine whether beams or doors provide adequate protection from the fire spread in terms of its resistance and (b) to determine material's reaction-to-fire. These are known as fire resistance tests and reaction-to-fire tests, where the latter incorporates factors such as flammability and fire toxicity testing, illustrated in Figure 5-2.

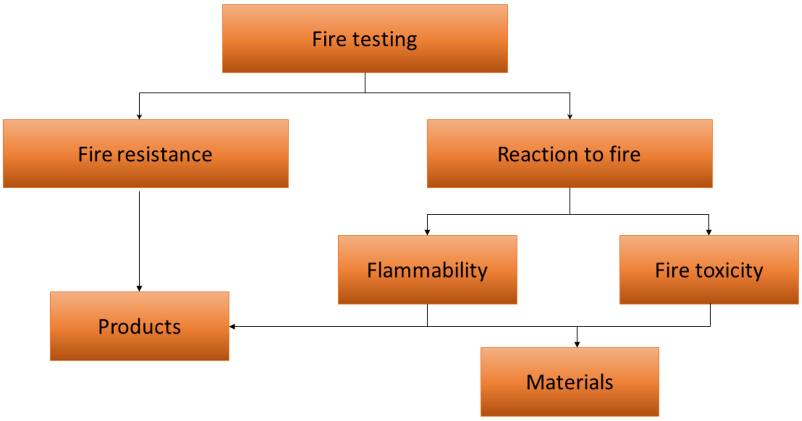



*Figure 5-2: Areas of fire testing (recreated from Horrocks and Price, 2008)*

Tests are typically performed in equipment designed to emulate, as closely as possible, the type of situations that the material would experience during a fire scenario. Various testing methods are available, including (a) small-scale tests, which usually involve lab specimens of a few millimetres to a few centimetres in size, (b) medium-scale tests involving samples of a meter or more in size, and (c) full-scale tests.

When simulating the various stages of an enclosure fire, the prevailing conditions should be addressed appropriately. An induction period (involving smouldering) is often present before flaming ignition happens in most fires. It usually takes a rise in gas temperature of around $600 \pm 1000$ °C before combustion is ventilation controlled, and then a decay phase occurs as the fuel is burnt. This behaviour is shown schematically in Figure 5-3, which emphasises where reaction-to-fire and fire resistance apply to the time-temperature curve. Ventilation control occurs when the amount of oxygen entering a compartment is lower than required for the complete combustion of exposed fuels. The HRR in the compartment is reduced accordingly. Flashover is the transition from localised burning of items to full room involvement and is associated with a sudden increase in temperature and heat release rate.

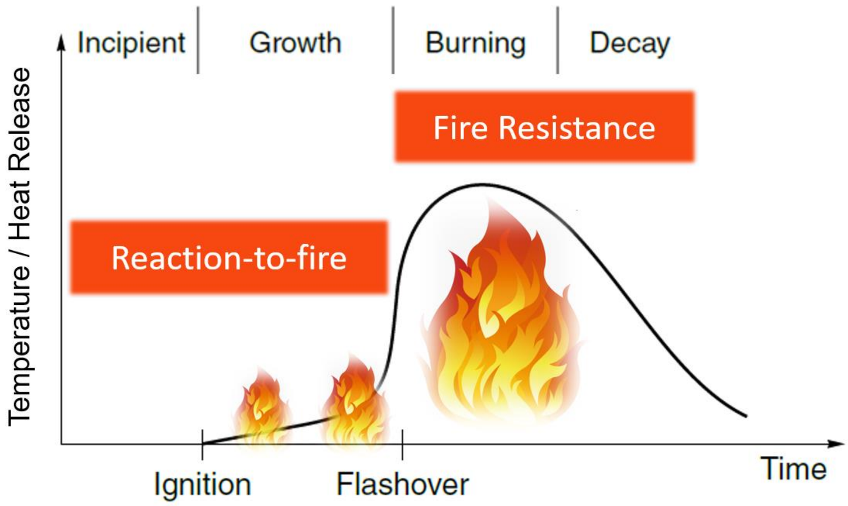



*Figure 5-3: Fire development time-temperature of heat release curve showing where reaction-to-fire and fire resistance tests are most applicable (recreated from Buchanan and Abu, 2017)*

Heat/energy must be applied under a realistic condition so that the effects of fire can be fully simulated, where the following should be considered:

- Ignition: piloted ignition results in flaming combustion, which is characterised by a flame source (tobacco, cigarette, glow wire), small sample size ($1 - 10$ cm), and sample surface temperatures that are near ignition temperatures ($300 - 400$ °C), as well as well-ventilated conditions.
- Developing fire: A fire characterized by continuous flaming combustion, with an external heat flux of around $20 - 60$ kW/m$^2$. For this to occur, the sample size must be larger ($10 - 100$ cm), the ambient temperature preferably above the ignition temperature ($400 - 600$ °C), and a well-ventilated area must be available.
- Fully developed fire: A high external heat flux ($> 50$ kW/m$^2$), large sample sizes ($1 \pm 5$ m), temperatures above the spontaneous ignition temperature ($> 600$ °C), and low ventilation characterize the final stage of fire growth.

Consequently, an infinite number of different fire situations could affect any material, and these cannot all be simulated, and even the simulation of a single realistic scenario is challenging. It is also difficult to predict how additional combustible elements can contribute to fire development.

In a fire, factors such as:

a) The magnitude of the fire;
b) The length of time the material was exposed to the fire;
c) The location or orientation of the material in relation to walls, floors, ceilings, or cladding;
d) How the material is held in place;
e) The response between the material and adjacent materials;

will all influence material behaviour.

Any test system is intended to try to manage the amount of fire exposure in a repeatable manner. The fact that building materials have passed a set of tests does not mean that the fire risk will be eliminated or prevented; nonetheless, it should mitigate the spread and effect of fire.

The majority of fire safety rules and regulations are based on two techniques. The first strategy entails preventing or reducing the risk of ignition. Because it is impossible to prohibit ignition completely, the second technique manages the consequences of a subsequent fire. Frequently, regulations include a variety of fire tests that have been included in various codes.

Flammability testing can be used to identify and quantify the essential fire qualities of construction materials or products. Flammability tests are divided into two categories. (1) A specimen with linear dimensions of centimetres is subjected to a small heat source, such as a Bunsen burner form of flame or a hot wire, for a brief period (seconds) in the first flammability test type. (2) The second flammability test characterizes material behaviour under more harsh thermal exposure circumstances, reflecting the developing pre-flashover stages of a compartment fire. This sort of testing is used to assess a product's contribution to the early stages of a fire's growth in terms of ease of ignition, heat release rate, smoke production, heat flux, the heat of combustion, and flame spread.

These flammability features, or fire parameters, will influence how appropriate it is to use different materials in new designs. These characteristics are critical for protecting life safety, such as timely evacuation.

There are just a few material tests that provide critical information on flammability parameters. Many industry-specific, empirical tests, on the other hand, are used to assess the fire safety of a wide range of environments, frequently through product testing, particularly in more harmful uses, including mass transportation, upholstered furniture, and electrical items. Specific tests measure only one of the fire parameters, whereas more sophisticated tests can examine multiple material properties and fire parameters at once.

This section will discuss the properties mentioned above to adequately comprehend how building materials react to fire and provide insight into which test method provides which property as a result.

## 5.3 Reaction-to-Fire Tests

### 5.3.1 Introduction

The subjects of reaction-to-fire testing are the flammability and ignitability of products and how they will contribute to the spread of fire. The common mistake is that reaction-to-fire tests are only applicable to products with fire-retardant properties. Reaction-to-fire tests apply to a broad selection of construction products. As seen in Figure 5-2, the toxicity of fire effluent is measured in tandem with flammability tests. The principal cause of fatality in fires has long been recognized as inhalation of hazardous and incapacitating gases.

Figure 5-3 indicates the applicable period of reaction-to-fire tests on a temperature or heat release versus time graph. As one can see, such tests relevant to all construction products imitate a fire that starts in a room and grows up to the flashover point. Reaction-to-fire tests are typically smaller in size than fire resistance testing (Babrauskas, 2008). They fundamentally control how a material reacts to temperature and heat fluxes in a burning fire.

Compliance with building code regulations is one of the critical drivers of reaction-to-fire testing. Insurance companies and other relevant authorities, on the other hand, may urge that a better fire-response performance be obtained. Furthermore, manufacturers conduct reaction-to-fire testing in order to develop sophisticated products that can compete in the marketplace. Another significant driver of reaction-to-fire testing is the assessment and validation of fire modelling design scenarios. Developing solid predictions of fire performance through modelling minimizes the number of fire tests required to reach a specific design goal.

This section will describe the relevant standards and testing methods that are categorised as reaction-to-fire tests. Recent advances in flammability testing have been published to predict large-scale fire behaviour from small-scale tests or even material property measurements connected to full-scale fire behaviour models (Hull and Stec, 2009).

The reaction-to-fire tests to be considered in the following sections are:

1. Cone Calorimeter
2. Oxygen Bomb Calorimeter
3. Room Corner test
4. Lateral Ignition Flame Transport (LIFT) test
5. Single Burning Item (SBI)
6. Single Flame Source test (ignitability test)
7. Fire Propagation Apparatus (FPA)
8. Non-combustibility Apparatus
9. Non-combustibility Apparatus according to SANS
10. Flooring Radiant Panel test
11. Inverted Channel Tunnel test
12. Small-scale Burning Characteristics of Building Materials

For each of the tests considered below, the details will be presented as follows:

- Name of the test
- International standards use the test apparatus and methodology
- Definition of test and setup
- Operation of the test (although for many setups, the reader is referred to Appendix C for more information)
- Results and interpretation of results

For each section, data provided is from the referenced international standards listed, unless noted otherwise.

### 5.3.2 Cone Calorimeter

*International Applicable Standards: ISO 5660-1; ASTM E1354; ASTM E1740; ASTM D6113; ASTM F1550; NFPA 271; ASTM E1474; BS 476 Part 15*

#### *5.3.2.1 Background and development*

Developed by the National Institute of Standards and Technology (NIST) in the early 1980s (Babrauskas and Wickstrom, 1989), the Cone Calorimeter is a bench-scale fire testing instrument widely used in fire safety engineering.

Due to early development and standardisation, the tentative proposal to standardize cone calorimeter measurements, ASTM P190, was issued in 1986. The full version was released in 1990 and became ASTM E1354-90. In 1990, a draft of the ISO standard for the Cone Calorimeter method was presented. The ISO 5660-1 final document (ISO, 2015a) was published in 1993, and it was later modified to include the determination of smoke generation published in ISO 5660-2 (ISO, 2002). The theory behind cone calorimetry is that the quantity of heat emitted from a burning sample is proportional to the amount of oxygen used throughout the combustion process (Schartel and Hull, 2007). As a result, the amount of heat released by burning combustibles is directly proportional to the severity of a fire. It is the measurement of the most significant concern in predicting the development of the fire and its effects, such as a material's contribution to fire development and spread, by observing how a fire develops in its early stages.

By examining the behaviour of materials subjected to controlled levels of radiant heat without an external ignition source and in a well-defined fire scenario, the Cone Calorimeter is used to get a complete set of material fire properties. In a forced combustion test, the fuel sample is subjected to an external radiant heat source to determine its flammability. Instead of testing a complete product or setup, the Cone Calorimeter performs this test on specific components or a material indicative of the end-use application. Because of the shape of the electric heater, the instrument is called a Cone Calorimeter.

Numerous worldwide standards defining the equipment have been published, and several national standardisation organisations have recently developed product standards for using the Cone Calorimeter to analyse and classify product performance such as (1) electric cables (ASTM D6113), (2) furniture (ASTM E1474) and (3) wall lining materials (ASTM E1740).

#### *5.3.2.2 Operation*

The Cone Calorimeter is made up of numerous components. Temperature, mass loss, gas flow, and gas concentration are the only characteristics that these parts measure, log, set, and change. These parts are described in Figure 5-4.

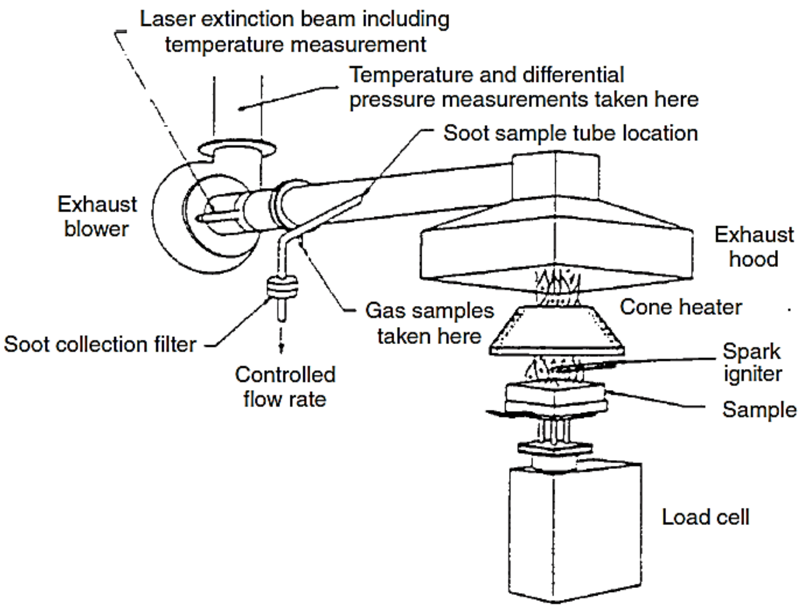
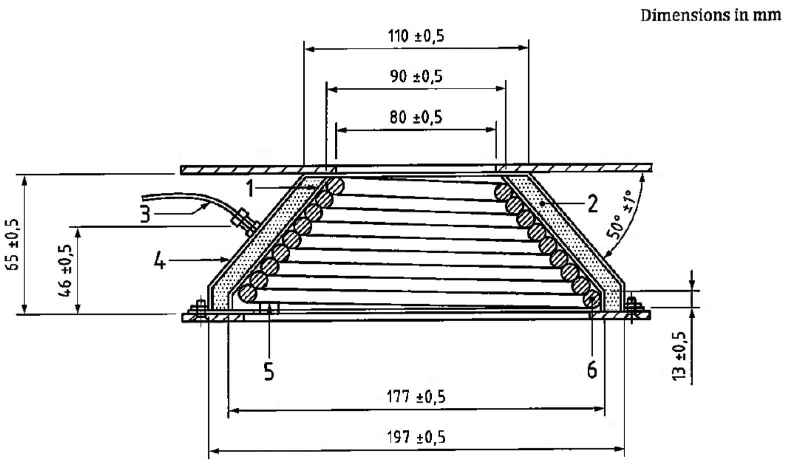



*Figure 5-4: Schematic of the Cone Calorimeter (Horrocks and Price, 2008)*

The test specifications are described in Table 5-1. A specimen is placed into the load cell in a metal sample holder. The majority of tests are performed with a horizontal orientation. The sample is then exposed to controlled irradiance levels by the truncated cone-shaped heater, Figure 5-5.




**Key**
1 inner shell
2 refractory fibre packing
3 thermocouple
4 outer shell
5 space block

*Figure 5-5: Cone Heater (ISO 5660-1, 2015)*

*Table 5-1: Test specifications for the Cone Calorimeter*

| | |
|---|---|
| **Specimens** | 100 mm × 100 mm.<br>Composite or uniform construction |
| **Specimen Position** | Horizontally or vertically for non-melting specimens |
| **Ignition Source** | Radiant electrical heater<br>External irradiances range: 0 to 100 kW/m$^2$<br>Normal specimens: 25 kW/m$^2$ and 35 kW/m$^2$<br>Fire-resistant materials: 50 kW/m$^2$ |
| **Ignition Size** | Truncated cone-shaped |
| **Test Duration** | Minimum of 5 minutes and maximum 30 minutes |

Babrauskas (1982) determined that the electric heater in the Cone Calorimeter behaves as a grey body with an emissivity close to unity based on correlations between heater temperature and radiant heat flux. Once enough pyrolysis gases are generated, ignition occurs through a spark igniter and the sample consequently burns. The sample will flame and start to burn if the conditions and the material properties permit burning.

After passing through the heating cone, an exhaust duct system collects the combustion gases with an exhausting cowl and a centrifugal fan. The nominal exhaust flow rate is 24 $l/s$. In the horizontal flue, the gas sampling ring is located before the fan. The sampling gas fraction is first filtered to remove particles, followed by a cold trap and a drying agent to eliminate any remaining moisture. The filters and water trap requirements depend on whether $CO_2$, CO and $H_2O$ fractions are measured.

Between the gas sampling ring and the fan is a smoke measurement device that uses a laser photometric beam to measure the amount of smoke produced. The oxygen analyser is the only analyser that is required for basic cone calorimeter investigations. To better understand the burning process and reduce the number of uncertainties in the results, additional analysers such as carbon monoxide, carbon dioxide, and water vapour are frequently installed.

The flame retardancy of thinner samples is smaller; thus, cone calorimetric tests are sensitive to sample thickness. Furthermore, the HRR measurements are influenced by the endothermic behaviour of flame-retarding additives. The HRR measured by the Cone Calorimeter would be overstated if it was not corrected properly. Babrauskas and Twilley (1988) developed a user guide intended to provide supplemental information on the installation, setup, daily operational procedures, maintenance, troubleshooting, and calibration procedures of the Cone Calorimeter.

#### *5.3.2.3 Results*

The Cone Calorimeter is one of the more sophisticated systems and can measure several flammability characteristics simultaneously. The (a) rate of heat released is the most valuable measurement; conceptually, it can be approximated using specific additional measurements. These include (b) the time to ignition in seconds, (c) the mass-loss rate (kg/s) during combustion, (d) the time to and value of the maximum/total amount of heat released (MJ/m2) during combustion, (d) the critical heat flux (kW), (e) effective heat of combustion (MJ/kg), (f) smoke production rate (m2/s), and (g) release rates and concentrations of combustion gasses such as CO and $CO_2$. If smoke generation and gas yields are reported, the standard mandates continuous measurement of smoke obscuration and exhaust gas temperatures.

The HRR from the burning specimen is determined by measuring the amount of $O_2$ consumed from the air flowing through the apparatus. In a cone calorimeter, the heat release rate at ignition ($HRR_{ig}$) is around $20 - 100$ kW/m$^2$, and the critical mass loss rate is around $1 - 6$ g·s$^{-1}$·m$^{-2}$.

When the material's surface temperature equals its ignition temperature during testing, the ignition's critical mass loss rate occurs. The applied heat flux does not affect the ignition temperature ($T_{ig}$).

The time it takes for the surface to reach the ignition temperature is known as the time to ignition ($t_{ig}$). However, an inspection of Equation 5.1 reveals that a linear relationship exists between external heat flux and $t_{ig}{}^{-0.5}$. Critical heat flux is thus required to reach the ignition temperature for thermally thick samples.

$$t_{ig} = \frac{\pi}{4} K\rho c \left[\frac{T_{ig} - T_0}{\dot{q}_{ext} - CHF}\right]^2 \qquad 5.1$$

where:

| | | |
|---|---|---|
| $t_{ig}$ | = | Time to ignition (seconds) |
| $k$ | = | Thermal conductivity (W/m·K) |
| $\rho$ | = | Density (kg/m$^3$) |
| $c_p$ | = | Specific heat capacity (J/kg·K) |
| $T_0$ | = | Ambient temperature (℃) |
| $\dot{q}_{ext}$ | = | Applied heat flux (kW/m$^2$) |
| $CHF$ | = | Critical heat flux for ignition (kW/m$^2$) |

To assess the ignitability of a sample, the time of ignition, $t_{ig}$ and the lowest heat input required to ignite the material, $T_{ig}$ is determined. The critical heat flux is unique to each material and can define how a material ignites. Ignitability does not always correspond to flammability as determined by other methods.

Experiments can establish the surface flame spread rate, which requires the flame spread rate related to the heat released. The heat released is proportional to the amount of material burnt. However, for specific products, the ignitability and flame propagation effects are insignificant.

Other critical setup aspects, such as horizontal sample orientation, melt dripping prevention, and well-ventilated combustion, are visible but not addressed. The impact of these features on the outcomes is well understood. Schartel *et al.* (2005) reviewed cone calorimeter experiments. According to the authors, some cone calorimeter testing properties are less visible and are frequently overlooked while running such tests or discussing the results. These overlooked characteristics will be discussed in Chapter 6.

The Cone Calorimeter test, strictly speaking, measures performance based on the interplay of material attributes, specimen, and the prescribed design fire scenario. The results can be used to assess material-specific features, distinguishing them from other well-known fire reaction tests. Although not formally adopted by any classification standards, cone calorimeter tests can be a universal method for ranking and comparing materials' fire behaviour.

Fire modelling, predictions of real-scale fire behaviour, and fire scenarios can also be defined and facilitate the drive towards performance-based design. Pass or failure criterion-based tests investigated by the Cone Calorimeter may also facilitate the development process of new materials and products.

### 5.3.3 Oxygen Bomb Calorimeter

*International Applicable Standards: EN ISO 1716; ASTM D5865*

#### *5.3.3.1 Background and development*

The bomb calorimeter is the most widely used equipment for determining a material's heat of combustion (calorific value). The equipment can determine the possible maximum total heat output of a substance during combustion, regardless of the products' end-use. This equipment burns a test specimen of a specific mass under controlled conditions. Under these conditions, the heat of combustion is computed based on the observed temperature rise while considering heat loss.

Figure 5-6 present a proprietary bomb calorimeter and a schematic view of a bomb calorimeter, respectively.

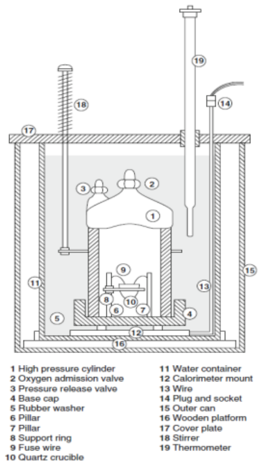



*Figure 5-6: (Left) Commercial Bomb calorimeter (Fire Testing Technology, 2021), and (Right) Schematic of a Bomb Calorimeter (Janssens, 2016)*

#### *5.3.3.2 Results*

The Oxygen Bomb Calorimeter can measure heat generated in various applications and is designed to meet current international standards. The gross heat of combustion of a solid or liquid fuel is measured, as previously described. The heat released due to condensation of water vapour is included in the measured gross heat of combustion. Since the cooling water temperature remains close to ambient during a test, all water vapour generated in the combustion process condenses completely.

In practice, combustion products are typically removed from the system when the temperature rises above the dew point. As a result, quantifying the potential heat released in a fire is more realistic, assuming that all water vapour remains in the gaseous state (Janssens, 2016). The ASTM D5865 and EN ISO 1716 (EN ISO, 2010) standards estimate gross heat combustion processes.

The net heat of combustion is the corresponding heat released per mass unit of fuel burned, equal to the gross heat of combustion measured in an oxygen bomb calorimeter minus the latent heat of vaporization of the water in the combustion products. This value is affected by the fuel's moisture and hydrogen content as described below:

$$\Delta h_{c,net} = \Delta h_{c,gross} - (8.936 Y_H + Y_W)\Delta h_v \tag{5.2}$$

where:

| | | |
|---|---|---|
| $\Delta h_{c,net}$ | = | Net heat of combustion (kJ/g) |
| $\Delta h_{c,gross}$ | = | Gross heat of combustion (kJ/g) |
| $Y_H$ | = | Mass fraction of hydrogen in the fuel (g/g) |
| $Y_W$ | = | Moisture content of the fuel (g/g) |
| $\Delta h_v$ | = | Latent heat of vaporization of water (2.442 kJ/g at 25°C) |

The gross heat and net heat of combustion are usually reported at a standard temperature of 25 °C.

### 5.3.4 Room Corner Test

*International Applicable Standards: ISO 9705; ASTM D5424; EN 14390; ASTM D553; ASTM E1537; ASTM E2257; ASTM E1590; ASTM E1822; NFPA 286; NFPA 265; UL 1685; ASTM E603*

#### *5.3.4.1 Background and development*

This large-scale test method is used to assess the fire behaviour of wall linings and ceiling products. The products are installed on the surface of a small room and directly exposed to a specified ignition source (ISO, 2015b).

The test simulates a room fire scenario, with the fire starting in the corner of the room and being ventilated by a door opening. Tests performed in accordance with ISO 9705 provide data for the early stages of a fire, from ignition to flashover. The apparatus, also known as a large-scale oxygen consumption calorimetry test, is the most commonly used large-scale fire experiment testing apparatus globally. The test method, like other calorimetry equipment, does not evaluate the fire resistance of building products.

The Room Corner Test utilises a 0.30 m × 0.30 m propane-fired burner, located 0.05 m from the walls in the corner of a 2.40 m × 3.60 m floor area and height 2.40 m test compartment. The product under test is mounted on three of the compartment's walls and the ceiling. The well-ventilated conditions are provided through a doorway sized 0.8 m × 2.0 m. The testing device and test specifications are shown in Figure 5-7 and Table 5-2.

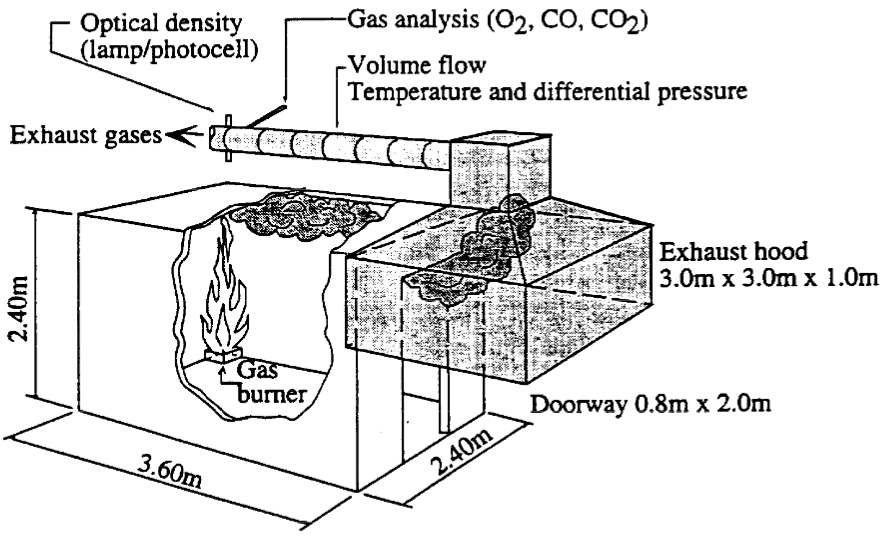



*Figure 5-7: Test setup of room corner test (Dillon, 1998)*

*Table 5-2: Test specifications for ISO 9705 (EN 14390)*

| | |
|---|---|
| **Specimens** | Enough sample material to cover three walls and the ceiling of the test room. The wall behind the doorway is unprotected |
| **Specimen Position** | Forms a room lining on three walls and ceiling |
| **Ignition Source** | Propane fuel burner placed in one corner, in contact with both walls. The burner heat output is 100 kW for the first ten minutes, followed by 300 kW for an additional ten minutes |
| **Ignition Size** | Steel sandbox with dimensions of 0.17 m × 0.17 m × 0.145 m |
| **Test Duration** | 20 minutes or until flashover |

#### *5.3.4.2 Results*

Several countries utilise the ISO 9705 test method to classify surface materials. The Room Corner Test was chosen to determine limit values for the Euroclasses in a reference scenario for the SBI test, as discussed in Section 4.2. The Room Corner test may be used in exceptional cases for direct classification of the Euroclasses. Such requirements may arise for products or product groups that, due to technical constraints, cannot be tested in the SBI.

The Room Corner test is important in the testing community due to its contribution towards the Euroclass system development. Table 5-3 discusses the various findings of this reaction-to-fire testing method. It should be noted that the smoke production rate is only measured in ISO 9705 and NFPA 286, as discussed in Appendix C, and for all tests that use this apparatus.

*Table 5-3: Test findings of ISO 9705 (EN 14390)*

| | |
|---|---|
| **Findings** | Upper layer temperature of 600℃<br>Emerging flames through the doorway<br>Heat flux of 20 kW/$m^2$ to the floor<br>HRR of 1 MW<br>Smoke production rate (SPR)<br>Occurrence of flashover |

As stated in Table C- 1 regarding the test duration, one crucial test result is whether flashover within the room is reached or not. Flashover, in this instance, is defined as the sum of the HRR from the burning product, said to be equal to the HRR criterion of 1 MW. It must be stated that the presence or absence of the sample material on the ceiling of the room can be one of the most critical factors as to whether or not flashover occurs.

The Room Corner Test was a reference scenario for the SBI test. A subsequent analysis of 30 building products across Europe in the Room Corner Test was conducted. It resulted in a correlation between the fire growth rate of the burning intensity (FIGRA) for the Room Corner test (EN 14390) and FIGRA for the SBI test. The correlation between the tests also links EN 14390 flashover to specific Euroclasses as shown in Table 5-4, as discussed in Section 3.4.

*Table 5-4: Tendency of products to reach flashover in Room Corner test*

| Euroclass | Limit value FIGRA (SBI) (W/s) | Expected burning |
|---|---|---|
| A2 | 120 | No flashover |
| B | 120 | No flashover |
| C | 250 | No flashover at 100 kW |
| D | 750 | No flashover before 2 min at 100 kW |
| E | > 750 | Flashover before 2 min |

It should be noted that different standards used the room corner test but have differences in the experimental setup, resulting in measured properties that cannot be easily compared. Appendix C provides further detail on this.

### 5.3.5 Lateral Ignition Flame Transport Test (LIFT)

*International Applicable Standards: ISO 5658-2; ASTM E1321; ASTM E1317*

#### *5.3.5.1 Background and development*

As mentioned in Section 2.4.4, the Lateral Ignition Flame Transport (LIFT) apparatus was standardized as the ISO 5658-2 and ASTM E1321 test, which was developed to characterise the materials' lateral flame spread. In 1985 a study was conducted by the ISO to develop a bench-scale test method for determining the ignition and lateral (opposed flow) flame spread (transport) properties of materials.

The LIFT apparatus firstly measures the lateral flame spread across a range of relevant fluxes or surface temperatures that are typical of fires. Secondly, an appropriate time of ignition is determined. The test specifications are described in Table 5-5. A schematic view of the LIFT apparatus is shown in Figure 5-8.

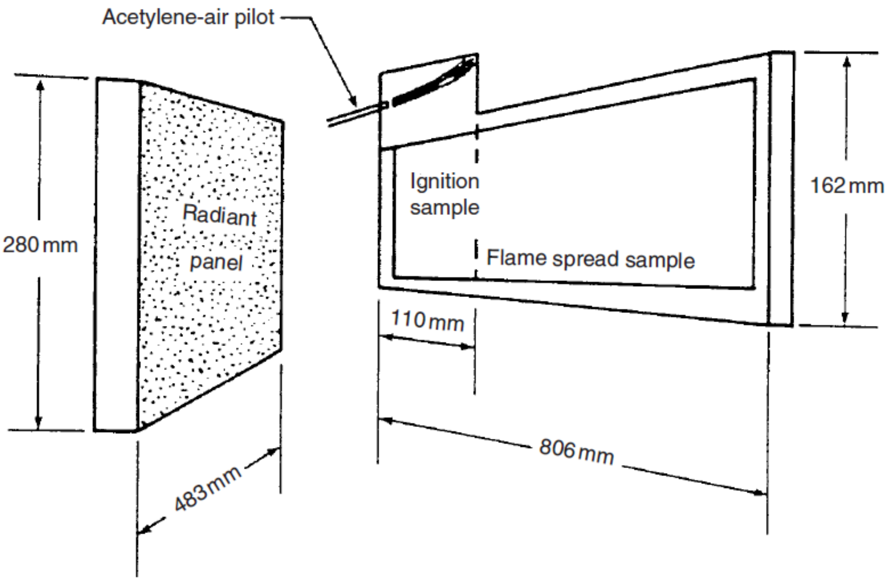



*Figure 5-8: LIFT Apparatus (Horrocks and Price, 2001)*

*Table 5-5: Test specifications for LIFT Apparatus*

| | |
|---|---|
| **Specimens** | 155 mm × 800 mm for lateral flame spread test and 155 mm × 155 mm for ignition test |
| **Specimen Position** | Vertical orientation |
| **Ignition Source** | Propane fuel radiant heat panel with an output of 40 kW/m$^2$ Piloted ignition with a pilot flame |
| **Ignition Position** | Vertical orientation 15 ° to the specimen |

#### *5.3.5.2 Results*

The LIFT test yields data that can be used to compare the performance of essentially flat materials, composites, or assemblies that are typically utilized as exposed wall surfaces. As previously stated, the data from the two processes can be connected with a theory of ignition and flame propagation to formulate the fundamental material flammability parameters. Parameters such as the flame temperature, velocity of lateral flame spread, and ignitability parameters, including the time to ignition, ignition temperature, and thermal inertia of materials, can be assessed.

The critical heat flux for ignition temperature and the flame heating parameter are two more essential parameters investigated. The flame heating parameter, denoted by $\emptyset$, can be calculated directly from the LIFT test during opposite flow flame spread. It depicted flame heat transfer as well as opposing flow velocity effects. (Cleary and Quintiere, 1991).

Any flame front that emerges throughout the experiment is documented, and a record of the flame front's horizontal progression along the length of the specimen in terms of the time it takes to travel to various distances is kept. It is possible to predict the velocity of lateral flame spread on a vertical surface with a given external flux and no forced lateral airflow.

The flame spread distance against time history, the flame front velocity vs heat flux, the critical heat flux at extinction, and the average heat required for prolonged burning are examples of comparative graphs provided from tests. Table 5-6 lists other noteworthy discoveries and factors used as input data for current fire growth models that stem from the LIFT test.

*Table 5-6: Test findings for LIFT Apparatus*

| | |
|---|---|
| **Findings** | CFE - Critical flux at extinguishment<br>$\dot{Q}_{sb}$- Heat for sustained burning<br>$\dot{Q}_t$- Total heat release<br>$\dot{Q}_p$- Peak heat release |

### 5.3.6 Single Burning Item (SBI)

*International Applicable Standards: EN 13823*

#### *5.3.6.1 Background and development*

The Single Burning Item test, the last test procedure in the harmonized European system for classifying reaction-to-fire building products, was published in 2001. To understand what this section will attempt to provide, one must first understand the basic philosophy of the SBI test, including its capabilities and limitations. The standard was created to assess the potential contribution of building products, such as surface lining materials, to the development of a fire.

A group of nine fire laboratories nominated by nine Member States created the SBI test. The Official Laboratories Group was the name given to the group (OLG). The OLG worked under the strict supervision of the European Commission's Fire Regulators Group, making the SBI test the first to be developed in part by regulators (Messerschmidt, 2008). After the SBI test was developed, the goal was to be accepted as an EN standard, as discussed in Section 4.2.

The developers' goal was to measure specific variables that could be used in the classification system. The classification system was developed primarily based on the FIre Growth RAte (FIGRA) index, calculated using the SBI test method parameters as discussed in Section 4.2. Limitations of this test method considering information regarding its development (Sundström, 2007), will be further highlighted in Chapter 6.

The SBI test is an intermediate-scale test where two test samples of the same material are mounted in a corner configuration covering two wings. The test apparatus is shown in Figure 5-9. The test specifications are described in Table 5-7. Over the test duration, the performance of the test specimen is evaluated according to the following parameters: lateral flame spread, heat production, falling flame droplets and particles and smoke production.

During a short period, the secondary burner is used to measure the burner's heat output and smoke development before ignition of the primary burner. The detailed operation procedure is set out in the SBI standard (BS EN, 2010a).

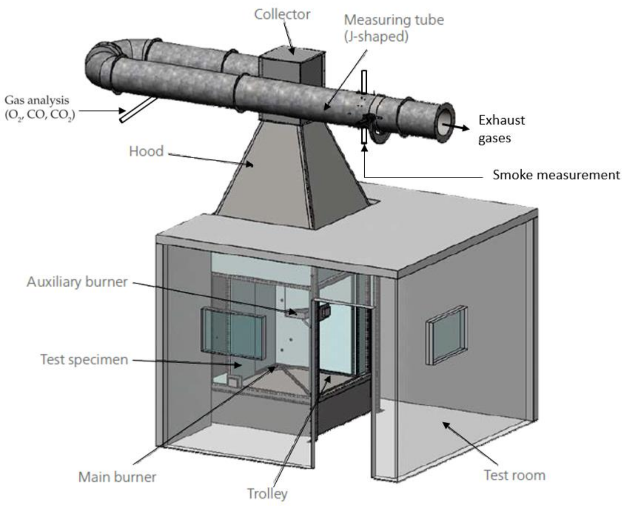



*Figure 5-9: Single Burning Item Test Apparatus (NETZSCH® TAURUS® Instruments GmbH, 2021)*

*Table 5-7: Test specifications of the SBI Apparatus*

| | |
|---|---|
| **Specimens** | Two test samples, 1.0 m × 1.5 m and 0.5 m × 1.5 m |
| **Specimen Position** | Corner configuration mounted |
| **Ignition Source** | Triangular shaped propane diffusion sandbox burner. An output of 30 kW |
| **Ignition Position** | The specimen corner's foundation. |
| **Test Duration** | 20 minutes |

### *5.3.6.2 Results*

An experiment using the SBI is shown in Figure 5-10. Most measurements are taken automatically, while others are done visually. The ambient pressure (Pa), relative humidity (% $H_2O$), and temperature (°C) are all measured and recorded.

*Figure 5-10: Experiment conducted in the SBI (Van Mierlo and Sette, 2005)*

These values are used to compute the volume flow, heat release rate, and smoke production rate (SPR). The FIre Growth RAte (FIGRA) parameter defined as the maximum heat release rate divided by time in units of W/s is also calculated.

The horizontal (lateral) spread of flame and the falling of flaming droplets and particles are observed visually. Only within the first 600 seconds of the exposure period, and only when the droplets/particles reach the level of the lower edge of the specimen outside the burner zone, shall the fall of flaming droplets or particles be recorded. The burner zone boundary is demarcated by a 3 mm wide quarter-circle drawn on the trolley floor.

Sustained flames reaching the far edge of the long wing specimen at any height between 500 mm and 1000 mm at any time during the test must be recorded. The determining phenomenon shall be the boundary of sustained flaming at the specimen's surface for a minimum of 5 seconds.

Concerning the SBI, a number of fire characteristics were considered. An index representing the rate of increase in the heat release rate (FIGRA) or the total heat released in the first 10 minutes ($THR_{600s}$). An index representing the rate of increase in smoke production rate (SMOGRA) and total smoke produced in the first 10 minutes ($THP_{600s}$). The SBI classification criteria for all non-flooring products are in Table A- 6.

Each test requires that the product's burning behaviour be represented by graphs of average heat release rate $HRR_{av}$ (t), total heat release THR(t), and $\left\{1000 \times \frac{HRRav\ (t)}{(t - 300)}\right\}$ for the time interval $0 \leq t \leq 1500$ s. The product's smoke production behaviour shall be represented by graphs of $SPR_{av(t)}$, total smoke production TSP(t), and $\{10\ 000 \times \frac{SPRav(t)}{(t-300)}\}$.

The FIGRA and SMOGRA indices use threshold values for total heat release and smoke production, set to zero if they fall below them. The values for the FIRGA indices and different levels of thresholds lead to $FIGRA_{0,2\ MJ}$ and $FIGRA_{0,4\ MJ}$. These threshold values, smoke growth rate index (SMOGRA), the total heat release ($THR_{600s}$) and the total smoke production $TSP_{600s}$ within the exposure period shall be graphed.

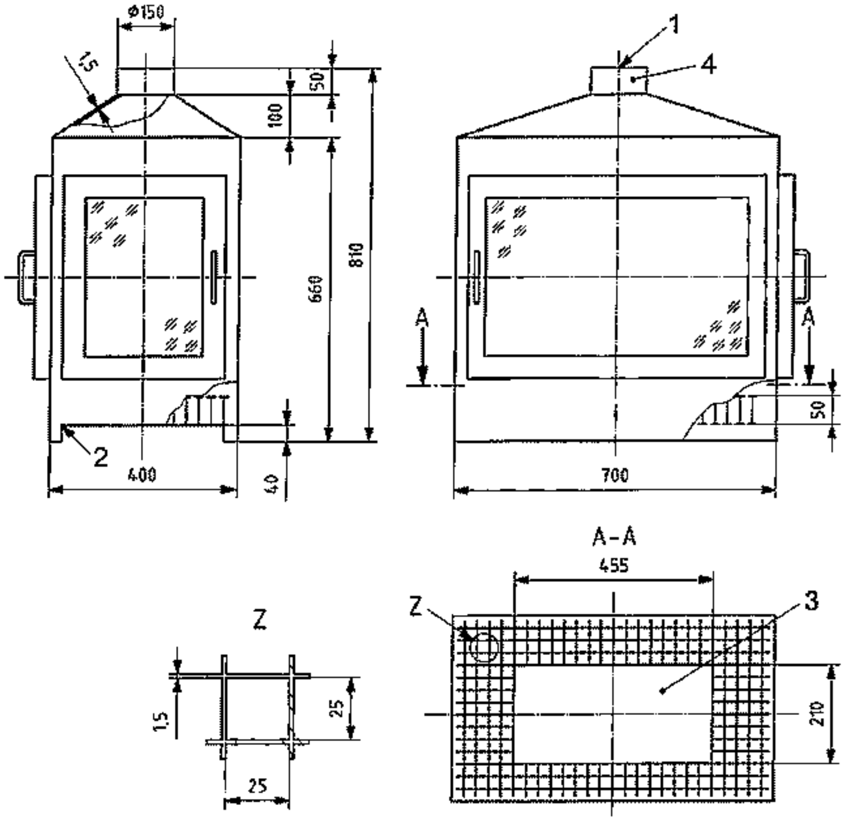
### 5.3.7 Single Flame Source Test (Ignitability Test)

*International Applicable Standards: EN ISO 11925-2*

#### *5.3.7.1 Background and development*

The Single Flame Source Test is based on the German Kleinbrenner method for determining the ignitability of building materials by direct small flame impingement under zero impressed light. The apparatus is designed to comply with ISO 11925-2: Reaction to flame tests for building products (Fire Testing Technology, 2010).

Its primary goal is to define a product's reaction-to-fire performance. Often referred to as the Ignitability Apparatus, the method might be known to assess ignitability; however, this is addressed by measuring the flame spread capabilities, as will be discussed. The classification requirements are presented in Table A- 7. The test apparatus can also classify flooring products, and the respective requirements are provided in Table A- 8. The schematic of the test is illustrated in Figure 5-11.




**Key**
1 measuring point for air velocity
2 metal grid mesh
3 horizontal plate
4 chimney

NOTE All dimensions are nominal values in millimetres unless tolerances are given.

*Figure 5-11: Combustion chamber schematic of the ISO 11925-2 (ISO 11925-2, 2010)*

As shown in Figure 5-12, an extensively adjustable burner assembly allows the small-premixed flame to be tilted towards the specimen and offered to it in a single fluid movement. A fully adjustable specimen support frame allows the specimen holder to move laterally. Two different specimen holders are also depicted. The flame can be used either in the centre of the specimen or at laterally spaced points. The specimen holders can hold a standard sample of a specific thickness and samples that melt or shrink away from the flame without being ignited. The test specifications are provided in Table 5-8, with a note to be taken of the two flame application periods that are described.

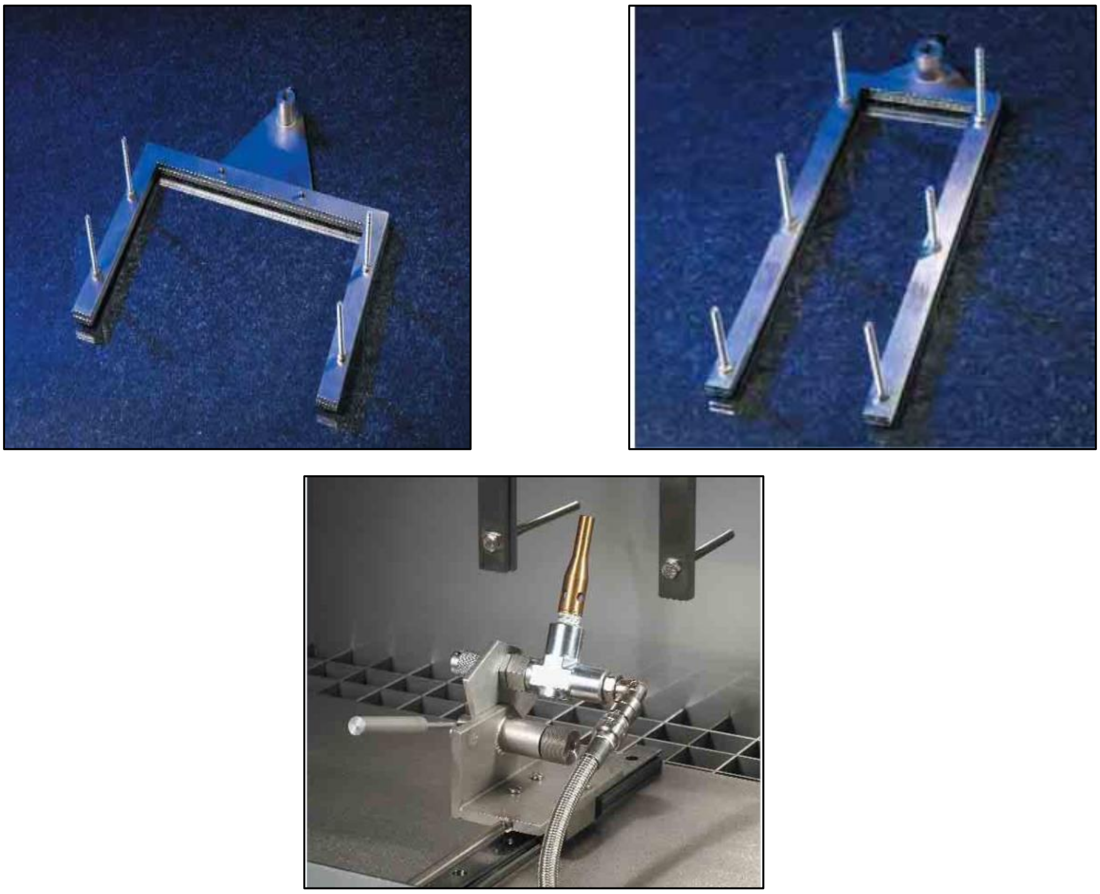


*Figure 5-12: (Top left) Standard sample holder, (Top right) Sample holder for whittling products without ignition, and (Bottom) Adjustable burner assembly (Fire Testing Technology, 2010)*

*Table 5-8: Test specifications for the Ignitability Apparatus*

| | |
|---|---|
| **Specimens** | 250 mm long by 90 mm wide |
| **Specimen Position** | Thickness of 60 mm<br>Vertically mounted |
| **Ignition Source** | Propane fuel burner of 95% purity. An output of 0.8 kW |
| **Ignition Position** | Tilted at 45° to the specimen mounted on runners. |
| **Test Duration** | If the flame application is 15 s, total duration is 20 s<br>If the flame application is 30 s, total duration is 60 s |

#### *5.3.7.2 Results*

Each exposure condition must test a minimum of six representative product specimens. According to the standard, three specimens must be cut lengthwise and three crosswise. Additional information is provided in the standard regarding the number of specimens to be tested if product alterations are incurred.

Table 5-9 lists the relevant test results that are attainable by the ignitability test. The filter paper is placed in an aluminium foil tray beneath the specimen holder during the tests to observe the occurrence of any flaming particles which will cause the filter paper to ignite.

*Table 5-9: Result recordings for the Ignitability Test*

| | |
|---|---|
| **Findings** | Ignition occurrence<br>The flame tip is 150 mm above the application point<br>Depending on the ignition of the filter paper, flaming droplets are observed.<br>Examine the test specimen's physical behaviour |

### 5.3.8 Fire Propagation Apparatus

*International Applicable Standards: BS 476-6; NFPA 287; ASTM E2058; ISO 12136*

#### *5.3.8.1 Background and development*

In the 1960s, the Fire Propagation Apparatus (FPA) developed by the British as the BS 476-6 (BS, 1989) served as an extension of the principles of the Cone Calorimeter to study the flammability and heat release parameters for polymers, standard fire fuels and other chemicals. In the USA, it is known as the 50 kW lab-scale flammability apparatus, while in Europe, it is known as the Tewarson apparatus. As a multivalent bench-scale fire calorimeter, the apparatus can study the effects of under-ventilation on the combustion of natural and synthetic polymers (Brohez *et al.*, 2006). The apparatus was also developed to assess the potential contribution to fire growth of lining material in an enclosure. The test assessment involves data derived from the flue gas temperature measurements and assigned an index as explained in Section 3.4.4.

The discussions below will follow the NFPA 287 (NFPA, 2022), the most accessible standard, although the apparatus is used variously. The main test specifications are listed in Table 5-10. An infrared heating system, a load cell system, test section, ignition pilot flame, combustion air distribution system, product gas analysis system, and exhaust system comprise the fire propagation apparatus as indicated in Figure 5-13.

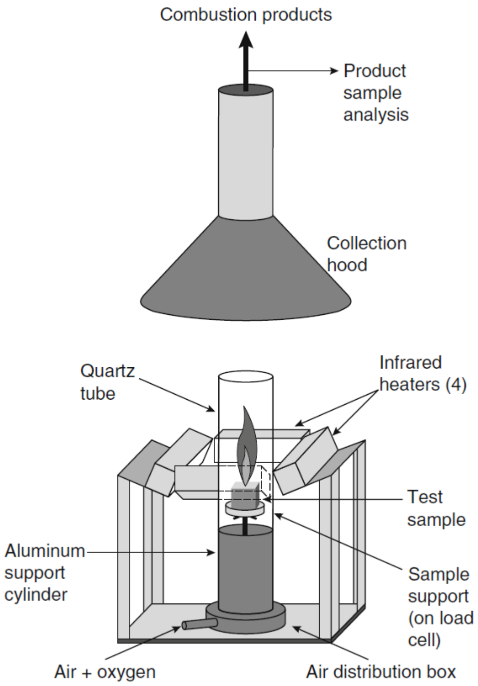



*Figure 5-13: FPA designed by FM Global Research* (NFPA, 2022)

*Table 5-10: Test specification for the Fire Propagation Apparatus*

| | |
|---|---|
| **Specimens** | 100 mm in diameter |
| **Specimen Position** | Sample holder sized 102 mm × 102 mm. Placed on a load cell |
| **Ignition Source** | Ethylene-air pilot flame |
| **Ignition Size** | Producing a 10 mm flame length |
| **Test Duration** | 2 minutes after the end of visible flaming OR<br>Flame lengths of 35 $\pm$ 10 mm above the rim of the collection funnel for more than 30 s |

### *5.3.8.2 Results*

The apparatus is designed to provide the following distinguishing features:

- Provide for at least a prescribed flow of ordinary air or, if oxygen-enriched air is to be used, a prescribed flow of oxygen-vitiated air
- Measurement of fire propagation HRR and exhaust product flow from an upward-moving self-sustaining fire on a vertical test specimen 0.305 m high
- The ability to determine a sample's smoke yield

Experiments performed with this test apparatus yields specific measured characteristics which correlate to certain flammability indices. Additional outcomes are the chemical and convective heat release rates, ignition time, first appearance of specimen vapours, the flame height of 1 min intervals, flame colour, smokiness, flame behaviour, and flame extinction. Table 5-11 summarises indices obtained from the FPA test method.

*Table 5-11: Indices resulting from the Fire Propagation Test*

| Index | Abbreviation | Unit | Definition |
|---|---|---|---|
| Critical heat flux | CHF | $kW/m^2$ | Minimum heat flux ≤ where no ignition occurs |
| Thermal response parameter | TRP | $kW{\cdot}s^{1/2}/m^2$ | Material characteristic providing resistance to ignition upon exposure to a heat flux |
| Fire propagation index | FPI | $m^{5/3}/kW^{2/3}{\cdot}s^{1/2}$ | In terms of chemical HRR, a material's proclivity to support fire propagation beyond the ignition zone. |
| Effective heat of combustion | EHC | kJ/kg | $\frac{Measured\ HRR}{Mass\ loss}$ |
| Smoke yield | $y_s$ | - | $\frac{Mass\ of\ smoke\ particulates\ generated}{Mass\ of\ fuel\ vaporised}$ |

The CHF shall be calculated from the four lowest values for heat flux at $15, 20, 25$ and $30$ $kW/m^2$ compared to the TRP, which is from the four highest values for the external heat flux of 45, $50, 55$ and $60$ $kW/m^2$. The apparatus may also be used for other test purposes, such as those described in Table 5-12. The test procedures differ, as do the results produced, but the standard provides a multifaceted apparatus.

*Table 5-12: Various Test Procedures and Results of the Apparatus*

| Procedure | Test | Result |
|---|---|---|
| 1 | Ignition | $t_{ig}$ |
| 2 | Combustibility | $\dot{Q}_{chem}$, $\dot{Q}_c$, $\dot{m}$, D |
| 3 | Fire Propagation | $\dot{Q}_{chem}$ |

where:

| | | |
|---|---|---|
| $t_{ig}$ | = | Time to ignition |
| $\dot{Q}_{chem}$ | = | Chemical heat release rate (kW) |
| $\dot{Q}_c$ | = | Convective heat release rate (kW) |
| $\dot{m}$ | = | Combustion mass loss rate of the specimen (kg/s) |
| D | = | Extinction coefficient in smoke measuring system ($m^{-1}$) |

### 5.3.9 Non-combustibility Apparatus

*International Applicable Standards: EN ISO 1182; ASTM E2652*

#### *5.3.9.1 Background and development*

EN ISO 1182 (ISO 1182, 2010) has been developed as a pure material test, and a product cannot be tested under end-of-life conditions. It was created to select construction products that, while not wholly inert, produce only a tiny amount of heat and flame when exposed to temperatures of around $750\ °C$.

A device such as this determines the Non-combustibility of homogenous materials and substantial components of non-homogeneous building materials under specific conditions. A problem in defining specimen specifications led to the limitation of applying the method to testing homogeneous building products and substantial components of nonhomogeneous building products. Because the design of non-homogeneous products strongly influences test results, only homogeneous building products or homogeneous components of a product are tested.

The European construction products regulation requires the test to grade the fire resistance of wall linings, roofing and floor coverings. The schematic of the test apparatus is shown in Figure 5-14, and the test specifications are provided in Table 5-13.

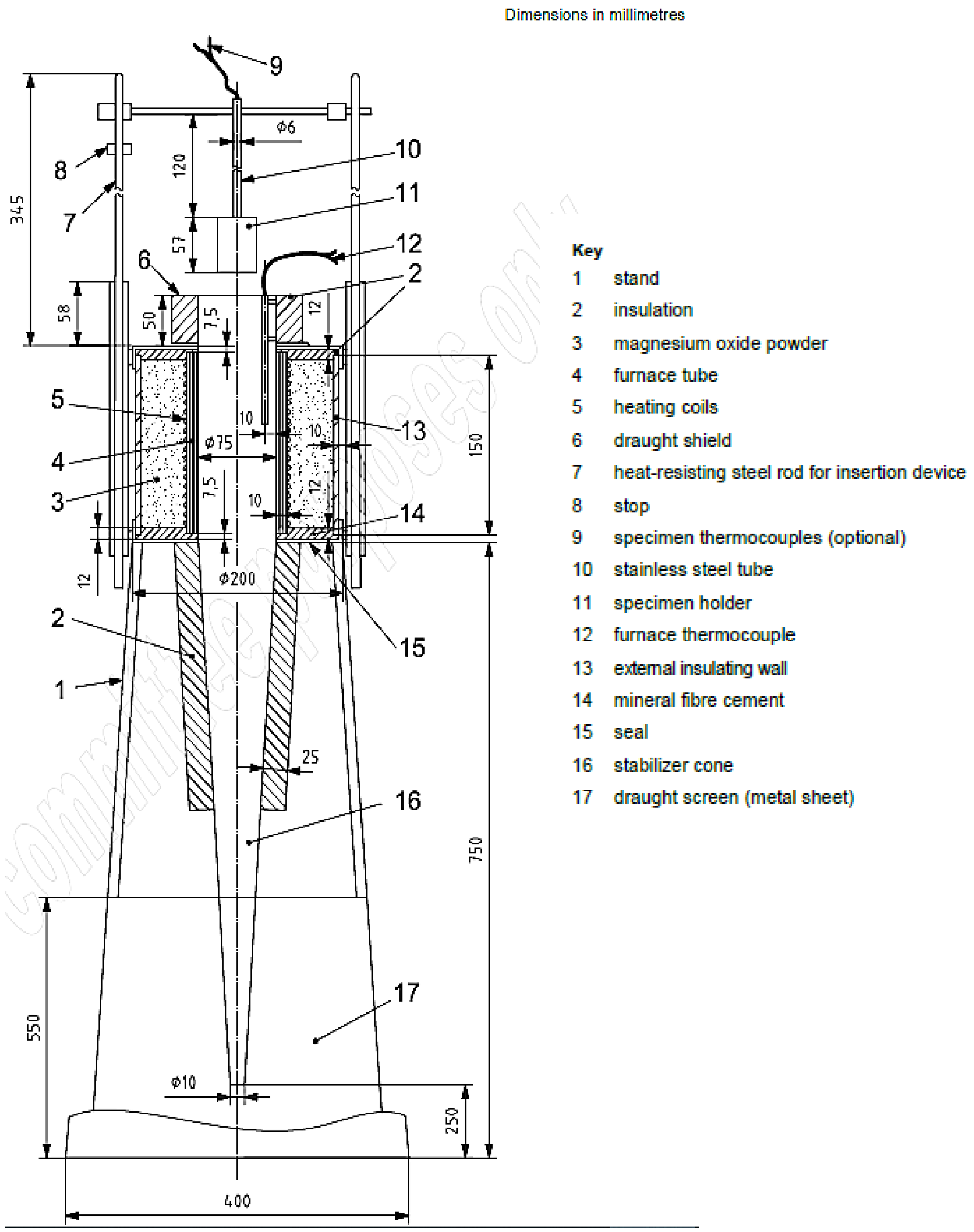



*Figure 5-14: Non-combustibility apparatus (ISO 1182, 2010)*

*Table 5-13: Test specifications of the Non-Combustibility Apparatus*

| | |
|---|---|
| **Specimens** | Five cylindrical samples<br>Diameter 45 mm, height 50 ± 3 mm, volume 76 ± 8 $cm^3$ |
| **Specimen Position** | Vertical in specimen holder in the centre of the furnace |
| **Heat Source** | A cylindrical electrical furnace at 750°C |
| **Test Duration** | 30 minutes, temperature stabilization dependable |

#### *5.3.9.2 Results*

The non-combustibility apparatus qualifies all types of construction products to the highest performance criteria. The Bomb Calorimeter (EN ISO 1716) can also be utilized for classification purposes, as shown in Table A- 1. The test conclusions upon which the classification is based are stipulated in Table 5-14.

*Table 5-14: Test conclusions of the Non-Combustibility Apparatus*

| | |
|---|---|
| **Requirements** | Average furnace temperature rise not exceeding 30℃<br>Average specimen surface temperature rise not exceeding 30℃<br>The average duration of sustained flaming is less than 10 seconds<br>Average mass loss less than 50% |

The temperature rise as stated in calculated as follows:

$$\Delta T = T_{max} - T_f \tag{5.3}$$

where:

| | | |
|---|---|---|
| $\Delta T$ | = | Temperature rise (°C) |
| $T_{max}$ | = | Discrete value at maximum temperature over test period (°C) |
| $T_f$ | = | Average temperature over the final 1 min of the test period (°C) |

The observation of any steady, blue-coloured luminous gas zones should be made during the test. One should note that the HRR is not a measured parameter of this test, seeing as only the mass loss in grams is expressed and not the mass-loss rate. The HRR can be calculated to present a helpful parameter in input data for performance-based designs. If a product combusts at 750℃, knowing the amount of heat and the rate of heat released might be helpful to alter the material to meet the requirement as specified in the International Standard.

### 5.3.10 Non-combustibility Apparatus According to SANS

*International Applicable Standards: SANS 10177-5*

#### *5.3.10.1 Background and development*

Although not explicitly stated that SANS 10177-5 (SANS, 2005d) adopted the EN ISO 1182 test standard in its entirety, there are significant similarities between the two standards. The test technique determines the non-combustibility of homogeneous and non-homogeneous construction materials, except electrical components and cable, at 750 ℃, and the scope is equivalent. However, the classification method and its reference documents are not similar, highlighting some critical concerns addressed in Chapter 6.

#### *5.3.10.2 Operation*

The essential operation and test apparatus are similar to Figure 5-14, with minor dimensional changes indicated in Figure 5-15. There are no engineering drawings provided for the specimen holder nor the relative position of the furnace, specimen and thermocouples in SANS 10177-5. The apparatus user is left to ensure the correct size parts are built and installed without exceeding the tolerances.

The essential operation and parts are similar to its European counterpart; the furnace consists of a tube with heating coils wound around it. A plate of the asbestos board completes the top and bottom of the furnace. To the lower end of the furnace is attached a cone-shaped stabilizer which is joint to the furnace utilizing an asbestos seal.

One should note that according to The Association for the Eradication of Asbestos and Asbestos Products (2008), South Africa banned the use of asbestos in 2008. However, the new regulations make provision for asbestos for research purposes. Nevertheless, since importation is prohibited and many health risks associated with asbestos exist, the question is raised of how the use of asbestos in this apparatus is still permitted. Regarding the Non-combustibility test, with the asbestos being utilized as fire-resistant insulating boards, adverse health effects can result from exposure to asbestos dust particles. The use of alternative insulation material, such as a mineral fibre insulating material, should be considered in revising this standard.

No mention of any other equipment used, such as a viewing mirror or control system, is made, resulting in a vague comprehension of how the test instrument works. The test apparatus is also capable in this standard to test rectangular specimens, as discussed in Table 5-15.

*Table 5-15: Test specifications of SANS 10177-5*

| | | | |
|---|---|---|---|
| **Specimen** | **Cylindrical** | Three samples<br>45 mm diameter<br>$50 \pm 3$ mm height | Three samples<br>45 mm diameter<br>$50 \pm 3$ mm height |
| | **Rectangular** | Volume $80 \pm 5$ cm$^3$ | Volume $80 \pm 5$ cm$^3$ |
| **Specimen Position** | Vertical in specimen holder in the centre of the furnace | | |
| **Heat Source** | A cylindrical electrical furnace at 750℃ | | |
| **Test Duration** | 20 minutes, temperature stabilization dependable | | |

The test procedure follows inserting the specimen into the specimen holder and lowering it into the furnace using the insertion device is described in the standard. The heating period is commenced and continued for the total testing period. The measurements and observations listed are made throughout this period. Figure 5-15 presents a diagram of the setup, with critical dimensions highlighted. Dimensions that vary in relation to its EN counterpart are indicated.

#### *5.3.10.3 Results*

Recordings of the temperature readings from the furnace and specimen thermocouples are made as described in Table 5-16. The material shall be deemed non-combustible if any of the three tested specimens meet the following criteria:

*Table 5-16: Test conclusions of SANS 10177-5*

| | |
|---|---|
| **Requirements** | Average furnace temperature rise not exceeding 50℃<br>Specimen surface temperature rise not exceeding 50℃<br>No continuous flame observed for longer than 10 s |

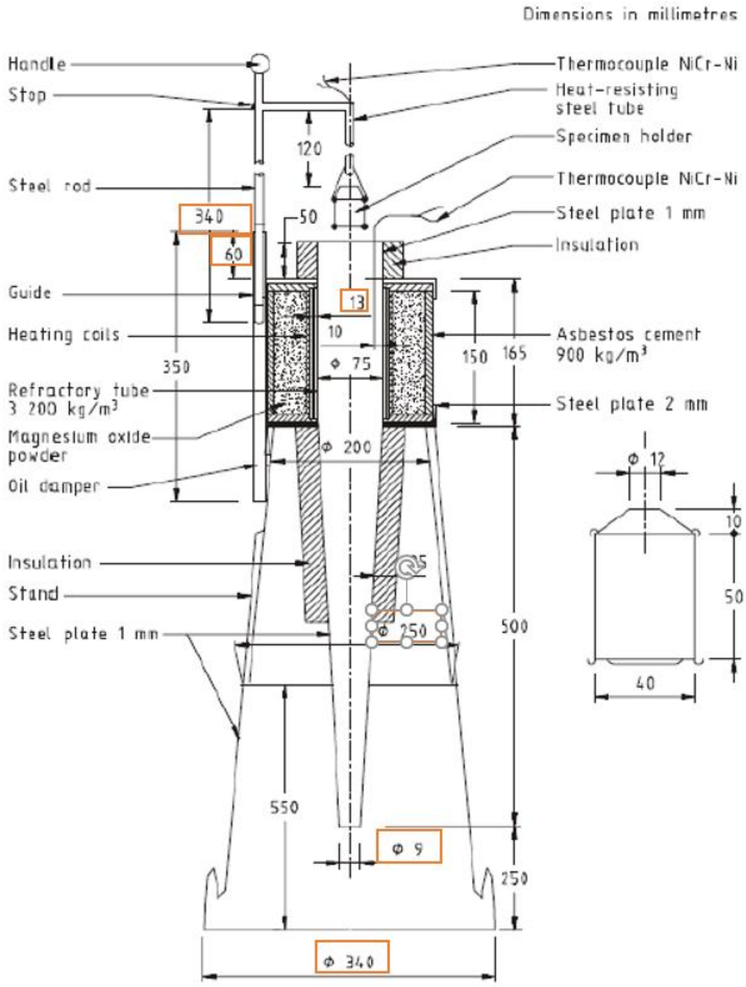



*Figure 5-15: Schematic of SANS 10177-5 test apparatus (recreated from (SANS, 2005d))*

### 5.3.11 Flooring Radiant Panel Test Apparatus

*International Applicable Standards: EN ISO 9239-1; ASTM E970; ASTM E648; NFPA 253*

#### *5.3.11.1 Background and development*

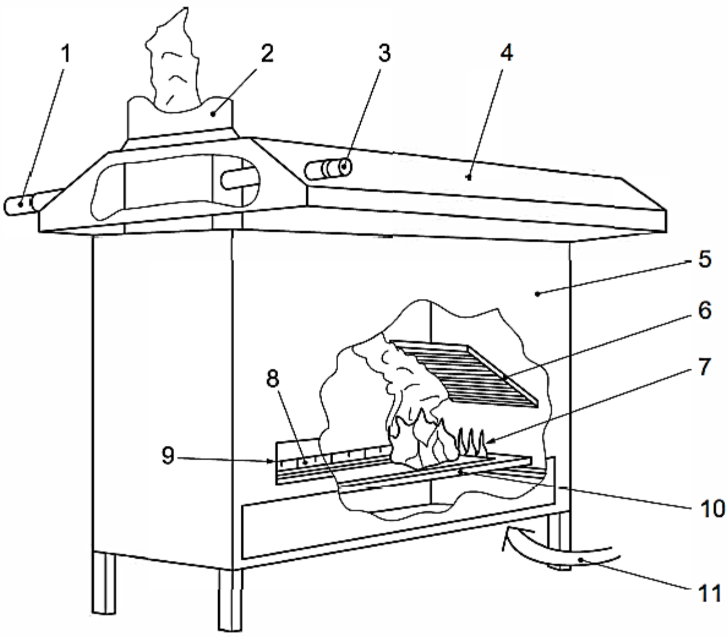
This apparatus was formally known as the reaction-to-fire test for floorings for determining the burning behaviour using a radiant heat source. When the horizontally mounted floor covering systems are ignited with pilot flames and exposed to a heat flux radiant gradient in a test chamber, ISO 9239-1 (EN ISO, 2010) provides a method for analysing wind-opposed burning behaviour in terms of flame spread and smoke generation.

All types of flooring can be coated with this method, including carpets, cork, wood, rubber, and plastics. When describing or evaluating the fire hazard of flooring or the fire risk, it poses under actual fire conditions, this standard should not be used alone. A line burner is located at the end of the specimen with the highest heat flux. The ignition of the line gas burner takes place utilizing a controlled high-voltage ignition spark. The small stainless-steel burner inflames the specimen from several holes and ignites the specimen's zero line, as shown in Figure 5-16.

The testing principle of this apparatus is relatively straightforward as it only includes a few parts to determine the burning behaviour in terms of the flame spread of a specimen, as shown in Figure 5-17.

The technical detail of the setup is also shown. The test specifications, along with the standard procedure, as stipulated in Table 5-17.

*Figure 5-16: Line burner in operation (NETZSCH® TAURUS® Instruments, 2021)*




**Key**

1 lamp
2 exhaust duct
3 detector
4 exhaust hood
5 test chamber
6 gas-fired radiant panel
7 pilot flames from line burner
8 scale
9 observation window
10 specimen holder with specimen together on sliding platform
11 air inlet all around specimen at bottom of chamber

*Figure 5-17: Perspective view of EN ISO 9239-1 indicating test principles (EN ISO 9239-1, 2010)*

*Table 5-17: Test specifications of the Flooring Radiant Panel Apparatus*

| | |
|---|---|
| **Specimens** | One specimen was tested in one direction, and one specimen was perpendicular to the first specimen tested. The worst result is repeated twice in that configuration. |
| **Specimen Size** | 230 mm × 1050 mm |
| **Specimen Position** | Horizontally placed in L-profile designed sample holder |
| **Heat Flux Source** | Gas-heated radiator (surface area of 0.135 $m^2$), inclined 30° to the horizontal |
| **Heat flux output** | Heat flux of 11 kW/m² at the hot end to 1.1 kW/m² at the opposite end |
| **Ignition Source** | Stainless-steel line piloted propane gas burner |
| **Ignition Size** | 35 holes, 3 mm above the edge of the sample holder |
| **Test Duration** | Until flame extinguishment |

#### *5.3.11.2 Results*

The critical heat flux, which acts on the potion of the sample surface where the flames do not spread and may extinguish, is determined. The distance burned until flame extinguishment is translated into an equivalent critical radiant flux in kW/m² by calibration. If the specimen is still burning after 30 minutes, the flame front position calculates the critical heat flux.

Additional results are provided in Table 5-18. The combustion distances are measured as a function of time as the distance between the flame front and the sample zero line.

*Table 5-18: Test results of the Flooring Radiant Panel Apparatus*

| | |
|---|---|
| **Findings** | Flame propagation distance over the test duration<br>Smoke gas density as a function of time ($\% \times minutes$)<br>Critical heat flux (kW/$m^2$) |

Any flame front development is observed following ignition. An assessment is made of the rate at which flames spread horizontally along with the specimen according to the time it takes to do so. Smoke production is measured by the emissions of light in the exhaust stack. This method indicates the performance of a floor covering and may also reflect the performance of its substrate if applicable. Modifications to the backing, bonding to the substrate, etc., may influence test results.

This test method forms part of EN 13501-1. Results of this standard are described in Table A- 9, illustrating that a combination of tests is required to meet one class criteria.

### 5.3.12 Inverted Channel Tunnel Test

*International Applicable Standards: SANS 10177-10*

#### *5.3.12.1 Background and development*

The SANS 10177 Part 10 describes the characteristics of burning building materials: ignition, flame spread, and heat contribution. It applies to all combustible or non-combustible materials used for surface application and serves as a materials classification method. By measuring the maximum flame spread, this test method determines the fire spreading potential of building envelope materials by comparing their burning behaviour.

A fire performance classification must be conducted prior to any large-scale performance or application tests of the material. (SANS, 2007). The apparatus is referred to as an inverted channel tunnel and resembles the upper half of a corridor or a three-sided inverted channel. It comprises three main parts, the metal frame, specimen support brackets and the fire source. The channel is 7.4 m in length and 2.4 m in height. The inside is cladded with rigid insulating fibreboard. The two walls are 750 mm apart from the other dimension shown in Figure 5-18. The test specifications regarding the specimen, ignition source and test duration are presented in Table 5-19.

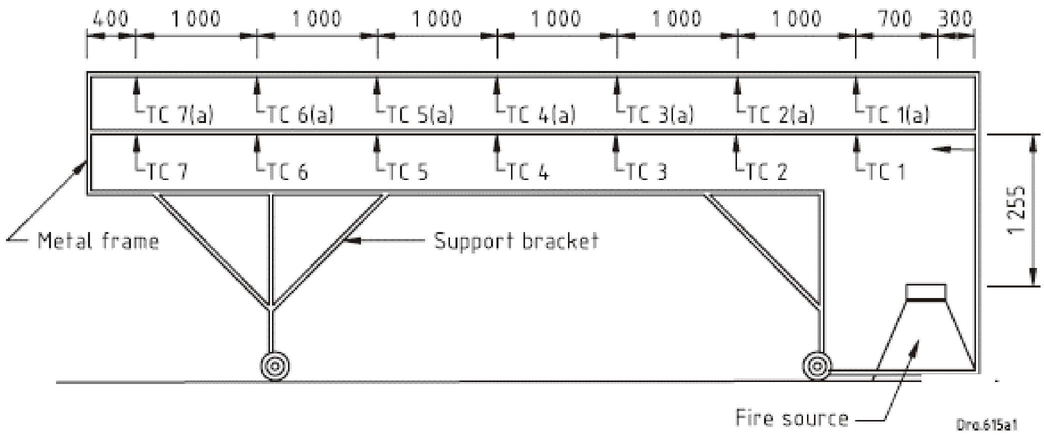



*Figure 5-18: Side view of the inverted channel tunnel with TC referring to thermocouple positions (SANS 10177- 10, 2007)*

*Table 5-19: Test specifications for Inverted Channel Tunnel*

| | |
|---|---|
| **Specimens** | Single material or a composite as per practice guideline |
| **Specimen Size** | Dimensions to make up the 7,4 m length of the channel |
| **Specimen Position** | Horizontally placed in the length of the channel |
| **Ignition Source** | Hexane pan, Producing 18 kW |
| **Ignition Size** | 305 mm × 305 mm × 125 mm<br>Volume filled max = 4 litres |
| **Test Duration** | 10 minutes or until all fuel has been consumed |

The reader can refer to SANS 10177-10 for the material testing procedure. Variation with this test method exists in that a test specimen can be installed in a test frame simulating a typical building frame structure or installed as is in practice.

### *5.3.12.2 Results*

The flames, or resultant damage, must not spread beyond the ignition source area for materials tested in compliance with SANS 10177-5 to be considered non-combustible. However, tests have shown that materials with low combustible content but classified as combustible will not exhibit any flame spread. The test results regarding the observations that are required to be made are highlighted in Table 5-20.

*Table 5-20: Test results of the Inverted Channel Tunnel*

| | |
|---|---|
| **Observations** | Time of ignition<br>Burning behaviour<br>Dripping<br>Flame propagation.<br>Flaming droplets<br>Duration of surface flaming<br>Length of surface flaming and surface char |

The observations tie in with the measurements required to determine the combustibility of all materials according to SANS 10177-5 and classify them according to SANS 428 (SANS, 2012). All measurements in Table 5-21 refer to the specific total measured distance, in mm, that the test specimen met regarding the specific measurement topic described in the table.

*Table 5-21: Measurements during testing*

| | |
|---|---|
| **Measurements** | Flame spread<br>Dripped without flaming droplets<br>Dripped with flaming droplets, burning brand dropped on the floor<br>Dripped with droplets and burning brand continued burning on the floor |

Figure 5-19 illustrates a test performed by a laboratory in South Africa. A test that receives pass criteria is seen on the left, where the fire is deemed to be under control. The failure instances are visible through observation of the properties mentioned in Table 5-21. A high flame propagation with the flame exiting the channel can be seen, suggesting the test specimen is inflamed. Burning brands are noticed on the floor, which stems from the material being tested.

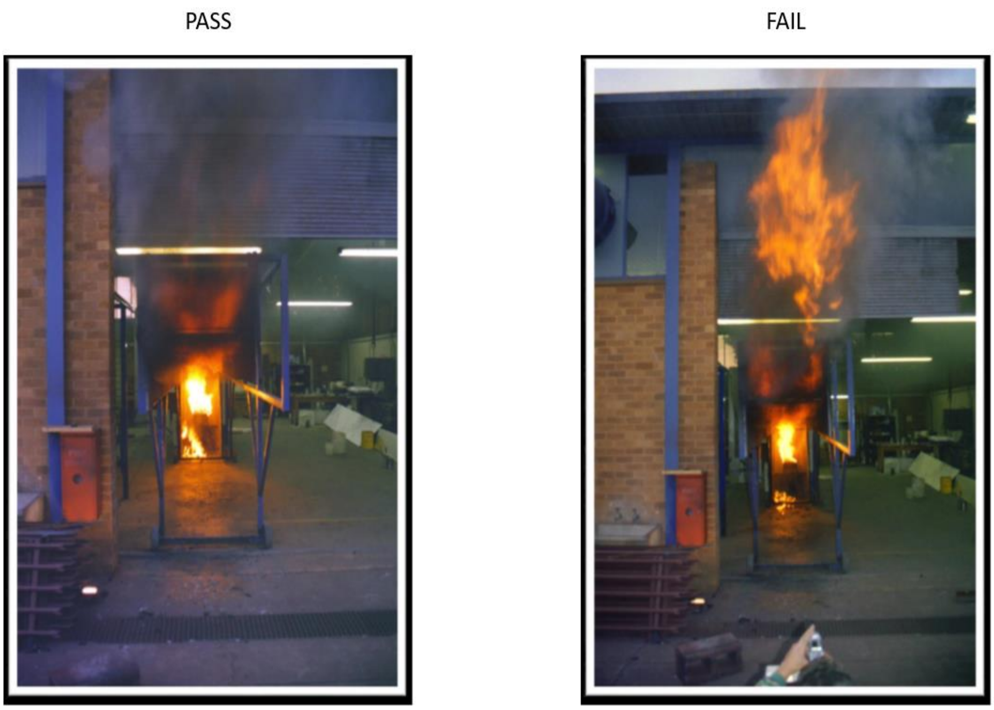



*Figure 5-19: Pass and failure illustrations (FireLab, 2020)*

### 5.3.13 Small-scale Burning Characteristics of Building Materials

*International Applicable Standards: SANS 10177-9*

#### *5.3.13.1 Background and development*

According to Section 2.4.4, SANS 10177-9 is a South African National Standard that uses a controlled ignition source to establish the basic fire properties of insulation materials, roof components, ceiling components, and side cladding components are exposed to a small ignition source.

Among the testing methods covered in SANS 10177, determining whether a material will burn quickly, how widely the flame will spread, and how much heat it will emit forms part of the methods.

When exposed to an ignition source, the result from this test gives a good idea of the material's probable behaviour. However, this test method is not applicable for the approval of any product or material. The outcome, however, is aimed to serve as a fire performance or qualitative measure prior to any large-scale application or performance testing.

The apparatus consists of a vertical test channel, as illustrated in Figures 5-20 and 5-21. The three main components of the apparatus are described in Table 5-22.

The reader can refer to the standard regarding the calibration procedure, and the test specifications are provided in Table 5-23.

*Table 5-22: Vertical test channel components*

| Sheet metal furnace stack | Bunsen burner | Thermocouple |
|---|---|---|
| •305 mm by 305 mm and 2.1 m high<br>•Foot support 305 mm above the floor<br>•Open at top and bottom<br>•Door consist of full-length wire glass to fit and remove specimen | •Ø 9.5 mm head and mm long tube<br>•Placed on the floor below specimen<br>•Propane fuel burner producing 200 mm flame | •K-type<br>•100 mm from the top in the centre of the stack<br>•Record heat contribution |

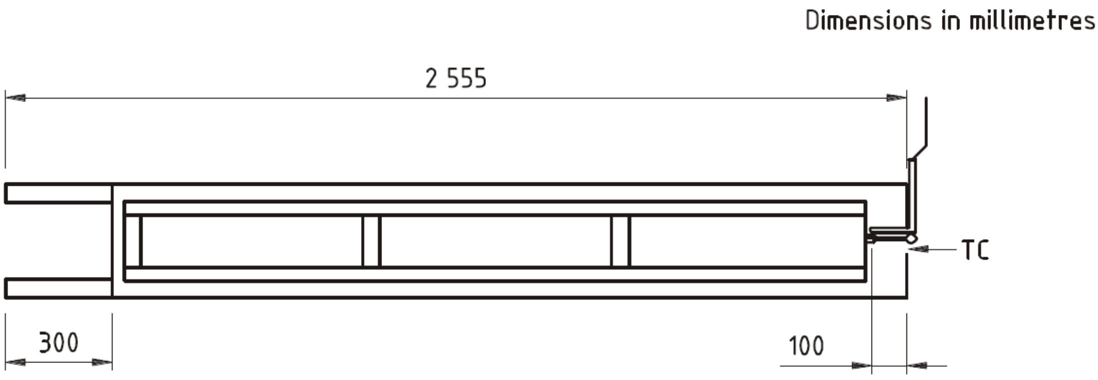



*Figure 5-20: Front section of the vertical test tunnel (SANS, 2006)*

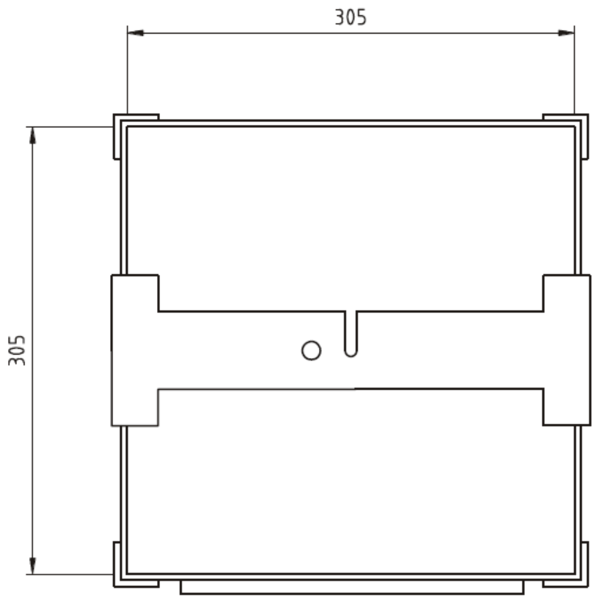



*Figure 5-21: Top section of the vertical test tunnel (SANS, 2006)*

*Table 5-23: Test specifications of the vertical test tunnel*

| | |
|---|---|
| **Specimens** | Single material or a composite as per practice guideline |
| **Specimen Size** | 150 mm wide × 1200 mm long |
| **Specimen Position** | Suspended in furnace stack. Bottom of specimen 100 mm above Bunsen burner |
| **Ignition Source** | Bunsen burner, 200 mm flame length |
| **Ignition Position** | 30° from the vertical of the specimen |
| **Test Duration** | 10 minutes |

### *5.3.13.2 Results*

This standard uses a small ignition source of a Bunsen burner under controlled conditions to observe building materials' relevant basic fire properties. Measurements and conclusions are made about the respective material such as the:

- Ease of ignition
- Degree of spread of flame
- Total burnt distance (from bottom edge till the furthest burning point) of the specimen (mm)
- Heat contribution of the area under the time-temperature curve between the ambient temperature and the temperature at the end of the test (℃ · min )

This method does not by any means approve any material or product. Further reporting of the following aspects is made:

- Time to ignition
- Time to burn the entire length of the specimen
- Molten droplets during flaming
- Material burning after removal of burner after 12 and 24 s
- Length of flame spread or heat damage
- Heat contribution over test duration
- Maximum temperature in stack during test period

## 5.4 Fire Resistance Tests

The fire resistance of any constructing aspect relies upon many factors, which includes the severity of the furnace test, the material, the geometry and help stipulations of the element, restraint from the surrounding shape and the utilized loads at the time of the fire (Buchanan and Abu, 2017). Fire resistance tests are used to evaluate a structure's or system's ability to resist the spread of fire from one region to another, as well as its fire separating properties. As illustrated in Figure 5-3, fire resistance is essential for post-flashover fire events. Fire resistance aids in limiting the spread of a fire from the source room while maintaining the compartment's structural integrity (Buchanan and Abu, 2017).

The following are places where fire resistance tests are required (Babrauskas and Peacock, 1992):

- Structural framing: columns, beams, trusses.
- Exterior and interior bearing walls
- Interior non-bearing walls and partitions
- Doors
- Floor and ceilings
- Windows

The building codes of all countries specify the required fire-resistance rating that building elements should endure. The typical values range from 30 minutes to 4 hours and increase in increments of 30 minutes. However, this is only applicable to most international standards except for South Africa that has no endurance criteria for 90 minutes. Fire resistance tests allow a standard comparison method between structural assemblies' fire performance. Historically the fire resistance of structural members could only be determined by testing. Although the industry will deem the tests costly (Buchanan and Abu, 2017), small bench-scale tests cannot assess all the potential problems causing effects. Because numerical approaches for calculating the fire resistance of various structural parts are significantly less expensive and time-consuming, solutions that originated from these methods are gaining favour to overcome this constraint.

The fire performance of structural members depends on the material properties of the building component. When exposed to a predetermined temperature-time exposure during a fire, structural members exhibit predictable temperature distributions. Temperature increases cause materials to deform and change properties. If the deformations and property changes are known, structural mechanics methods can be used to predict fire resistance performance.

Building elements need to be assigned fire-resistance ratings to compare the fire severity specified by codes (e.g., a 60-minute fire rating for a three-storey office block). A full-scale fire resistance test on representative specimens is the most common method of evaluating fire resistance.

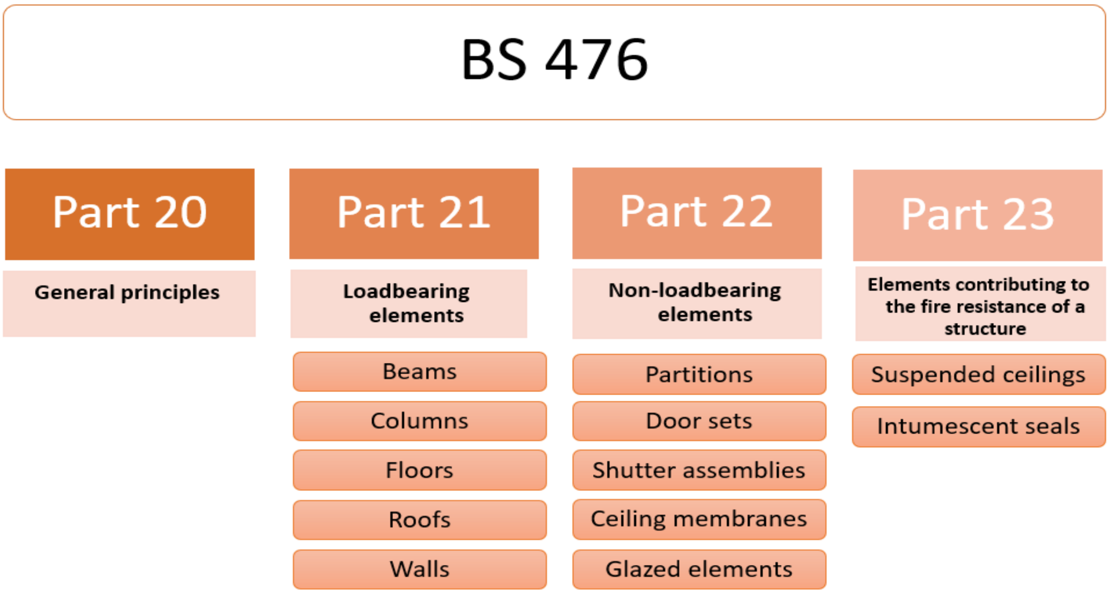
### 5.4.1 Full-scale Furnace Testing (Vertical)

*International Applicable Standards: BS 476 (20-23); BS EN 1363 (1-2); BS EN 1364 (1); BS EN 1365 (1); BS EN 1366 (1-3); ISO 834 (1, 4, 8); BS EN 1634-1; ASTM E814; ISO 3009; ASTM E119; UL 10 (B-C); UL 1709; UL 1479; UL 263; UL 2079; ISO 3008*

#### *5.4.1.1 Background and development*

Multiple codes incorporate the test method of full-scale furnace testing. The discussions below are based on the BS 476 series of test methods. BS 476: Part 20:1987: "Method for determination of the fire resistance of elements in construction" describes the general principles of fire resistance testing of construction elements (BS, 1987).

It establishes a set of explicit standards for determining a component's loadbearing capacity, fire containment (integrity), and thermal transmittance (insulation). The testing standard is backed up by three more standards that provide detailed information on how to test various types of construction elements:




The typical fire resistance test accurately simulates heat transmission inside an enclosed room with a fully established, post-flashover fire. The occupants of the compartment will perish if the compartment reaches flashover. The performance of building elements against the standard time-temperature curve established by the standard is determined by their performance in a large furnace capable of handling sized specimens. The fire-resistance qualities of the material are quite helpful in determining how a specimen and its assemblies will behave. Test specimens discussed in this section are tested in a vertical orientation, indicating their end-use application. Vertical separating features like walls and partitions can be heated from both sides, but not both simultaneously, as shown in Figure 5-22. Similar test methods are applied to flooring systems, beams and columns.

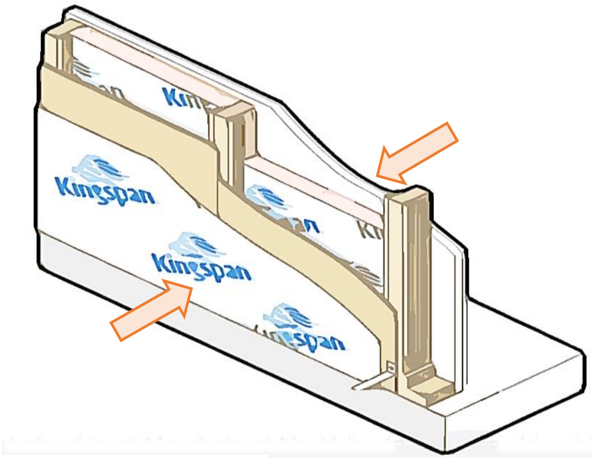



*Figure 5-22: Vertical separating elements (recreated from Kingspan Insulation UK, 2020)*

The load-bearing capacity, fire containment, and thermal transmittance of the assemblies being tested are all examined during the assessment. BS 476 - Parts 21 and 22 will be analysed and compared since some processes within the testing regime differ for loadbearing and non-loadbearing elements, as shown in Table 5-24. The test specifications are provided in Table 5-24, and the testing chamber is shown in Figure 5-23. The testing conditions consist of the heating regime and pressure requirements.

*Figure 5-23: Large scale vertical fire resistance test furnace (CMTS, 2021)*

*Table 5-24: Test specifications of a vertical furnace test BS 476-20*

| | Non-loadbearing | Loadbearing |
|---|---|---|
| **Specimens** | Full-size elements of construction | Full size elements of construction |
| **Specimen Size** | 3 m × 3 m separating elements<br>3 m wide non-separating elements | 2.4 m × 3 m separating elements |
| **Specimen condition** | Standard use | Mechanical or deadweight loading simulating end-use loads |
| **Chamber depth** | Between 600 mm and 1300 mm | Between 600 mm and 1300 mm |
| **Ignition Source** | Natural gas or liquid fuel | Natural gas or liquid fuel |
| **Ignition Position** | Not specified | Not specified |
| **Test Duration** | Until failure of criteria or until the agreed time criteria | Until failure of criteria or until the agreed time criteria |

A test construction's fire resistance shall be assessed based on one or more performance criteria, including loadbearing capacity, structural integrity, and insulation, depending on the elements being tested. In the event of a failure, or if the testing centre and sponsor agree on a time period before the test, the test duration applies to all performance criteria. The test is terminated at the end of the heating period for non-loadbearing and loadbearing elements. Two criteria of the partition's fire behaviour are measured in the fire test: its integrity and its insulation.

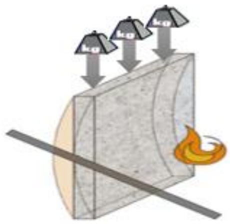
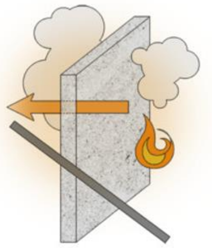
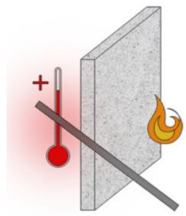
#### *5.4.1.2 Results*

The discussions above will vary regarding the test specimens, installation process conditioning processes and performance criteria. However, it will not differ regarding the test conditions and application of furnace instrumentation.

Depending on their intended use, the specimens are evaluated against one or more performance criteria. When a rapid change in the deformation rate of a vertical element is visually noticed, it is considered a failure of the loadbearing capacity criterion. The failure descriptions of the test construction stability, integrity and insulation criteria are provided in Table 5-25, as introduced previously.

When burning is seen on the unexposed face of the element, or when the impermeability conditions are surpassed, the element fails. Failure of the cotton pad test, resulting in fibre pad flames due to hot gases, is one of these circumstances. If the cotton pad test is not employed, failure shall then be deemed to have occurred according to the specifications described in Table 5-25.

*Table 5-25: Failure description of a vertical furnace test BS 476-20* (recreated from José Tomás, 2016)

| Criteria | Failure description | Illustration |
|---|---|---|
| **Stability** | Specimen fails to support the test loading |  |
| **Integrity** | A Ø6mm gap gauge can penetrate through a gap into the furnace and be moved for a distance of at least 150 mm |  |
| | A Ø25 mm gap gauge can penetrate through a gap into the furnace | |
| **Insulation** | Mean temperature on unexposed face rise by $\geq 140\ ^\circ C + ambient$ |  |
| | The initial mean of unexposed face temperature $\geq 180\ ^\circ C$ | |
| | Occurrence of integrity failure | |

The results are given as the total time from start to finish, rounded to the nearest minute. The time allotted for insulation failure cannot be longer than the time allotted for integrity failure. Insulation materials delay the process of temperature rise of structural members, thereby enhancing their fire resistance. Several insulation materials are available, widespread use of mineral wool and glass fibre (Yu and Kodur, 2014). The results are provided as a full report with additional measurements and observations (BS, 1987).

### 5.4.2 Fire Resistance Test for Building Elements to SANS

*International Applicable Standards: SANS 10177-2*

#### *5.4.2.1 Background and development*

The approach in SANS testing to fire resistance is very similar to that in BS 476, but with several minor differences and omissions of specific requirements (e.g., pressure). Also, all elements are dealt with under a single standard. SANS 10177-2 covers the method of test used to determine the fire resistance of certain elements such as those listed below. The length of time within which a test specimen of specified dimensions will satisfy the stability, integrity, and insulation performance criteria.

- Wall loadbearing and non-loadbearing
- Partition
- Column
- Beam
- Floor
- Ceiling
- Door and shutter assembly

This standard specifies that the temperature within the furnace is controlled according to the standard time-temperature curve described in Equation 2.9. The relationship provides the values of the time and its corresponding temperature illustrated by the curve in Figure 2-1. The furnace temperature is the average temperature recorded by the thermocouples. At least five thermocouples must be used with the following requirements stated in Table 5-26. Tolerances are provided in the standards to ensure the accuracy of the temperature control.

The surface thermocouples are suggested to be covered by an asbestos square pad, 150 mm × 150 mm × 3 mm. As mentioned in Section 5.3.10, the importation and use of asbestos are banned in South Africa. Therefore, this standard is outdated, and alternative solutions towards covering the thermocouples with appropriate materials should be utilised.

*Table 5-26: Thermocouple requirement per element*

| Element | Requirement |
|---|---|
| **Wall and floor** | One to each 1.5 $m^2$ of surface |
| **Beam** | One to every 1 m of length |
| **Column** | Two to every 1m of height |

The standard requires a full-sized representative specimen to be tested, or the dimensions stipulated in Table 5-27 should be satisfied. Fire resistance testing should assess the end-use application of an element or assembly.

*Table 5-27: Test specifications for SANS 10177-2*

| | Walls/ Partition | Floor/ceiling | Beam | Column |
|---|---|---|---|---|
| **Specimens** | Full-size | Full-size | Full-size | Full-size |
| **Specimen Size** | 2.8 m × 2 m | 4 m × 2 m | 4 m span | 3 m height |
| **Specimen position** | Heat applied to one face only | Per client requirements | Per client requirements | Heat applied to all sides |
| **Ignition Source** | Gas, liquid fuel | Gas, liquid fuel | Gas, liquid fuel | Gas, liquid fuel |
| **Ignition Position** | Not specified | Not specified | Not specified | Not specified |
| **Test Duration** | Until failure of criteria or until the agreed time criteria | Until failure of criteria or until the agreed time criteria | Until failure of criteria or until the agreed time criteria | Until failure of criteria or until the agreed time criteria |

#### *5.4.2.2 Results*

Various observations must be made during the fire-resistant testing. Most of these observations are in terms of the performance criteria to which the element is being tested.

Stability:

- The deformation should be measured, and the time of specimen collapse
- Time at which loadbearing item cannot support test load
- Maximum permissible deflection for a beam is not exceeded
- Monitor temperatures of a protected or encased steel column or beam

Integrity:

- Development of cracks, holes or openings on separating elements

Insulation:

- Monitor temperatures and determine the highest average temperature reached by the unexposed face

All changes and occurrences that are non-criteria related but which could create hazards in a building should be observed (e.g., smoke or noxious vapours from the unexposed face). The fire resistance shall be recorded in terms of the time (min) from the commencement of the test until failure occurs in respect of the appropriate performance criteria. In a bid to tie in with the observations mentioned above, the specific failure criteria should be determined. These criteria are similar to the British standard discussed in Section 5.4.1, with some minor adjustments. The integrity and insulation criteria pertain to separating elements, as stated in Table 5-31. *L* is the span of the specimen (mm) where quoted below.

| | |
|---|---|
| Stability | •Collapse of test specimen<br>•Horizontal specimen fail when max deflection $\geq \frac{L}{30}$ |
| Integrity | •Formation of cracks, holes or openings<br>•Passing through of flames and hot gases |
| Insulation | •Average temperature of unexposed face $\geq 140\ ℃ +$ ambient<br>•Max temperature of unexposed face ≥ 180 ℃ + ambient<br>•Max temperature of unexposed face ≥ 220 ℃ |

SANS 1253 (SANS, 2016) refers to the requirements for fire-door and fire-shutter assemblies classes to provide fire resistance, as shown in Table 5-28. This standard makes a normative reference to SANS 10177-2 as the full-scale furnace test should be utilized to assess the requirements of SANS 1253.

*Table 5-28: Fire resistance classification of doors*

| Class | Minimum Resistance periods (min) | | |
|---|---|---|---|
| | Stability | Integrity | Insulation |
| **E** | 30 | 30 | 30 |
| **A** | 60 | 30 | 30 |
| **B** | 120 | 60 | 60 |
| **D** | 120 | 120 | 120 |
| **C** | 120 | 120 | No requirement |
| **F** | 30 | 30 | No requirement |
| Clause | 4.9.2 | 4.9.3 | 4.9.4 |

### 5.4.3 Full-scale Furnace Testing (Horizontal)

*International Applicable Standards: BS 476 (20-24); BS EN 1363 (1-2); BS EN 1364 (2); BS EN 136 (2-4); ISO 834 (1, 5-7, 9); BS EN 1366 (1-3); UL 1479; ASTM E119; ASTM E1966; ASTM E814; UL 263; UL 2079; UL 10 (B-C); ISO 6944 (1-2); ISO 3008; UL 1709*

#### *5.4.3.1 Background and development*

The fire resistance of a material used in an assembly is an essential factor to consider when evaluating the performance of construction elements following the rules. The following discussion is based on the BS 476 test method series (BS, 1987). The general test techniques and calibration outlined in Section 5.4.1 will remain identical as long as the test specimen, apparatus, and test conditions require minor changes to accommodate a horizontal element.

The horizontal test furnace evaluates the fire resistance capabilities of horizontal construction assemblies such as a beam or slab. Horizontal separating elements such as floors and flat roofs are exposed to heat from the underside, as illustrated in Figure 5-24.

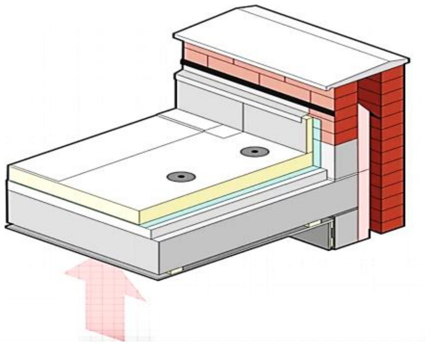


*Figure 5-24: Horizontal separating elements (recreated from Kingspan Insulation UK, 2020)*

The horizontal furnace can be used to conduct loadbearing and non-loadbearing tests on horizontally placed specimens and beams mounted in restraint frames. Furnaces are constructed similarly to those discussed in the previous sections. The test area dimensions are 3 m (width) × 4 m (height) × 1 m (depth), with the specimen being secured by a minimum of four sets of clamps in a restraint frame. The standard time-temperature curve described in Section 2.3.5 is used. The test specifications in Table 5-29 describe the required specimen size and the ignition sources to achieve the pre-set heating curve. The fire resistance test furnace and system diagram are indicated in Figure 5-25.

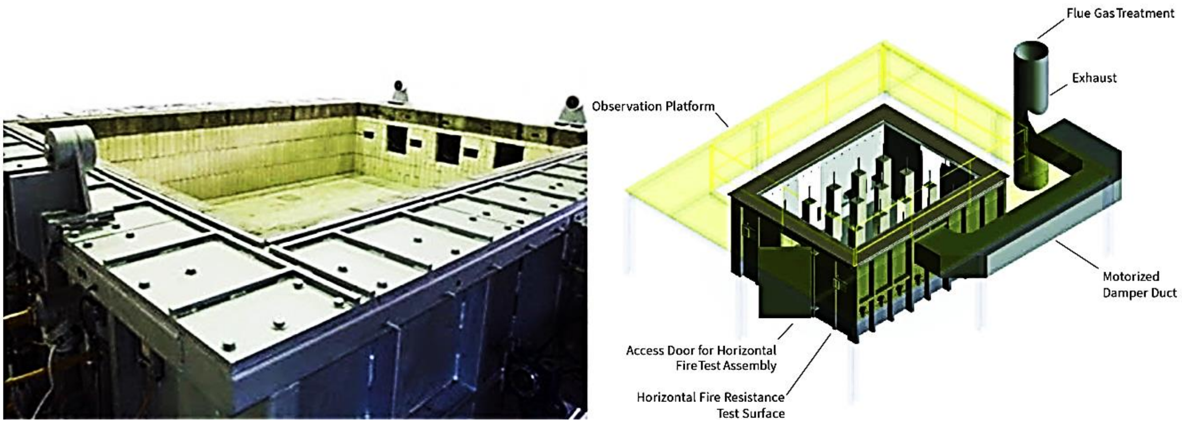



*Figure 5-25: Horizontal fire resistance furnace and system diagram* (Fire Testing Technology, 2021)

*Table 5-29: Test specifications of a horizontal furnace test*

| | |
|---|---|
| **Specimens** | Elements of construction full size |
| **Specimen Size** | 4 m $\times$ 3 m for separating elements<br>4 m wide span for non-separating elements |
| **Specimen Position** | Horizontal secured with four sets of clamps |
| **Chamber Depth** | 1000 mm $\leq depth \leq$ 2000 mm |
| **Ignition Source** | Natural gas or liquid fuel. 20 sets of Refractory Nozzle Mix Burners (2 groups of 10) |
| **Ignition Position** | Sidewalls or underside |
| **Test Duration** | Until failure or until the agreed time criteria |

#### *5.4.3.2 Results*

The loadbearing capacity, the ability to offer fire restraint, and the thermal transmittance of the materials and systems are all factors that go into determining fire resistance. When any of the standards listed in the standard are exceeded, the loadbearing capacity criterion is considered a failure. The tests specimen shall be deemed to have failed if it can no longer support the test loads and when either of the following values is exceeded:

- a deflection of $\frac{L}{20}$ ; where L is the span of the specimen (mm)
- where the rate of deflection (mm/min) exceeds the limit set by the equation:

$$rate\ of\ deflection = \frac{L^2}{9000d} \qquad (5.4)$$

where d is the distance from the top of the structural section to the bottom of the design tension zone (mm). This limit is not applied before a deflection of $\frac{L}{30}$. The criteria of integrity and insulations are still applicable to horizontal elements testes in a full-scale furnace.

## 5.5 Summary of criteria and tests

This chapter has summarised a large variety of reactions to fire and fire resistance tests to explain the variety of testing apparatuses and approaches currently available. The following sections summarise details regarding the tests.

### 5.5.1 Reaction-to-Fire Tests

The parameters mentioned in Section 3.3 are attainable in the various test described by various standards and codes. Some tests provide only one parameter, or an index, while others provide a range of parameters. A summary of the measurable parameters and their respective representation in a specific standard will be described in Table 5-30. It is essential to appreciate which test should be used to obtain each parameter.

*Table 5-30: Standards summary of measurable parameters*

| ***Parameter*** | ***Standard*** | ***Test*** |
|---|---|---|
| ***Thermal inertia*** | ISO 5658-2; ASTM E1321 | LIFT Apparatus |
| | ISO 5660-1; ASTM E1354 | Cone Calorimeter |
| | ISO 12136 | Fire Propagation Apparatus |
| ***Heat release rate*** | ISO 5658-2; ASTM E1321 | LIFT Apparatus |
| | ISO 5660-1; ASTM E1354 | Cone Calorimeter |
| | BS EN 13823 | Single Burning Item |
| | EN ISO 1716 | Bomb Calorimeter |
| ***Ignition*** | ISO 5658-2; ASTM E1321 | LIFT Apparatus |
| | ISO 5660-1; ASTM E1354 | Cone Calorimeter |
| | EN ISO 11925-2 | Ignitability Test |
| | SANS 10177-9 | Small-scale burning characteristics of building materials |
| ***Flame spread*** | ISO 5658-2; ASTM E1321 | LIFT Apparatus |
| | SANS 10177-10 | Inverted Channel Tunnel Test |
| | BS EN 13823 | Single Burning Item |
| | ISO 9239-1,2 | Reaction-to-fire tests for floorings |
| | EN ISO 11925-2 | Ignitability Test |
| | SANS 10177-9 | Small-scale burning characteristics of building materials |
| | ISO 12136 | Flame Propagation Apparatus |
| ***Heat of combustion*** | ISO 5660-1; ASTM E1354 | Cone Calorimeter |
| | EN ISO 1182; SANS 10177-5 | Non-combustibility Test |
| ***Flaming (sustained)*** | SANS 10177-2; EN 1636; ASTM E1119 | Fire Resistance Test |

### 5.5.2 Fire Resistance Tests

As mentioned in Section 5.4, testing elements requires performance criteria to evaluate a specimen's resistance to high temperatures. The main criteria that exist include stability or loadbearing capacity, integrity and insulation. Depending on the nature of the element used, one criterion or a combination is required for the element to achieve its target fire resistance. Several commonly found elements and the required criteria to be met during testing are shown in Table 5-31.

*Table 5-31: Failure criteria of various elements*

| | **Stability** | **Integrity** | **Insulation** |
|---|---|---|---|
| ***Partition*** | | ✓ | ✓ |
| ***Door*** | | ✓ | ✓ |
| ***Load-bearing wall*** | ✓ | ✓ | ✓ |
| ***Floor or ceiling*** | ✓ | ✓ | ✓ |
| ***Beam or column*** | ✓ | | |
| ***Fire-resistant glazing*** | | ✓ | |

## 5.6 Challenges of Fire Testing

This section will discuss the challenges that are experienced regarding fire testing. These aspects are often neglected from fire testing standards, and minimal attention is focused on the concerns. Although being responsible for most fire deaths, toxicity is not stipulated to be measured by most fire tests, and thus, its importance will be investigated. The second aspect that will be examined is the uncertainty of measurements in fire tests standards. With no certification requirements for a fire test laboratory in South Africa, this characteristic is essential for future developments and requirements to stay competitive with the European market.

### 5.6.1 Toxicity

From 1975 to 1995, a considerable corpus of research in fire toxicity was conducted to recognise the reluctance of fire toxicity testing. However, this area was neglected recently due to a lack of suitable bench-scale equipment capable of duplicating the toxicity of the deadliest established (under-ventilated) fires. ISO TS 19700 is a globally known standard for steady-state tube furnace development. The device can replicate different stages of a fire and quantify individual toxicants in fire effluents (Stec *et al.*, 2008).

Data from large-scale fires revealed significantly more significant amounts of two asphyxiant gases, namely carbon monoxide (CO) and hydrogen cyanide (HCN), for fires that occur when there is a lack of oxygen. To guarantee that these different fire stages can be accurately recreated and that the individual fire stages are managed independently, it is critical to analyze toxic threats from a fire. The implementation of international standards, such as ISO, provides the platform for the appropriate and proper use of toxic potency data in assessing fire hazards.

As structures and modes of transportation evolve and become more complex, there is a shift away from traditional assuring fire safety through prescriptive rules. Instead, the movement is focusing on fire risk assessments and engineering solutions. The assessment must include data on the heat release rate, fire effluent toxicity, and smoke generation.

### 5.6.2 Uncertainty in Fire Test Standards

ASTM issued a collection of 11 papers on uncertainty in fire test standards in 2012. Many of the studies looked at how diverse entities, such as testing labs, enforcement agencies, manufacturers, and practising engineers, deal with uncertainty while using the results of fire safety tests and calculations (Hall, 2012). For fire tests, there is a difference established between measurement uncertainty and variability in uncontrolled factors.

The previously mentioned small-scale calorimetry studies discuss the general requirements for testing and calibration laboratories outlined in ISO 17025 (2006). In terms of measurement uncertainty, confidence intervals are quantified as ranges. In addition to the ignitability of the specimen, uncertainty related to the arrangement of the components, test, laboratory draft, and the uniformity of the specimen exists. Unlike measurement uncertainty, the effects of such variability cannot be quantified. According to the study, the overall contribution of these factors to test variability is significantly more than the contribution of measurement uncertainty.

One method for quantifying test variability is to use a precision analysis. It is possible to use the repeatability of fire tests inside a laboratory and the reproducibility of fire tests across numerous laboratories. It is assumed that if the reproducibility of a test is proven to be genuine, the repeatability will be as well, as it is usually always preferred. Changes in the test material, not the specific user or the test procedure, are the primary causes of variation in test outcomes. As a result, the test's credibility grows.

Furthermore, each laboratory should ensure that the standards are strictly followed, calibrations are undertaken, and any problems identified and corrected. To ensure consistency, laboratories should receive more detailed instructions on how to configure and measure tests. Despite not providing a quantitative treatment of uncertainty, it illustrates the repeatability and reproducibility of a measurement.

## 5.7 Conclusion

This chapter provided the evaluation of fire tests on materials. The general setups and results from the data provided by fire tests were discussed. This information is crucial for appreciating the inner workings of the tests and the fire parameters they assess, such that a comparative analysis of the tests can be carried out in Chapter 6.

The most widely used standards such as the ASTM International, European Standards, British Standards and the South African National Standards 10177 suite of tests addressing fire testing methods and apparatuses used for testing building or construction products were examined in this chapter.

The primary focus was placed on (a) reaction-to-fire tests and (b) fire resistance tests, describing the development of the tests, how the tests are carried out and what results can be obtained. The fire parameters in terms of heat release rate, combustion reaction, flame spread, time to ignition, heat flux, smoke production, and toxicity related to the overall fire development were summarised. This summary introduces the following comparative analysis, illustrating that multiple tests can measure the same fire parameter. The question that has to be asked is, can a different suite of tests be formulated for assessing the relevant fire parameters since there are as shown alternative test methods?

Lastly, this chapter provided remarks on fire testing regarding aspects that have not been considered, such as toxicity and the uncertainty and variability in fire testing. These statements highlighted essential aspects that should be introduced into the development of fire tests standards going forward.

# 6 Comparative Analysis of Fire Test Standards

## 6.1 Introduction

This chapter brings together the discussions from the previous chapters and syntheses findings such that recommendations for taking fire testing forward in South Africa, and the developing world, can be made.

Ultimately, the author's opinion is that adopting the Eurocode classification and associated test standards would be most beneficial and pragmatic based on the analysis conducted below. However, from a scientific and engineering perspective, there are still shortcomings in the Eurocode guidelines, which are discussed, and recommendations for addressing these are provided. It is shown that the South African suite of standards should be thoroughly revised, and there are severe limitations to the current suite of codes.

In the discussions in Chapter 5 that have preceded this, various international standards have been presented. However, the European suite of tests inherently accounts for the test methodologies which they all utilize. ASTM, NFPA and UL provide similar results and could be used in South Africa. In general, the procedures are almost identical, and in some, there may be variations in how it is approached. However, it is highly beneficial having a single suite of tests that are harmonised. Hence in the discussions below, primarily the European suite of standards will be referred to as it is the suite of standards most likely to be adopted by South Africa. However, this inherently accounts for the other international tests and does not mean the other standards cannot be used.

This chapter is presented in five sections. Section 6.2 presents a summary of the fire tests discussed in Chapter 5. Not all the tests and standards are discussed throughout this work and addressed in detail below. Based on the results and findings of previous sections, only those test apparatuses and standards most relevant to developing fire safety in South Africa are addressed.

In Sections 6.4 and 6.5, the primary focus will be placed on (a) reaction-to-fire tests and (b) fire resistance tests, describing the approaches of the South African standards in contrast to the European suite of standards for each category of tests. Limits and recommendations will be discussed to help the drive to advance fire testing and fire-safe buildings in South Africa. Lastly, some remarks of fire testing regarding aspects that have not been considered, such as toxicity and the uncertainty of measurements in fire testing, are discussed in Section 5.6. Hopefully, these statements should bring to light some of the factors considered while conducting fire tests and formulating the relevant fire test standards.

Figure 6-1 illustrates the relevant topics that will be discussed in this chapter. As shown, emphasis will be placed on the testing methods, and the results they provide will be compared.

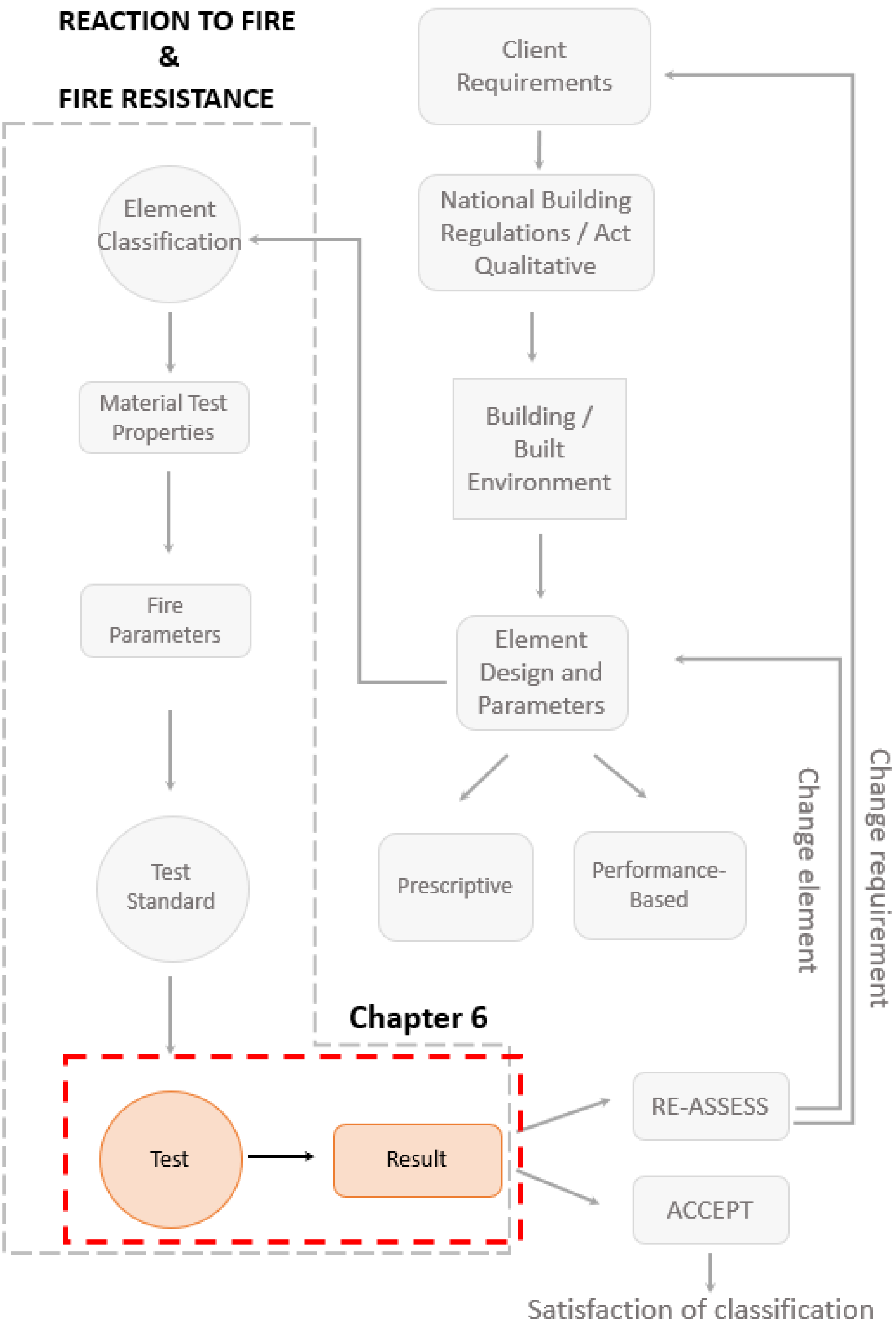



*Figure 6-1: Focus of Chapter 6*

## 6.2 Comparative Analysis Summary of Fire Tests Previously Discussed

A summary of all the fire tests discussed in Chapter 5 will be compared and contrasted in Table 6-1. As shown in the table, the fire tests discussed are, with regards to most aspects, not relatable, especially regarding the testing essentials and the heat sources employed by the tests. The only aspect that the tests might relate to is the properties and parameters quantified from these tests. Based on the size of samples, fire exposure, orientation of samples and ignition, very different results will be obtained for each test. The reader should consider the significant variation in detail between tests which the table helps emphasise the difficulty in directly relating results from one test to another.

A comparative analysis example will be discussed in the following subsection. Since not all the tests will be compared, Table 6-2 below provides a helpful indication of the differences between these fire tests and the relevant properties they measure. The items highlighted in red are indicative of the EN suite of standards. As shown in the table, these EN test standards complement one another. The one lacks in testing for a specific property, the other fire test standards measure that individual property. These material properties are equivalent to those discussed in Section 3.3.

The SANS tests highlighted in purple are shown to measure some of the material properties but does not consider the vital measurement of the heat release rate. Babrauskas and Peacock (1992) stated that the heat release rate measurements are fundamental and an essential variable in characterising the flammability of construction products, as discussed in Chapter 2. It should be noted that SANS also refers to a non-combustibility and fire resistance test; therefore, these have not been mentioned in the table to avoid repetition. However, the test standards measure the same properties and are indicated by these two tests' respective EN test standards.

*Table 6-1: Fire tests summary*

| Test no | Apparatus name | Reaction-to-fire | Fire resistance | Scale of test | Specimen size | Specimen orientation | Thermal exposure | Ignition mechanism |
|---|---|---|---|---|---|---|---|---|
| ISO 5660-1 | Cone calorimeter | ✓ | X | Bench | 0.01 $m^2$ | Horizontal | Radiant truncated conical heater | Spark |
| EN ISO 1716 | Bomb calorimeter | ✓ | X | Bench | ≤ 50 g | Vertical | Pressurised oxygen | A 10 cm fuse wire |
| ISO 9705 | Room corner test | ✓ | X | Large | 8.64 $m^2$ | three walls and ceiling | Propane fuel burner | Burner |
| ISO 5658-2 | LIFT test | ✓ | X | Large | 0.124 $m^2$ | Vertical | Propane fuel radiant panel | Pilot |
| BS EN 13823 | SBI test | ✓ | X | Large | 1.5 $m^2$ and 0.75 $m^2$ | Corner configuration | Triangular shaped propane diffusion | Burner |
| ISO 11925-2 | Ignitability test | ✓ | X | Intermediate | 0.0225 $m^2$ | Vertical | Propane fuel | Burner |
| ISO 12136 | Flame propagation apparatus | ✓ | X | Intermediate | Ø100 mm | Horizontal | Ethylene-air | Pilot |
| EN ISO 1182 | Non-combustibility test | ✓ | X | Bench | Ø45 mm, 76 $cm^3$, 50mm height | Vertical | Cylindrical radiant heat | Electrical furnace |
| SANS 10177-5 (adopted from EN) | Non-combustibility test | ✓ | X | Bench | Ø45 mm, 80 $cm^3$, 50mm height | Vertical | Cylindrical radiant heat | Electrical furnace |
| EN ISO 9239-1 | Floor radiant panel test | ✓ | X | Large | 0.2415 $m^2$ | Horizontal | Line propane gas | Pilot |
| SANS 10177-10 | Inverted channel tunnel test | ✓ | X | Large | 7.4 m | Horizontal | Hexane pan | Pilot |
| SANS 10177-9 | Small scale burning test | ✓ | X | Bench | 0.18 $m^2$ | Vertical | Propane fuel | Bunsen burner |
| BS 476 (20-23) | Full-scale furnace test | X | ✓ | Large | 6 $m^2$ | Horizontal/ Vertical | Natural gas or liquid fuel | Burner |
| SANS 10177-2 | Full-scale furnace test | X | ✓ | Large | Element dependable | Horizontal | Natural gas or liquid fuel | Burner |

*Table 6-2: Fire tests per material test property classification summary. EN classification tests are shown in red, with SANS tests shown in purple.*

| Fire Parameter | Apparatus name | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cone calorimeter | Bomb calorimeter | Room corner test | LIFT test | SBI test | Ignitability test | Flame propagation apparatus | Non-combustibility test | Floor radiant panel test | Inverted channel tunnel test | Small scale burning test | Full-scale furnace test |
| **CHF** | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | | ✓ | |
| **FlameSR** | | | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | |
| **IgTemp** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | |
| **Cal value** | ✓ | ✓ | ✓ | | ✓ | | ✓ | | | | ✓ | |
| **HRR** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | | | |
| **Smoke & Toxicity** | ✓ | | ✓ | | ✓ | | ✓ | | ✓ | | | |
| **Fire resistance** | | | | | | | | | | | | ✓ |

*CHF – Critical heat flux; IgTemp – Ignition temperature (spontaneous or piloted); Cal – Calorific value; HRR- Heat release rate; FlameSR – Flame spread rate; R – Structural resistance; E – Integrity resistance of systems; I – Insulation; Smoke – Smoke production rate; Toxicity – Toxicity of smoke*

## 6.3 Identification of a Suite of Standards for Fire Testing

As discussed in Section 3.3, various material properties are measured, and multiple properties can quantify a fire parameter which in turn satisfies the requirements stated by the NBR for a safe building. Thus, in Table 6-2, it is shown that the Room corner and SBI test are the only two test methods that quantify all of the required fire parameters. As discussed in Chapter 5, the other fire tests only quantify specific fire parameters as their operation and setup cannot measure all of the required material properties. The flame spread parameter seems the least likely to be measured by most apparatuses due to the difficulty of measuring flame spread using a bench-scale apparatus, as discussed in Section 6.4.2.

Provided the information in Table 6-2, one might wonder why it is not proposed that the FPA test be adopted, seeing as it measures all of the necessary material properties of a reaction-to-fire test as illustrated. As mentioned in Section 5.3.8, the FPA test is present in the BS 476 suite of tests. The suite consists of eight National and European reaction-to-fire tests as described in Table 6-3.

*Table 6-3: BS 476 suite of reaction-to-fire tests*

| Test Standard | Description | Test Apparatus |
|---|---|---|
| BS 476-4 | Non-combustibility test for materials | Non-combustibility apparatus with square |
| BS 476-6 | Method of test for fire propagation for products | FPA apparatus |
| BS 476-7 | Method of test to determine the classification of the surface spread of flame of products | Radiant panel |
| BS 476-11 | Method for assessing the heat emission from building material | Non-combustibility apparatus with cylindrical |
| BS EN 13823 | Building products excluding floorings exposed to the thermal attack by a single burning item | SBI test |
| BS EN ISO 1716 | Determination of the gross heat of combustion | Bomb Calorimeter |
| BS EN ISO 11925 | Single flame source | Ignitability test |
| BS EN ISO 1182 | Non-combustibility | Non-combustibility |

The table shows that most of these tests are adopted from the EN suite of harmonised tests apart from the Flooring Radiant Panel (EN 9239). Although some use the same apparatus, the other four national tests have different classification systems referred to in the specific test standards. Thus, there is no correlation between the test standards, which is problematic, as discussed in Section 3.4. The FPI classification system, as discussed in Section 3.4.4, identifies a specific index. The highest performance ranking is a Class 0, although this class is not a classification identified in any British Standard test. Regarding the fire resistance tests, performance in terms of the fire resistance achieved by structure elements is classified per BS EN 13501. This standard is an adoption of the EN 13501 classification system as discussed in Section 3.4.2.

Thus, although adopting the BS suite might be an enhancement from the SANS 10177 set of standards, the BS suite shares similar limitations to the SANS and has, as shown already, adopted the EN suite of standards. Additionally, some individuals might propose the ASTM International Standards. The ASTM provides several fire test standards, although it must be said that these tests do not form a single suite which is problematic and might not be viable for a country such as South Africa.

In the SABS systems, standards-based on British and Deutsche Industry standards are preferred for historical and technical reasons. Products sourced from these countries are mostly automatically accredited. The system does not automatically recognize the standards of the United States but follows those of the ISO and the European Committee for Standardization (CEN). Utilising a single set of standards will make comparisons and cross-referencing of fire tests simpler. For a developing country, it is vital to trade with European countries. If no trade barriers exist, fire test reports or certifications of imported materials can be directly accepted by the country that uses the same fire tests and classification system. Thus, as stated, it is proposed that the EN 13501 suite of standards be adopted. The limitations of this suite will be discussed in Section 6.4.2.

However, as discussed in the preceding chapters, the main objective of this work is to provide a fire-safe building or structure along with providing a detailed comparison of fire testing standards to provide a safe testing environment for South Africa. In order to reach these objectives, Table 6-4 was formulated based on the multitude of fire tests that have been provided in Chapter 5. The table reiterates the relationship established by Table 3-1 with the addition of listing which EN test measures which respective parameter. Also discussed is the proposed set of tests inclusive of the Cone Calorimeter and show the respective parameter that these tests measure. This table aims to provide motivation and proof for the proposed statement made by the author that the EN suite of harmonised fire testing standards could be adopted and replace the SANS 10177 suite of fire tests together with the proposal of the Cone Calorimeter test as seen in the table. The table and its contents will essentially provide a reason for the recommendations stated in the subsections to follow.

Ultimately, to highlight the logic of the table – the fire parameters listed on the left are measured through the material properties listed (e.g., critical heat flux). These are limited to within a specific value to satisfy the NBR requirements of each column. On the right-hand side, it shows the current EN suite of tests that test for each parameter. The final column shows the modified EN suite of tests proposed in this work that could be considered for South Africa.

*Table 6-4: Evidence of EN suite satisfying building regulations*

| | NBR Requirements | | | | | Test Standards | |
|---|---|---|---|---|---|---|---|
| **Fire Parameter** | **1. Safe evacuation** | **2. Spread of fire** | **3. Intensity of fire** | **4. Sufficient stability** | **5. Smoke spread** | **Current EN Suite (EN 13501)** | **Modified EN suite proposed in this work** |
| **a. Material ignitability** | | CHF, IgTemp | CHF, IgTemp, Cal, FlameSR | | | Bomb calorimeter, SBI, Ignitability, Floor radiant panel test | SBI, Floor radiant panel test, Cone calorimeter |
| **b. Surface flame spread** | | CHF, IgTemp, FlameSR | FlameSR | | | SBI, Ignitability, Floor radiant panel test | SBI, Floor radiant panel test, Cone calorimeter |
| **c. Fire intensity** | | HRR, Cal, FlameSR | HRR, Cal, FlameSR | | | Non-combustibility test | Cone calorimeter |
| **d. Smoke production** | Smoke, Toxicity | Smoke | | | Smoke, Toxicity | SBI test, Floor radiant panel test | SBI test, Floor radiant panel test, Cone calorimeter |
| **e. Structural stability** | R | | | R | | | |
| **f. Integrity** | E | E | E | | E | Full-scale furnace test | Full-scale furnace test |
| **g. Insulation** | I | I | I | | | | |

*CHF – Critical heat flux; IgTemp – Ignition temperature (spontaneous or piloted); Cal – Calorific value; HRR- Heat release rate; FlameSR – Flame spread rate; R – Structural resistance; E – Integrity resistance of systems; I – Insulation; Smoke – Smoke production rate; Toxicity – Toxicity of smoke*

Additionally, this replacement or proposed test mentioned above is illustrated in Table 6-5. In the table, the fire tests highlighted in blue denotes items that are part of the Eurocode suite of tests, but it is suggested that they be replaced with the Cone Calorimeter.

*Table 6-5: Fire tests per material test property, also highlighting the proposed tests (*) that could be replaced by the Cone Calorimeter (**)*

| **Fire Parameter** | **Apparatus name** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **SBI test** | **Floor radiant panel test** | **Fire resistance test** | ***Bomb calorimeter** | ***Ignitability test** | ***Non-combustibility test** | **** Cone calorimeter** |
| **CHF** | ✓ | ✓ | | | ✓ | | ✓ |
| **FlameSR** | ✓ | ✓ | | | ✓ | | |
| **IgTemp** | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ |
| **Cal value** | ✓ | ✓ | | ✓ | | | ✓ |
| **HRR** | ✓ | ✓ | | ✓ | ✓ | | ✓ |
| **Smoke & Toxicity** | ✓ | ✓ | | | | | ✓ |
| **Fire resistance** | | | ✓ | | | | |

## 6.4 Comparison of Reaction-to-Fire Tests

Following the proposal of a suite of tests for South Africa above, it is necessary to contrast how existing SANS tests contrast with current EN tests, which serves as the basis for the proposals above. Firstly, a high-level comparative analysis summary of the fire tests was provided in Section 6.2. As a specific example, the Non-combustibility apparatus of the European standard (ISO 1182, 2010), as discussed in Section 5.3.9, will be compared to the South African standard (SANS, 2005d), as discussed in Section 5.3.10. The aim is to show the significant differences and provide a discussion regarding these aspects. The methodology in Chapter 4 was observed, and both standards were thoroughly read and examined. Table 6-6 indicates the contrasting aspects between the two tests. The limitations and shortfalls of both standards are discussed. Relevant recommendations or substitute fire tests are considered in the subsections that follow.

### 6.4.1 SANS vs International Testing

*Table 6-6: Comparison between Non-combustibility apparatus standards*

<table>
<tr><th>Component</th><th colspan="4">EN ISO 1182</th><th>SANS 10177-5</th></tr>
<tr><td>Furnace tube density</td><td colspan="4">$2800 \pm 300$ kg/m$^3$</td><td>$3000 \pm 300$ kg/m$^3$</td></tr>
<tr><td>Volume of specimen</td><td colspan="4">$76 \pm 8$ cm$^3$</td><td>$80 \pm 5$ cm$^3$</td></tr>
<tr><td rowspan="5">Thermocouple placement in furnace wall calibration</td><td rowspan="2">Vertical axis</td><td colspan="3">Level</td><td rowspan="5">Mid-height of the furnace and 10 mm from the wall of the furnace</td></tr>
<tr><td>a at 30 mm</td><td>b at 0 mm</td><td>c at −30 mm</td></tr>
<tr><td>1 (at 0°)</td><td>$T_{1,a}$</td><td>$T_{1,b}$</td><td>$T_{1,c}$</td></tr>
<tr><td>2 (at 120°)</td><td>$T_{2,a}$</td><td>$T_{2,b}$</td><td>$T_{2,c}$</td></tr>
<tr><td>3 (at 240°)</td><td>$T_{3,a}$</td><td>$T_{3,b}$</td><td>$T_{3,c}$</td></tr>
<tr><td>Number of thermocouples in calibration</td><td colspan="4">Nine on the furnace wall, with positions as above</td><td>One on the furnace wall</td></tr>
<tr><td>Calibration process described</td><td colspan="4">✓</td><td>X</td></tr>
<tr><td>Viewing sample inside</td><td colspan="4">Mirror used</td><td>None</td></tr>
<tr><td>Results</td><td colspan="4">Mass loss recorded</td><td>No mass loss recorded</td></tr>
<tr><td>Sustained flaming</td><td colspan="4">5 seconds</td><td>10 seconds</td></tr>
<tr><td>Number of specimens</td><td colspan="4">Five</td><td>Three</td></tr>
<tr><td>Temperature rise</td><td colspan="4">30°C calculated as<br>$\Delta T = T_{max} - T_f$</td><td>50°C above the initial furnace</td></tr>
</table>

Four non-combustibility requirements exist for building fire safety, namely: (1) fire spread prevention in vacant spaces; (2) avoidance of high fuel load; (3) avoidance of flame spread hazard on surfaces within the inhabited space; and (4) avoidance of igniting of materials near to heat sources. Tests should provide sufficient data to ascertain whether these can be achieved.

From the information presented in the table above, the following observations between the SANS and EN tests can be made:

- There are differences in the apparatus and the specimen size.
- EN standards place greater emphasis on the calibration of temperature measurements, ensuring better accuracy.
- The SANS test does not describe a calibration process which creates uncertainty of the measurements and whether the results can be trusted.
- The result is only a binary pass/fail result.
- SANS tests fewer samples than the EN standard.
- Inconsistencies in the fire tests methodologies and execution are more significant in the SANS standards.

The results from the EN standard are mass loss, flaming observations and temperature rise. In contrast, the SANS standard tests only for temperature rise and flaming. Suppose the SANS calibration process is lacking, and the result is dependent on the temperature. In that case, the outcome cannot necessarily be trusted or meaningful in classifying a product, and there are likely to be distinct differences in results between test labs. Thus, in terms of implementing these standards to satisfy any building regulations as required, the outcomes would not be favourable. As shown in Table 6-4, the Non-combustibility test only satisfies one fire parameter. Table 6-5 indicates that the Cone Calorimeter can substitute the Non-combustibility test since it measures more material properties and complies with more requirements. Further remarks are discussed in the subsections that follow.

### 6.4.2 European Suite Remarks and Limitations

**Non-combustibility**

Each of the four reaction-to-fire test standards that form part of the European harmonised set of standards will be discussed regarding their shortfalls and limitations. Based on this assessment, it can be observed that the cone calorimeter addresses many of the shortcomings listed.

According to a study by Carpenter and Janssens (2005) in which they assessed the combustibility of materials based on HRR measurements, the limitations regarding the EN non-combustibility apparatus was concluded to be:

- It is not possible to evaluate laminated and coated materials due to their limited scope.
- Material properties are not necessarily tested in the manner used in most building applications.
- The procedure does not assess an inherent property, and the test results are limited to the test apparatus and conditions used.
- It is impossible to test materials that soften, melt, or otherwise detach from the measuring thermocouples.
- The possibility of self-heating is not considered.
- The test technique only provides a binary pass/fail result, not a quantitative heat generation or combustibility evaluation.

The practical and fundamental limitations indicate that the four apparatuses are not suitable for determining whether a material is combustible since combustion relies on the amount of heat released.

The Euroclass classification for reaction-to-fire performance has attempted to circumvent the limitations. The requirements for the classification classes are dependable on the calorific potential of the product.

Ahonen *et al.* (1985) assessed the combustibility of construction products based on the HRR measurements. It was concluded that the combustibility is more realistic based upon the HRR than on the performance of the products in a furnace or bomb type non-combustibility tests. No consistency between the temperature rises in the Non-combustibility furnace (ISO 1182) and HRR measured based on the oxygen consumption was shown in the study.

**Bomb Calorimeter**

With regards to the oxygen calorimetry-based test apparatus of the Euroclass standards, the oxygen bomb calorimeter has a significant number of limitations, such as:

- Fire conditions are not considered when evaluating materials and products.
- The HRR as a function of time is not measured; the total heat released is rather measured.
- The material's dynamic behaviour is not determined.

**Room corner test**

The room corner test has extensively been discussed in Section 4.2. Although it is one of the leading large-scale fire testing apparatuses, it does present a few limitations:

- The test method requires 30 $m^2$ of material to be evaluated.
- The time-consuming process of mounting the product in the test room before commencement and dismounting the test after termination.
- A test in the room corner apparatus is expensive to perform.
- Inconvenient for product development and control.

**SBI test**

Being the last Euroclass test to be standardised, a significant amount of research has been formulated around the SBI test. This research, unfortunately, still led to comments and remarks regarding the test apparatus and standard:

- Because the apparatus bears no resemblance to a standard room, the data cannot be utilized as a reference scenario for an actual room fire.
- It is challenging to consider the results for performance-based design. Variables such as time to ignition, flame spread, and heat release rate cannot be measured meaningfully using this method.
- Observing the ignition of a massive gas burner flame or the position of a flame front behind it is not optimal.
- If the HRR of a material is to be used in an engineering context, it must be measured per unit area.
- Because the heat release rate is monitored as the pyrolyzing area grows, the data is limited to the SBI scenario and cannot be used in engineering design (Horrocks, A.R.; Price, 2001).

The SBI test data has been noted to have an unsatisfactory level of reproducibility and hence cannot be utilized as a reference scenario for a real-life room fire (Horrocks and Price, 2001).

**Overview**

The Euroclasses classification system can be regarded as comprehensive and immediately applicable to all building items. The only exception to this rule is when small-scale experiments are not appropriate for categorization. As previously stated, it may be necessary to develop the Euroclass system further to accommodate intended uses that present hazards that are not adequately addressed by the current system (for example, the current reference scenario/test, and thus the classification system, is not appropriate to the fire hazard). Furthermore, dealing with items whose test behaviour poses unique challenges (i.e., where the classification based on the small-scale tests is not appropriate).

### 6.4.3 Limitations of South African Standards

As mentioned in Section 3.4.3, South Africa has no harmonized set of testing standards. None of the current SANS 10177 suite standards makes a normative reference to the same classification process. The vast number of limitations described in Table 6-6 indicates the SANS 10177-5 standard limitations. The standard inherently possesses the same shortcomings as described for the European Non-combustibility test. The classification system is the most significant drawback of the SANS 10177-9 test described in Section 3.4.3. The indices measured are not comparable to that of the European tests, and it cannot accommodate a material test that does not fall into any of those categories. There is no clear distinction between combustible and non-combustible materials; thus, the test method is used in conjunction with the Non-combustibility test.

Lastly, the SANS 10177-10 test is only utilized for flame spread measurement, and the test has no resemblance to a large-scale fire test. The only international test that might be perceived to have some comparability is the Steiner tunnel ASTM E84 (ASTM, 2014). A flame spread test, the E84, is not regarded as an engineering test, and its results do not reflect the hazards associated with fire spread in actual buildings (Babrauskas *et al.*, 1997, 2012).

Suppose a product has been tested in Europe according to whichever standard is required. In that case, the same product cannot be sold in the South African market before being re-tested according to South African standards. The number of limitations that arises from this requirement are:

- South Africa does not distinguish between reaction-to-fire and fire resistance tests.
- Research on reaction-to-fire tests has not been conducted in South Africa.
- An international client must fund the testing twice to have an identical product tested in South Africa.
- No equivalent tests exist in South Africa, as described by the comparative analysis example.
- Results of fire tests can often not be compared.
- No coherent classification system or index criteria for reaction-to-fire tests exist.
- South African tests methods are time-consuming, expensive and not small-scale.
- Loss in the market due to products not being allowed to be sold in South Africa and difficulty exporting items to Europe.

The SANS 10400-T committee is considering adopting the European standards for reaction-to-fire tests to combat these limitations and develop a sounder relationship with the European market.

Specific standards were recently adopted in South Africa from the European suite of harmonised tests to reduce the uncertainties and difficulties experienced by testing laboratories in SA. The descriptions of the standards are provided in Table 6-7. All five reaction-to-fire tests are now SANS standards, but they are not suitably referenced from codes.

The building regulations have not been updated to accommodate these tests, resulting in barriers between the South African and European testing community. Specific tests in the SANS 10177 suite have not been withdrawn, such as the SANS 10177-5, non-combustibility test, which leads to confusion as to which non-combustibility test to implement, as five are present, but only one is typically referenced. It was demonstrated that the tests presented in Table 6-6 differ vastly. Hopefully, this thesis can assist in emphasizing the importance of a harmonised set of fire testing standards. As well as assist in reducing the plethora of tests to a core of more manageable standards.

*Table 6-7: Description of current SANS approach to reaction-to-fire test standards*

| EN Standard | South African Standard | Test Description |
|---|---|---|
| EN 13823 | SANS 53823 | SBI test |
| EN 13501-1 | SANS 53501-1 | Fire classification |
| EN 1182 | SANS 11820 | Non-combustibility test |
| EN 1716 | SANS 1743 | Determination of calorific value |
| EN 11925-2 | SANS 11925-2 | Ignitability test |

### 6.4.4 Recommendations

Based upon the limitations mentioned in Section 6.4.2, a recommendation is made to address these shortcomings. Since the HRR is the most vital measurement (Babrauskas and Peacock, 1992), suggestions in this work are to replace the Non-combustibility test along with the Bomb calorimeter. The large-scale routine-based test would be too onerous to perform, and thus researchers have considered that bench-scale HRR tests can be used to demonstrate non-combustibility.

The Cone Calorimeter is proposed to be the primary replacement apparatus since it measures the HRR of a material being tested. The Japanese and New Zealand (Hakkarainen and Hayashi, 2001) regulators have suggested alternate criteria based upon combustibility HRR tests and utilised the Cone Calorimeter for such assessments in their revised Building Standards Law.

As discussed in Section 6.2, the categorical pass-fail criteria are not helpful for performance-based designs. As a result, flame spread control should take the place of the previous requirement of non-combustibility as a performance-based goal.

Although large-scale HRR testing are required, Cleary and Quintiere (1991)proposed a parameter 'b' for relating large-scale flame spread and HRR results to bench-scale test results. The findings of genuine large-scale room fire tests were shown to be highly predictable. It was suggested that this method be implemented into building codes and utilized to replace the current non-combustibility rules.

However, the theory of the parameter is still based upon test results from the Cone Calorimeter. The following advantages can be said of the Cone Calorimeter:

- Lower external heat fluxes (less than 20 $kW/m^2$) target ignition and flammability, whereas higher external heat fluxes (more than 50 $kW/m^2$) target flame spread and combustion characteristics. Hence a range of fire response scenarios can be simulated.
- The relevant and active mechanisms are subject to significant modification. The external heat flux influences the results of cone calorimeter experiments.
- The influence of the heat source is decreased by employing a separate exhaust system for the heater.
- Its regulatory strengths are well-defined circumstances, repeatability, and extensive data evaluation of one or two distinctive values. Developing pyrolysis and burning models can benefit from the use of defined, and in some ways ideal, burning behaviour.
- It is possible to obtain reasonable input values for fire simulations.
- The more significant hazard, wind-aided flame propagation, must be addressed immediately. It is not essential to perform a flame spread test to define flame spread behaviour because data from the Cone Calorimeter test can be used to compute flame spread behaviour.

### 6.4.5 Limitations to the Modified EN Suite of Tests with Reference to the Cone Calorimeter

As discussed in Section 5.3.2, the Cone Calorimeter was initially developed to determine the HRR and adequate heat of combustion of building materials. The heat released is quantified by oxygen calorimetry. Although there are many positive aspects of the Cone Calorimeter, this section will discuss some shortcomings to understand its incomparability to some other tests. Some of the inadequacies are listed below. However, many of these items also apply to other test setups. The limitations are:

- Because the heat release rate cannot be measured directly, it must be derived from other measures, resulting in some mistakes and assumptions. Hence, the calibration and accuracy of the test system are essential.
- The heat of combustion value can be off by up to 5% (Huggett, 1980).
- The retainer frame (i.e., 100 × 100 mm box housing samples) is steel and functions as a heat sink, lowering the amount of energy delivered to the specimen. According to a study conducted at NIST, the retainer frame's heat sink function reduces heat release rate values by roughly 8% (Babrauskas, Twilley and Parker, 1993).
- The heat flux to be employed is not specified in cone calorimeter specifications.
- Tests can be performed horizontally, vertically, with or without the retainer frame and with or without the spark igniter.
- Some data from cone calorimeters represents material qualities, whereas others are very reliant on the arrangement.
- The peak heat release rate is a well-known cone calorimeter test metric, but it has a complex and robust setup reliance.
- The measurement uncertainty of the calculations for the cone calorimeter is very strongly coupled with the oxygen analyzer accuracy (Schartel and Hull, 2007).
- Ignition qualities are not intrinsic features of materials because their values can vary greatly depending on how the cone calorimeter is set up, for utilizing a pilot flame instead of a spark igniter or adjusting the distance between the cone heater and the sample surface.
- A paramagnetic analyser and non-dispersive infrared CO and $CO_2$ analysers are used to analyze an effluent sample after being cooled to remove water. However, setting up the data analysis software could be inaccurate when dealing with huge CO yields (Hurley, 1995).

- In the presence of water-soluble gases like HCl or HBr, the heat released will be minimal because these will be removed from the effluent stream by the cooler along with the water.
- Overestimation and underestimations may occur depending on the composition of the material containing fire retardants.
- The testing configuration has a considerable impact on the mixed results of cone calorimeter experiments.
- As a fire scenario, it is not typical of most real fires because minor fires do not use the heat source, testing setting, or sample dripping that the cone calorimeter provides.
- In the flammability test, the specimen holder configuration can have a significant impact on the results.
- The irradiance is affected by the vertical and horizontal distances between the sample surface and the cone heater.

## 6.5 Comparison of Fire Resistance Tests

Since fire resistance is primarily required in static structures like buildings, which are governed by local governments and, in many cases, local building standards, there are various test specifications and little worldwide consensus. Mass transportation is another primary necessity for fire resistance, and each business has its own set of standards.

The example used to perform the comparative analysis pertains to a fire resistance test of a non-loadbearing wall sandwich panel element. The EN and SANS tests are utilized to identify the difference in their methodologies and classification systems for an identical product, as shown in Table 6-8.

*Table 6-8: Comparative analysis of fire resistance tests*

| Component | EN 1363-1 | SANS 10177-1 |
|---|---|---|
| **Standard tested against** | EN 1364-1 | SANS 10177-2 |
| **Heating curve used** | Standard time-temperature for "internal" walls and external fire | Standard time-temperature |
| **Standard description** | Fire resistance test for non-loadbearing elements | Fire resistance test for building elements |
| **Standard testing for** | Walls | All building elements |
| **Requirement** | Client brief | Client brief |
| **Classification Standard** | EN 13501-2 | SANS 10400-T |
| **Criteria** | Integrity, insulation and radiation | Stability, insulation and integrity |
| **Rating index** | E, EI, EW | Time |

### 6.5.1 Limitations Resulting from the Comparison

The following section will discuss the limitations of comparing furnace testing for South Africa and the European standards. The following points are a summary of the shortfalls:

- The main difference between the two standards implemented for testing is the heating curve used. The EN 1364-1 (BS EN, 2015) has two references. The standard time-temperature curve is utilised for internal walls, and the external fire development for external walls is tested according to EN 1363-2 (BS EN. The SANS 10177-2 only makes use of the standard time-temperature curve. As illustrated in Figure 2-1, the external heating curve reaches a peak value of 660 ℃, which is much lower than the rising temperatures of the standard ISO 834 curve.
- Therefore, the results of these tests cannot be compared to one another, and it is suggested that the tests be performed using the same heating curve.
- The classification system in SANS 10400-T is based upon the occupancy of a building and not necessarily focused on the element itself.
- The criteria requirement in SANS 10177-2 is only a time-based index and not a specific criterion for fire resistance as in the EN.
- The SANS test standard is inherently not used for walling systems and panel testing. As a result, it is a standard used in an application for which it was not designed.
- As stated in Section 5.4.2, the SANS test still utilizes asbestos pads.
- The SANS 10177-2 stipulates no pressure measurements within the furnace. According to Steel (1981), the pressure in a furnace is a significant parameter in obtaining the fire endurance rating for construction products.

If the client requires this walling system to carry a load, which is often the case if the panel is used as a partitioning wall in a building structure, the following limitations of the SANS test standards exist:

- The SANS test does not provide guidelines for a loadbearing test.
- A partitioning wall is only said to contribute fire load $\leq 5$ kg/m$^2$ to the system, no indication is provided of the application of the load force (SANS, 2020).

The number of shortfalls in the SANS 10400-T and the SANS 10177-2 highlights that these two standards have been written incoherently and do not cater to all modes of construction product applications.

The most significant drawback of the SANS 10177-2 is not measuring the pressure throughout the furnace. The static furnace pressure must be measured and controlled according to ISO 834 (1999) standard, which discusses fire resistance tests for building elements to maintain a positive pressure over the upper two-thirds of the door. According to this statement, the pressure measurements are essential to test according to the standard time-temperature curve that the SANS 10177-2 test utilises.

The disregard of this procedure and the fact that no regulation occurs is a concerning matter for the fire testing industry. Anecdotal concerns have developed in the South African industry regarding the products that have been tested and installed in buildings and homes.

## 6.6 Conclusion

This chapter compared and contrasted the fire tests that were mentioned in Chapter 5. An overall summary was provided illustrating the multitude of differences amongst the tests. It can also be seen that some of the fire test standards can replace other tests that are deemed to be inadequate. The consensus is that most of the fire tests cannot be compared to one another.

Not all the tests and standards were discussed throughout this work and addressed in detail. Based on the results and findings of previous sections, only those test apparatuses and standards most relevant to developing fire safety in South Africa were addressed. Reaction-to-fire tests and fire resistance tests, describing the approaches of the South African standards in contrast to the European suite of standards for each category of tests, were discussed. The European harmonised set of standards posed inadequacies amongst the fire tests.

As discussed, it was shown that the Cone Calorimeter has several shortfalls, although considered by many as a replacement fire test standard for the Non-combustibility test and the Single Flame Source (ignitability) test (Ahonen *et al.*, 1985; Babrauskas, 2017). Carrying out the same analysis, the South African fire resistance standards provided several limitations and highlighted questions about adequacy for testing non-loadbearing or loadbearing partitioning walls. The standards nondescription of pressure measurements is also of concern.

Ultimately, the author's opinion is that adopting the Eurocode classification and associated test standards would be most beneficial and pragmatic. As shown in Table 6-2, the Cone Calorimeter presents a more important measurement of fire parameters than the Non-combustibility and the Ignitability tests. Thus, future developments should include the adoption of the Cone Calorimeter tests standard.

However, the European classification system, including its harmonised fire test standards, is more viable in South Africa. Other international standards could also be adopted and enhance current SA tests. It is beneficial to have a single set of referenced standards.

# 7 Conclusions and Recommendations

## 7.1 General Overview

The main objective of this thesis was to provide a detailed comparison of fire testing standards to provide a safe testing environment for South Africa. The objectives of this thesis, as discussed in Chapter 1, have been addressed as discussed below.

An extensive literature study was performed in Chapter 2 to gain a thorough understanding of heat transfer principles and assist in understanding the mechanisms by which heat is transferred through materials in testing. A background to fire behaviour phenomena, fire engineering standards and performance-based safety design was presented in the literature review. These concepts are fundamental for carrying out and evaluating fire testing standards on building and construction products.

Obtaining insight into the results of fire testing and how this relates to the importance of ensuring fire safety in buildings were discussed in Chapter 3. To achieve this objective, the South African National Building Regulations were presented and examined. Compliance with the national building regulations of South Africa led to the introduction of fire parameters that are quantified by material test properties. The European, South African and FPI classification processes were examined based on the established relationship between the parameters and the regulations.

Chapter 4 provided a framework and background for the comparative analysis by discussing an analysis procedure and the aspects required to be considered when comparing fire test standards. The plethora of available fire test standards was discussed in Chapter 5. Reaction-to-fire and fire resistance tests were the primary focus of the discussions. The development of the tests, how the tests are carried out and what results can be obtained were considered.

The fire testing standards were compared and contrasted in Chapter 6. Consideration of the various options available was provided, along with details on which fire test standards can and cannot be used where material safety in a building is of concern. Ultimately guidance on an idealised set of standards that can be used to comprehensively test products in SA were discussed. This guidance was supported by the identification of the limitations in existing South African fire test standards.

Results from the work highlight that there is an extensive number of standards available. Variations exist between reaction-to-fire and fire resistance tests, and there is no “perfect” test due to inherent limitations in all apparatuses and methodologies.

## 7.2 Project Findings

The results obtained in this thesis are summarised in this section. The results include the application of fire testing results highlighted in Chapter 3 and the results from the comparative analysis considered in Chapter 6. Only the most important findings are highlighted here, while the reader is encouraged to refer to the respective chapters for an in-depth discussion.

### 7.2.1 Fire Testing and Classification Processes

The history of fire test standards has evolved; however, the end has not been reached. To summarize, the primary reason for conducting fire tests is to ensure (a) compliance with fire safety laws, regulations, and specifications. (b) To assure product development research and quality assurance. (c) Gathering data for fire safety engineering design and analysis, and (d) improving production control support. A more excellent grasp of what is being measured, i.e., what should be measured to understand the global performance of the element of the structure being evaluated, is required to meet this need? A relationship was established between the material test properties, the fire parameters and the NBR requirements for a safe building. The relationship led to the introduction of classification systems to conclude how the fire parameters or material test properties are used after being evaluated.

The European and South African classification process were discussed. Comparing and contrasting these two processes leads to the following conclusions:

- The European approach provides seven classes for flammability of materials compared to SA's five classes.
- Harmonised European classification system as opposed to standalone tests.
- European system leads to a more significant number of tests (5) potentially required per product.
- SA only provides two tests that give comparable results to the European tests.
- Classifications are not relatable between the SA and European approaches.
- Fire resistance classifications are similar but with different annotations.

These conclusions forced us to understand the requirements and influences on testing methods that lead to classification methods. Fire tests also needed to be understood to establish the limitations and the reasons for the differences between these two classifications systems.

### 7.2.2 South Africa National Standards Results

It was established that South African has a suite of standards for fire testing of building materials, namely the SANS 10177 set of standards. However, this suite is not harmonised since most tests do not utilise the same classification process. The test methods used are deemed outdated and inadequate to measure the necessary material test properties required to quantify specific fire parameters to comply with the building regulations. Also, several limitations were presented.

The SANS 10177-5 standard inherently possesses several shortcomings where the most critical limitation is that the test can only satisfy one fire parameter. Thus, utilizing it as a fire test to satisfy NBR requirements is not advisable since the test method lacks depth and useability. The most considerable drawback of the SANS 10177-9 test described in Section 3.4.3 is its classification system. The indices measured are not comparable to that of the European tests, and it cannot accommodate a material test that does not fall into any of those categories. There is no clear distinction between combustible and non-combustible materials; thus, the test method is used in conjunction with the Non-combustibility test, which is not helpful.

Lastly, the SANS 10177-10 test is only utilized for flame spread measurement, and the test has no resemblance to a large-scale fire test. The SANS 10177 standards are currently limited by not providing a harmonised set of standards. The number of limitations that arises from South African standards are:

- South Africa does not distinguish between reaction-to-fire and fire resistance tests clearly.
- Research on reaction-to-fire tests has not been conducted in South Africa.
- An international client must fund the testing twice to have an identical product tested in South Africa.
- No equivalent tests exist in South Africa, as described by the comparative analysis example.
- Results of fire tests can often not be compared.
- No coherent classification system or index criteria for reaction-to-fire tests exist.
- South African tests methods are time-consuming, expensive and not small-scale.
- Loss in the market due to products not being allowed to be sold in South Africa, or opportunities for South African developers to sell products internationally.

### 7.2.3 European National Standards Results

Even though proposed as a suite to be adopted in South Africa, the Eurocode presents several limitations, as discussed in Section 6.4.2. It was shown in Table 6-2 that not all tests measure all fire properties; however, the suite of Eurocodes is complementary to each other.

The three most likely fire situations are taken into account by the European harmonized classification system. The system created test methods for describing each scenario and the contribution it makes to a classification.

The current Euroclass system has several limitations (for example, the current reference scenario is not appropriate in defining the fire hazard for some selected materials). Additionally, the system cannot deal with the classification based on small-scale tests products whose test presents particular difficulties. The system must therefore be developed further to accommodate more test applications. Several other countries adopted the Eurocodes, and it is proven to be a set of possible standards to test the reaction-to-fire and fire resistance of construction products.

## 7.3 Recommendations

Standards can be used as a competitive tool or as a tool for protectionism. There is, however, a global trend in standards toward harmonization - that is, to create one standard for products, processes, or materials that are recognized and accepted globally. The standards community struggles to meet harmonization challenges, which is an admirable goal but a challenging one.

At present, there are many fire safety engineering tests available, and it is urged that older provisions be replaced with more appropriate tests. Thus, a large number of fire test standards can be simplified. The simplification can be achieved by focusing on a fire test method that provides the most satisfactory measurements known worldwide as the Cone Calorimeter.

The following aspects are advantages of utilizing the Cone Calorimeter:

- The Cone Calorimeter generates quantitative data that may be used to classify materials and can be used in performance-based fire designs.
- Specimens are exposed to conditions that are similar to those encountered in natural fires.
- End-of-life testing is possible for layered and composite items.
- Helpful in measuring smoke and toxicity, the importance hereof is stated in Section 5.6.1.
- A more important measurement of fire parameters than the Non-combustibility and the ignitability tests is presented.
- The Cone Calorimeter is one of the more sophisticated systems and can measure several flammability characteristics simultaneously.

However, the Cone Calorimeter did present several limitations discussed in Section 6.4.5. Therefore, it still requires to be complemented by the Eurocodes harmonised set of standards.

A harmonised suite of tests is most beneficial since there has been enough research completed on it. Communication barriers will be minimized if a country such as South Africa trades with the European nations. Nonetheless, there is room for improvement within the harmonised set of standards. Thus, future developments should include the adoption of the Cone Calorimeter tests standard. Ultimately the European classification system EN13501-2, including its harmonised fire test standards EN 13501-1, is more viable in South Africa and could be adopted. This shift toward European standards will enhance the development of the fire testing industry in South Africa, and emphasis will be placed on fire safety in the country. Due to accurate fire testing and proven results, South African-based building materials will be deemed safe enough to provide a fire-safe building.

## 7.4 Future Research

In recent times there has been an emphasis on new testing methods not covered in this work. There have been international developments in fire testing, such as developing the Heat-Transfer Rate Inducing System (H-TRIS) standardised fire exposure. However, such systems have not become standards, yet thus it is not considered in this work. The fire test method might form part of fire test standards in the future, and then the discussions above are required to be evaluated.

Since building codes and standards are highly interrelated, replacing fire test standards is not a simple process. Further work needs to be carried out on how to most effectively address all construction and related products in South Africa and implement such changes in a plethora of codes ranging from walls to electrical cables. It would be beneficial to simplify and reduce the total number of tests required for all construction products to a minimum and have them as coherent as possible.

The work presented is primarily focused on South Africa. However, much of this work could be applied to other countries by considering locally available codes, technical capacity and national building requirements.

# Bibliography

ABCB. (2005), *International Fire Engineering Guidelines Edition*, edited by Tubbs, B., Thomas, R., Moule, A., Ashe, B., Oleszkiewicz, I. and Benichou, N., Australian Building Codes Board, Canberra.

Ahonen, A., Weckman, H. and Yli-Penttilä, M. (1985), "Application of oxygen-consumption calorimetry to non-combustibility testing", *Fire and Materials*, Wiley, Vol. 9 No. 3, pp. 135–144.

ASTM. (2008), *ASTM E119-08 Standard Test Methods for Fire Test of Building Construction and Materials*, Vol. 552, ASTM International, West Conshohocken, PA, available at:https://doi.org/10.1520/E0119-08.

ASTM. (2014), *ASTM E84-14 - Standard Test Method for Surface Burning Characteristics of Building Materials*, ASTM International, West Conshohocken, PA, available at:https://doi.org/10.1520/E0084-14.

ASTM. (2017), *ASTM E2257 - 17 Standard Test Method for Room Fire Test of Wall and Ceiling Materials and Assemblies*, ASTM International, West Conshohocken, PA, available at:https://doi.org/10.1520/E2257-17.

ASTM. (2018), *ASTM E1321 - 18 Standard Test Method for Determining Material Ignition and Flame Spread Properties*, ASTM International, West Conshohocken, PA, available at:https://doi.org/10.1520/E1321-18.

ASTM. (2019), *ASTM E2058 - 19 Standard Test Methods for Measurement of Material Flammability Using a Fire Propagation Apparatus (FPA)*, Vol. 04.07, ASTM International, West Conshohocken, PA, available at:https://doi.org/10.1520/E2058-19.

ASTM. (2020), *ASTM E108 - 20a Standard Test Methods for Fire Tests of Roof Coverings*, ASTM International, West Conshohocken, PA, available at:https://doi.org/10.1520/E0108-20A.

ASTM. (2021a), *ASTM E162 - 21 Standard Test Method for Surface Flammability of Materials Using a Radiant Heat Energy Source*, Vol. 04.07, ASTM International, West Conshohocken, PA, available at:https://doi.org/10.1520/E0162-21.

ASTM. (2021b), *ASTM D3675 - 21a Standard Test Method for Surface Flammability of Flexible Cellular Materials Using a Radiant Heat Energy Source*, Vol. 08.02, ASTM International, West Conshohocken, PA, available at:https://doi.org/10.1520/D3675-21a.

ASTM. (2021c), *ASTM E84 - 21a Standard Test Method for Surface Burning Characteristics of Building Materials*, Vol. 04.07, ASTM International, West Conshohocken, PA, available at:https://doi.org/10.1520/E0084-21a.

Azhakesan, A.., Shields, T. and W H Silcock, G.W.. (1994), "Developments on the Fire Propagation Test", *International Association for Fire Safety Science*, pp. 349–360.

Babrauskas, V. (1982), *Development of the Cone Calorimeter-A Bench-Scale Heat Release Rate Apparatus Based on Oxygen Consumption*, Washington, DC, available at:https://doi.org/10.6028/NBS.IR.82-2611.

Babrauskas, V. (2004), *Ignition Handbook*, *Ignition Handbook*, Vol. 40, Fire Science Publishers, Issaquah, WA, available at:https://doi.org/10.1023/b:fire.0000026981.83829.a5.

Babrauskas, V. (2008), "ASTM Fire Standards and Related Technical Material, 7th ed., 2 Vols. American Society for Standards and Materials, West Conshohocken, USA (2007). 3080pp., $365, total, softbound. Printed edition, ISBN:978-0-8031-5684-5. CD-ROM edition (priced and sold sep", *Fire Safety Journal*, Elsevier, Vol. 43 No. 1, pp. 77–79.

Babrauskas, V. (2017), "Engineering Variables to Replace the Concept of 'Noncombustibility'", *Fire Technology*, Vol. 53, pp. 353–373.

Babrauskas, V., Lucas, D., Eisenberg, D., Singla, V., Dedeo, M. and Blum, A. (2012), "Flame retardants in building insulation: A case for re-evaluating building codes", *Building Research and Information*, Vol. 40 No. 6, pp. 738–755.

Babrauskas, V. and Peacock, R.D. (1992), "Heat release rate: The single most important variable in fire hazard", *Fire Safety Journal*, Elsevier, Vol. 18 No. 3, pp. 255–272.

Babrauskas, V., White, J.A. and Urbas, J. (1997), "Testing for Surface Spread of Flame: New Tests to Come into Use", *Building Standards*, NIST, Vol. 66 No. 2, p. 16.

Babrauskas, V. and Wickstrom, U. (1989), "The Rational Development Of Bench-scale Fire Tests For Full-scale Fire Prediction", *Fire Safety Science*, Vol. 2 No. February 2015, pp. 813–822.

Babrauskas, V. and Williamson, R.B. (1978), "The historical basis of fire resistance testing - Part I", *Fire Technology*, Vol. 14 No. 3, pp. 184–194.

Bailey, C. (2004), "A Simplistic or Holistic Approach to Structural Fire Engineering?", *CTBUH 2004 Seoul Conference*, CTBUH, Seoul.

Bankoff, B., Lubken, U. and Sand, J. (2012), *Flammable Cities: Urban Conflagration and the Making of the Modern World*, University of Wisconsin Press, Madison, WI, USA.

Beitel, J. and Iwankiw, N. (2008), *Analysis of Needs and Existing Capabilities for Full-Scale Fire Resistance Testing*, Baltimore, MD.

Bisby, L., Gales, J. and Maluk, C. (2013), "A contemporary review of large-scale non-standard structural fire testing", *Fire Science Reviews*, Springer Nature, Vol. 2 No. 1, p. 1.

Bøhm, B. (1978), "Fire resistance tests and differentiated design procedures - The Building Code: Aims and means", *Fire Technology*, Vol. 14 No. 3, pp. 239–246.

Brohez, S., Marlair, G. and Delvosalle, C. (2006), "Fire calorimetry relying on the use of the fire propagation apparatus. Part I: Early learning from use in Europe", *Fire and Materials*, Vol. 30 No. 2, pp. 131–149.

BS. (1987), *BS 476-20: Fire Tests on Building Materials and Structures*, British Standards Institution, London.

BS. (1989), *BS 476-6:1989 Fire Tests on Building Materials and Structures - Method of Test for Fire Propagation for Products*, 2nd ed., British Standards Institution, London, available at: https://shop.bsigroup.com/products/fire-tests-on-building-materials-and-structures-method-of-test-for-fire-propagation-for-products/preview (accessed 25 October 2021).

BS EN. (1999), *BS EN 1363-2:1999 Alternative and Additional Procedures*, British Standards Institution, London, available at: shop.bsigroup.com/products/fire-resistance-tests-alternative-and-additional-procedures/details.

BS EN. (2010a), *BS EN 13823:2010- Reaction to Fire Tests for Building Products — Building Products Excluding Floorings Exposed to the Thermal Attack by a Single Burning Item*, British Standards Institution, London.

BS EN. (2010b), *BS EN 15725:2010 Extended Application Reports on the Fire Performance of Construction Products and Building Elements*, British Standards Institution, London, available at: https://shop.bsigroup.com/products/extended-application-reports-on-the-fire-performance-of-construction-products-and-building-elements.

BS EN. (2015), *BS EN 1364-1:2015 Fire Resistance Tests for Non-Loadbearing Elements Walls - European Standards*, British Standards Institution, London, available at: shop.bsigroup.com/products/fire/resistance/tests/for/non/loadbearing/elements/walls/details.

BS EN. (2016), *BS EN 13501-2:2016 Fire Classification of Construction Products and Building Elements - Classification Using Data from Fire Resistance Tests, Excluding Ventilation Services*, British Standards Institution, London, available at: https://shop.bsigroup.com/products/fire-classification-of-construction-products-and-building-elements-classification-using-data-from-fire-resistance-tests-excluding-ventilation-services?pid=000000000030410030.

Buchanan, A.H. and Abu, A.K. (2017), *Structural Design For Fire Safety*, Second., John Wiley & Sons Ltd, Sussex, UK.

Canter, D. (1980), "Fires and human behaviour: Emerging issues", *Fire Safety Journal*, Elsevier, Vol. 3 No. 1, pp. 41–46.

Carpenter, K. and Janssens, M. (2005), "Using Heat Release Rate to Assess Combustibility of Building Products in the Cone Calorimeter", *Fire Technology 2005 41:2*, Springer, Vol. 41 No. 2, pp. 79–92.

Carpet Institute of Australia Limited. (2021), *Frequently Asked Questions on Testing to AS ISO 9239-1 for the Building Code of Australia*, Melbourne.

Cleary, T. and Quintiere, J. (1991), "A Framework For Utilizing Fire Property Tests", *Fire Safety Science*, Vol. 3, pp. 647–656.

CMTS. (2021), "Fire Resistance Test Furnace & Fire Test Apparatus - CMTS", available at: https://www.cmtsproduct.com/fire-resistance-test-furnace/ (accessed 15 October 2021).

Dietenberger, M.A. (1996), "Ignitability analysis using the cone calorimeter and LIFT apparatus", *Proceedings of the International Conference on Fire Safety*, Product Safety Corporation, Columbus, OH, pp. 189–197.

DIN EN. (2010), *EN 1363-1:2010 Fire Tests General Requirements*, German Institute for Standardization, Berlin.

Drysdale, D. (2011), *An Introduction to Fire Dynamics*, *Introduction to Fire Dynamis*, Third., Vol. 66, John Wiley & Sons Ltd, University of Edinburgh, Scotland, UK, available at:https://doi.org/10.1016/0010-2180(86)90037-4.

Emmons, H.W. (1974), "Fire and Fire Protection", *Scientific American*, Vol. 231 No. 1, pp. 21–27.

EN. (2009), *EN 13501-1:2005 Fire Classification of Construction Products and Building Elements - Part 1: Classification Using Data from Reaction to Fire Tests*, Vol. 3, European Committee for Standardization, London.

EN 1991-1-2:2002. (2002), *BS EN 1991-1-2:2002*, British Standards Institution, London.

EPDB. (2018), "Performance-Based Design and Prescriptive Methods", *FIRE SAFE EUROPE*, available at: https://firesafeeurope.eu/performance-based-design-prescriptive-methods/.

European Commission. (2003), "The European Classification System for the Reaction-to-Fire Performance of Construction Products", European Commission, Brussels.

European Union. (2011), "Regulation ( EU ) No 305 / 2011 of the European Parliament and of the Council", *European Union*, European Union, Vol. 4 No. 4, pp. 1–29.

European Union. (2020), *EU Member Countries in Brief*, European Union, available at: https://europa.eu/european-union/about-eu/countries/member-countries_en (accessed 24 October 2021).

Fernández-Pello, A. and Williams, F.A. (1977), "A Theory of Laminar Flame Spread Over Flat Surfaces of Solid Combustibles", *Combustion and Flame*, Elsevier, Vol. 28, pp. 251–277.

Fire Testing Technology. (2010), *The Single-Flame Source Test THE BENCHMARK IN FIRE TESTING*, Sussex, UK.

Fire Testing Technology. (2021), “Horizontal Fire Resistance Test Furnace - Fire Testing Technology”, *Horizontal Fire Resistance Test Furnace*, January, available at: https://www.fire-testing.com/horizontal-fire-resistance-test-furnace/.

FM Global. (1989), *Cable Fire Propagation Specification Test Standard, Approval Standard, Class Number 3972, FM Global, 1151*, Federal Mutual, Boston-Providence Turnpike, Norwood, MA, available at: https://standards.globalspec.com/std/1280655/fmapproval-3972.

Gales, J., Chorlton, B. and Jeanneret, C. (2020), *The Historical Narrative of the Standard Temperature–Time Heating Curve for Structures*, *Fire Technology*, Vol. 57, available at:https://doi.org/10.1007/s10694-020-01040-7.

Gerhard Gous. (2021), “Zutari Drywalling Test”, *LinkedIn Post*, available at: https://www.linkedin.com/in/gerhard-gous-5b10323b/detail/recent-activity/ (accessed 31 October 2021).

Government of the Republic of South Africa. (1977), *National Building Regulations and Building Standards Act*, Government Gazette, Cape Town.

Hakkarainen, T. and Hayashi, Y. (2001), “Comparison of Japanese and European Fire Classification Systems for Surface Linings”, *Fire Science and Technology*, Vol. 21 No. 1, pp. 19–42.

Hall, J.R. (2012), “Uncertainty in Fire Standards and What to Do About It”, *Journal of Testing and Evaluation*, available at: www.astm.org.

Hasemi, Y. (2016), “Surface flame spread”, *SFPE Handbook of Fire Protection Engineering, Fifth Edition*, Springer New York, pp. 705–723.

History Editors. (2009), “Topics - HISTORY”, available at: https://www.history.com/topics (accessed 22 October 2021).

HM Government. (2010), *The Building Regulations 2010 - Regulation 7 - Materials and Workmanship*, 2nd ed., HM Government, England and Wales, available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/806919/AD_Regulation_7.pdf.

Homenish. (2020), “9 Types of Plywood with Pictures & Their Alternatives - Homenish”, *Home Improvement*, available at: https://www.homenish.com/types-of-plywood/ (accessed 4 November 2021).

Horrocks, A.R. and Price, D. (2001), *Fire Retardant Materials*, *Fire Safety Journal*, Vol. 36, Woodhead Publishing Limited, Cambridge, England, available at:https://doi.org/10.1016/s0379-7112(01)00027-3.

Horrocks, A.R. and Price, D. (2008), *Advances in Fire Retardant Materials Related Titles :*, First., Woodhead Publishing, Cambridge, England.

Hull, T.R. (2008), “Challenges in fire testing: Reaction to fire tests and assessment of fire toxicity”, *Advances in Fire Retardant Materials*, pp. 255–290.

Hull, T.R. and Stec, A.A. (2009), “Fire Retardancy of Polymers: New Strategies and Mechanisms”, *Royal Society of Chemistry*, Cambridge, England, pp. 1–14.

Hurley, M.J., Gottuk, D., Jr., J.R.., Harada, K., Kuligowski, E., Puchovsky, M., Torero, J.L., *et al.* (2016), *SFPE Handbook of Fire Protection Engineering*, *Fire Safety Journal*, Fifth., Vol. 29, Springer International Publishing, New York, available at:https://doi.org/10.1016/s0379-7112(97)00022-2.

Hurley, M.J. and Rosenbaum, E.R. (2015), *Performance-Based Fire Safety Design*, *Performance-Based Fire Safety Design*, 1st ed., CRC Press, Boca Raton, FL.

Incropera, F.P., Dewitt, D.P., Bergman, T.L. and Lavine, A.S. (2005), *Fundamentals of Heat and Mass Transfer*, *Fluid Mechanics and Its Applications*, Sixth., Vol. 112, John Wiley & Sons Ltd, available at:https://doi.org/10.1007/978-3-319-15793-1_19.

Ingberg, S.H. (1928), "Tests of Severity of Building Fires", *NFPA Quarterly*, Vol. 22 No. No. 1, pp. 43–61.

ISO. (1999), *ISO 834-1:1999 Fire Resistance Tests - Elements of Building Construction, Standard, I. (1999). Iso 834. 1999.*, Vol. 1, International Standards Organization, Switzerland.

ISO. (2002), *ISO 5660-2:2002 - Reaction-to-Fire Tests — Heat Release, Smoke Production and Mass Loss Rate — Part 2: Smoke Production Rate (Dynamic Measurement)*, First., British Standards Institution, London, available at: https://www.iso.org/standard/32431.html.

ISO. (2010), *ISO 11925-2:2010 Single Flame Source*, Third., International Standards Organization, Switzerland.

ISO. (2011), *ISO 12136:2011 - Reaction to Fire Tests — Measurement of Material Properties Using a Fire Propagation Apparatus*, International Standards Organization, Switzerland, available at: https://www.iso.org/standard/51237.html.

ISO. (2015a), *ISO 5660-1:2015 Reaction-to-Fire Tests- Heat Release, Smoke Production and Mass Loss Rate- Part 1: Heat Release Rate (Cone Calorimeter Method)*, Third., International Standards Organization, London.

ISO. (2015b), *ISO 9705-1:2016 - Reaction to Fire Tests — Room Corner Test for Wall and Ceiling Lining Products — Part 1: Test Method for a Small Room Configuration*, 1st ed., Vol. 02, International Standards Organization, Switzerland, available at: https://www.iso.org/standard/59895.html.

ISO. (2017), *ISO 4589-1:2017 - Plastics — Determination of Burning Behaviour by Oxygen Index — Part 1: General Requirements*, 2nd ed., International Standards Organization, Switzerland, available at: https://www.iso.org/standard/60785.html (accessed 22 October 2021).

ISO 1182. (2010), *ISO 1182 Reaction-to-Fire Tests for Products- Non-Combustibility Test*, Vol. 5, International Standards Organization, Switzerland.

Janssens, M. (2015), "Calorimetry", in Hurley, M.J., Gottuk, D., Hall, J.R., Harada, K., Kuligowski, E., Puchovsky, M., Torero, J., et al. (Eds.), *SFPE Handbook of Fire Protection Engineering*, Fifth., Springer New York, New York, NY, pp. 905–951.

Janssens, M.L. (2008), "Challenges in fire testing: a tester's viewpoint", *Advances in Fire Retardant Materials*, Woodhead Publishing, Cambridge, England, pp. 233–254.

José Tomás. (2019), "Reaction And Fire Resistance: How Are Materials Classified In The Event Of A Fire?", *ArchDaily*, available at: https://www.archdaily.com/916062/reaction-and-fire-resistance-how-are-materials-classified-in-the-event-of-a-fire (accessed 29 October 2021).

Khan, M.M. and Chaos, M. (2016), "Combustion characteristics of materials and generation of fire products", *SFPE Handbook of Fire Protection Engineering*, Fifth., Springer New York, New York, pp. 1143–1232.

Kingspan Insulation UK. (2020), "What are BS 476-20-23?", YouTube, available at: https://www.youtube.com/watch?v=uTE138ebnBY.

Lane, B. (2000), "Performance-Based Design for Fire Resistance", *Modern Steel Construction*, No. December, p. 5.

Lane, B. (2018), *Grenfell Tower - Fire Safety Investigation. PHASE 1 Report*, London.

Laubscher, J. (2011), "Tracing the origins of the Southern African building regulations, with specific reference to the period between 1650 and circa 1740", *Acta Structilia : Journal for the Physical and Development Sciences*, Vol. 18 No. 2, pp. 80–96.

Lautenberger, C., Torero, J. and Fernandez-Pello, C. (2006), *Understanding Materials Flammability, Flammability Testing of Materials Used in Construction, Transport and Mining*, Book, Woodhead Publishing Limited, Cambridge, England, available at:https://doi.org/10.1533/9781845691042.1.

Law, A. and Bisby, L. (2020), "The rise and rise of fire resistance", *Fire Safety Journal*, Elsevier Ltd, Vol. 116, p. 103188.

Lawson, J.R. (2009), *A History of Fire Testing*, Technical., NIST, Gaithersburg, MD.

Mercor Tecresa. (2018), "Euroclasses - European Reaction fire Classification Construction Materials", *EUROCLASSES – EUROPEAN REACTION TO FIRE CLASSIFICATION OF CONSTRUCTION MATERIALS*.

Messerschmidt, B. (2008), "The Capabilities and Limitations of the Single Burning Item (SBI) Test", *FireSeat - Fire and Building Safety in the Single European Market*, Vol. 1994, Rockwool International A/S, Denmark, pp. 70–81.

Messerschmidt, B. (2016), "Future proofing the Euroclass system", *Future Proofing the Euroclass System*, Fire Safe Europe, p. 2.

Van Mierlo, R. and Sette, B. (2005), "The Single Burning Item (SBI) test method-a decade of development and plans for the near future", *HERON*, Vol. 5 No. 4, pp. 191–207.

NETZSCH® TAURUS® Instruments. (2021), *Flooring Radiant Panel Tester- TBB 913*, Weimar, Germany.

NFPA. (2021a), *NFPA - Reporter's Guide: About Codes and Standards*, Quincy, Massachusetts, available at: https://www.nfpa.org/News-and-Research/Publications-and-media/Press-Room/Reporters-Guide-to-Fire-and-NFPA/About-codes-and-standards.

NFPA. (2021b), *NFPA 101: Life Safety Code*, National Fire Protection Association, Quincy, Massachusetts, available at: https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=101.

NFPA. (2022), *NFPA 287: Standard Test Methods for Measurement of Flammability of Materials in Cleanrooms Using a Fire Propagation Apparatus (FPA)*, National Fire Protection Association, Quincy, Massachusetts, available at: https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=287.

Parker, W.J. (1984), "Calculations of the heat release rate by oxygen consumption for various applications", *Journal of Fire Sciences*, Vol. 2 No. 5, pp. 380–395.

Proulx, G. (1993), "A stress model for people facing a fire", *Journal of Environmental Psychology*, Vol. 13 No. 2, pp. 137–147.

QSI Quartz. (2021), "The Difference between Fused Silica and Quartz Glass - QSI Quartz", available at: https://www.qsiquartz.com/the-difference-between-fused-silica-and-quartz-glass/ (accessed 8 October 2021).

Quintiere, J.G. and Harkleroad, M. (1984), *New Concepts for Measuring Flame Spread Properties*, Gaithersburg, MD, available at:https://doi.org/10.6028/NBS.IR.84-2943.

SABS. (1945), "SABS", available at: https://www.sabs.co.za/ (accessed 22 October 2021).

SABS. (2005), "SABS - ABOUT SABS OVERVIEW", available at: https://www.sabs.co.za/About-SABS/index.asp (accessed 22 October 2021).

SABS. (2021), "SABS - STANDARDS - ABOUT STANDARDS IN GENERAL", available at: https://www.sabs.co.za/Standardss/standards_about.asp (accessed 4 February 2021).

SANS. (2005a), *SANS 10177-1 : 2005 SOUTH AFRICAN NATIONAL STANDARD Fire Testing of Materials , Components and Elements Used in Buildings Part 1 : General Introduction to the Methods of Test*, South African Bureau of Standards, Pretoria.

SANS. (2005b), *SANS 10177-3 : 2005 : Fire Testing of Materials , Components and Elements Used in Buildings*, edited by 1.2, South African Bureau of Standards, Pretoria.

SANS. (2005c), *SANS 10177-4 : 2005 SOUTH AFRICAN NATIONAL STANDARD Fire Testing of Materials , Components and Elements Used in Buildings*, 1.4., South African Bureau of Standards, Pretoria.

SANS. (2005d), *SANS 10177-5 : 2005 SOUTH AFRICAN NATIONAL STANDARD Fire Testing of Materials, Components and Elements Used in Buildings*, South African Bureau of Standards, Pretoria.

SANS. (2006), *SANS 10177-9 : 2006 SOUTH AFRICAN NATIONAL STANDARD Fire Testing of Materials , Components and Elements Used in Buildings Part 9 : Small-Scale Burning Characteristics of Building Materials : Ignition, Flame Spread and Heat Contribution*, South African Bureau of Standards, Pretoria.

SANS. (2007), *SANS 10177-10 : 2007 South African National Standard. Fire Testing of Materials, Components and Elements Used in Buildings Part 10: Surface Burning Characteristics of Building Materials Using the Inverted Channel Tunnel Test*, South African Bureau of Standards, Pretoria.

SANS. (2012), *SANS 428 : 2012 SOUTH AFRICAN NATIONAL STANDARD Fire Performance Classification of Thermal Insulated Building Envelope Systems*, South African Bureau of Standards, Pretoria.

SANS. (2016), *SANS 1253 : 2016 Fire-Doors and Fire-Shutters*, 3.1., South African Bureau of Standards, Pretoria.

SANS. (2020), *SANS 10400-T : 2020 SOUTH AFRICAN NATIONAL The Application of the National Building Regulations Part T : Fire Protection*, 4th ed., South African Bureau of Standards, Pretoria.

Schartel, B., Bartholmai, M. and Knoll, U. (2005), "Some comments on the use of cone calorimeter data", *Polymer Degradation and Stability*, Vol. 88 No. 3, pp. 540–547.

Schartel, B. and Hull, T.R. (2007), "Cone calorimeter – a tool for measuring heat release rate", *Fire and Materials*, Vol. 31 No. June, pp. 327–354.

Selwyn, J. (2018), "What Happened In THe Grenfell Tower And How Many People Died?", *The Daily Mail*, available at: https://www.dailymail.co.uk/femail/fb-5829947/WHAT-HAPPENED-GRENFELL-TOWER-FIRE-PEOPLE-DIED.html (accessed 11 October 2021).

Shoub, H. (1961), "Early History of Fire Endurance Testing in The United States", *Symposium on Fire Test Methods*, ASTM International, West Conshohocken, PA, pp. 1–9.

Spearpoint, M. (2008), "Fire detection", *New Zealand Science Teacher*, No. 117, pp. 14–16.

Stec, A.A., Hull, T.R., Purser, J.A., Blomqvist, P. and Lebek, K. (2008), "A Comparison of Toxic Product Yields Obtained From Five Laboratories Using the Steady State Tube Furnace (ISO TS 19700)", *Fire Safety Science*, International Association for Fire Safety Science, pp. 653–664.

Steel, J.S. (1981), *Furnace Pressure Probe Investigation*, National Bureau of Standards, Washington, DC.

Structural Timber Association. (2014), "Fire safety in timber buildings", *Engineering Bulletin*, London, p. 8.

Sundström, B. (2007), *The Development of a European Fire Classification System for Building Products - Test Methods and Mathematical Modelling*, Lund, available at: https://portal.research.lu.se/en/publications/the-development-of-a-european-fire-classification-system-for-buil (accessed 15 September 2021).

Tewarson, A. (1977), “Heat release rate in fires”, *Fire and Materials*, Vol. 4 No. 4, pp. 185–191.

The Association for the Eradication of Asbestos and Asbestos Products. (2008), “Asbestos products now completely banned in South Africa”, available at: https://www.brandsouthafrica.com/south-africa-fast-facts/asbestos-ban-south-africa (accessed 12 October 2021).

Thureson, P., Sundström, B., Mikkola, E., Bluhme, D., Hansen, A.S. and Karlsson, B. (2008), “The use of fire classification in the Nordic countries-Proposals for harmonisation”, *SP Fire Technology SP REPORT*, p. 29.

TIPSASA. (2012), “Technical Communique - SANS 428 Revision August 2012”, Thermal Insulation Products & Systems Association SA, Johannesburg.

TIPSASA. (2019), “TIPSASA Fire Register September 2019”, Thermal Insulation Products & Systems Association SA, Pretoria.

Torero, J.L. (2019), *Interim Recommendations*, London, available at: https://www.grenfelltowerinquiry.org.uk/evidence/professor-jose-toreros-report-interim-recommendations.

UL. (2013), *UL Standard | UL 94*, 6th ed., Underwriters Laboratories, available at: https://standardscatalog.ul.com/ProductDetail.aspx?productId=UL94 (accessed 22 October 2021).

UL. (2018), *UL Standard | UL 723*, 11th ed., Underwriters Laboratories, available at: https://standardscatalog.ul.com/ProductDetail.aspx?productId=UL723 (accessed 22 October 2021).

De Villiers, W. and Boshoff, W.P. (2012), “The Southern African Housing Foundation - Regulation of Alternative Building Materials and Systems in South Africa”, *Building Capacity for Sustainable Development*, Stellenbosch University, Cape Town, p. 14.

Wang, Y., Burgess, I., Wald, F. and Gillie, M. (2012), *Performance-Based Fire Engineering of Structures*, *Performance-Based Fire Engineering of Structures*, CRC Press, Boca Raton, FL, available at:https://doi.org/10.1201/B12076.

Williams, F.A. (1977), “Mechanisms of fire spread”, *Symposium (International) on Combustion*, Vol. 16 No. 1, pp. 1281–1294.

Williamson, R., Revenaugh, A. and Mowrer, F. (1991), “Ignition Sources In-Room Fire Tests And Some Implications For Flame Spread Evaluation”, *Fire Safety Science*, International Association for Fire Safety Science, Vol. 3, pp. 657–666.

Wood, P.G. (1972), “The Behaviour of People in Fires”, *Fire Research Station*, Fire Research Station, Loughborough.

Yu, B. and Kodur, V. (2014), “Effect of temperature on strength and stiffness properties of near-surface mounted FRP reinforcement”, *Composites Part B: Engineering*, Elsevier, Vol. 58, pp. 510–517.

# Appendix A – European Classification Information

The classifications in the European system for various tests are provided in the tables to follow. The criterion for classification vastly differs from test to test. Often the classification is the only requirement provided, and the importance of these tables will then come into question. The tables provide alternative testing methods for the same classification if that specific test cannot be executed. This inter-activeness is an indication of the comparability of the European fire testing standards. Aspects that need clarification is also listed in this annexure.

*Table A- 1: EN versus UK classification and related test standards*

| European | | UK | |
|---|---|---|---|
| **Standard** | **Classification** | **Standard** | **Classification** |
| ISO 1182 & ISO 1716 | Class A1 | BS 476: Part 4 | Non-combustible |
| ISO 1182 or ISO 1716 & EN 13823 | Class A2 | BS 476: Part 11 | Limited combustibility |
| EN 13823 & EN ISO 11925-2 | Class B | BS 476: Parts 6 and 7 | Class 0 |
| EN 13823 & EN ISO 11925-2 | Class C | BS 476: Part 7 | Class 1 & 2 |
| EN 13823 & EN ISO 11925-2 | Class D | BS 476: Part 7 | Class 3 |
| EN ISO 11925-2 | Class E | BS 476: Part 7 | Class 4 |

*Table A- 2: Description of properties*

| Symbol | Definition | Symbol | Definition |
|---|---|---|---|
| $\Delta T$ | Temperature increase | $THR_{600s}$ | Total heat release in 600s |
| $\Delta m$ | Mass loss | LFS | Lateral flame spread |
| $t_f$ | Flame duration | SMOGRA | Smoke growth rate |
| HHV | Higher heating value | $TSP_{600s}$ | Total smoke production in 600s |
| FIGRA | Fire growth rate | $F_s$ | Flame spread |

*Table A- 3: Summary of property requirements for the Euroclass fire tests*

| | EN 11925 | EN ISO 13823 | | | EN ISO 1716 | EN ISO 1182 | | |
|---|---|---|---|---|---|---|---|---|
| **Class** | **$F_S$** | **FIGRA** | **LFS** | **$THR_{600s}$** | **PCS** | $\Delta T$ | $\Delta m$ | $t_f$ |
| A1 | | | | | $\leq 2.0\ MJ/kg$ | $\leq 30°C$ | $\leq 50°C$ | $0s$ |
| A2 | | $\leq 120\ W/s$ | $< edge$ | $\leq 7.5\ MJ$ | $\leq 3.0\ MJ/kg$ | - | | |
| B | $\leq 150\ mm\ 60s$ | $\leq 120\ W/s$ | $< edge$ | $\leq 7.5\ MJ$ | | - | | |
| C | $\leq 150\ mm\ 60s$ | $\leq 250\ W/s$ | $< edge$ | $\leq 7.5\ MJ$ | | - | | |
| D | $\leq 150\ mm\ 60s$ | $\leq 750\ W/s$ | | | | - | | |
| E | $\leq 150\ mm\ 60s$ | | | | | - | | |

*Table A- 4: EN classification possibilities*

| **Surface products** | | | **Floor coverings** | | |
|---|---|---|---|---|---|
| A1<br>A2s1d0<br>A2s2d0<br>A2s3d0 | <br>A2s1d1<br>A2s2d1<br>A2s3d1 | <br>A2s1d2<br>A2s2d2<br>A2s3d2 | $A1_{fl}$ | <br>$A2_{fl}s1$ | <br>$A2_{fl}s2$ |
| Bs1d0<br>Bs2d0<br>Bs3d0 | Bs1d1<br>Bs3d1<br>Bs2d1 | Bs1d2<br>Bs2d2<br>Bs3d2 | | $B_{fl}s1$ | $B_{fl}s2$ |
| Cs1d0<br>Cs2d0<br>Cs3d0 | Cs1d1<br>Cs3d1<br>Cs4d1 | Cs1d2<br>Cs2d2<br>Cs3d2 | | $C_{fl}s1$ | $C_{fl}s2$ |
| Ds1d0<br>Ds2d0<br>Ds3d0 | Ds1d1<br>Ds3d1<br>Ds4d1 | Ds1d2<br>Ds2d2<br>Ds3d2 | | $D_{fl}s1$ | $D_{fl}s2$ |
| E<br>Ed2 | | | $E_{fl}$ | | |
| F | | | $F_{fl}$ | | |

For instance, a Euroclass may be determined as Bs2d1, and B stands for the main class, s2 stands for smoke class 2, and d1 stands for droplets class 1.

*Table A- 5: European tests and classifications*

**CONSTRUCTION PRODUCTS**

<table>
<tr><th></th><th>EN 1182</th><th>EN 1716</th><th>EN 13823</th><th>EN 11925</th><th>EN 9239</th></tr>
<tr><td>A1</td><td bgcolor="gray"></td><td bgcolor="gray"></td><td></td><td></td><td></td></tr>
<tr><td>A2</td><td></td><td bgcolor="gray"></td><td bgcolor="gray"></td><td></td><td></td></tr>
<tr><td>B</td><td></td><td></td><td bgcolor="gray"></td><td bgcolor="gray"></td><td></td></tr>
<tr><td>C</td><td></td><td></td><td bgcolor="gray"></td><td bgcolor="gray"></td><td></td></tr>
<tr><td>D</td><td></td><td></td><td bgcolor="gray"></td><td bgcolor="gray"></td><td></td></tr>
<tr><td>E</td><td></td><td></td><td></td><td bgcolor="gray"></td><td></td></tr>
<tr><td>F</td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

**FLOORING**

<table>
<tr><th></th><th>EN 1182</th><th>EN 1716</th><th>EN 13823</th><th>EN 11925</th><th>EN 9239</th></tr>
<tr><td>A1fl</td><td bgcolor="gray"></td><td bgcolor="gray"></td><td></td><td></td><td></td></tr>
<tr><td>A2fl</td><td></td><td bgcolor="gray"></td><td></td><td></td><td bgcolor="gray"></td></tr>
<tr><td>B</td><td></td><td></td><td></td><td bgcolor="gray"></td><td bgcolor="gray"></td></tr>
<tr><td>C</td><td></td><td></td><td></td><td bgcolor="gray"></td><td bgcolor="gray"></td></tr>
<tr><td>D</td><td></td><td></td><td></td><td bgcolor="gray"></td><td bgcolor="gray"></td></tr>
<tr><td>E</td><td></td><td></td><td></td><td bgcolor="gray"></td><td></td></tr>
<tr><td>F</td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

**LINEAR PIPE INSULATION**

<table>
<tr><th></th><th>EN 1182</th><th>EN 1716</th><th>EN 13823</th><th>EN 11925</th><th>EN 9239</th></tr>
<tr><td>A1</td><td bgcolor="gray"></td><td bgcolor="gray"></td><td></td><td></td><td></td></tr>
<tr><td>A2</td><td bgcolor="gray"></td><td bgcolor="gray"></td><td bgcolor="gray"></td><td></td><td></td></tr>
<tr><td>B</td><td></td><td></td><td bgcolor="gray"></td><td bgcolor="gray"></td><td></td></tr>
<tr><td>C</td><td></td><td></td><td bgcolor="gray"></td><td bgcolor="gray"></td><td></td></tr>
<tr><td>D</td><td></td><td></td><td bgcolor="gray"></td><td bgcolor="gray"></td><td></td></tr>
<tr><td>E</td><td></td><td></td><td></td><td bgcolor="gray"></td><td></td></tr>
<tr><td>F</td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

*Table A- 6: SBI classification of combustion products*

| Class | Criteria for compliance | Other classification | Other test methods |
|---|---|---|---|
| A2 | FIGRA ≤ 120 W/s; and LFS < edge of specimen; and $THR_{600s}$ ≤ 7.5 MJ | Smoke production and Flaming droplets / particles | EN ISO 1182 or EN ISO 1716 |
| B | FIGRA ≤ 120 W/s; and LFS < edge of specimen; and $THR_{600s}$ ≤ 7.5 MJ | Smoke production and Flaming droplets / particles | EN ISO 11925-2 |
| C | FIGRA ≤ 120 W/s; and LFS < edge of specimen; and $THR_{600s}$ ≤ 15 MJ | Smoke production and Flaming droplets / particles | EN ISO 11925-2 |
| D | FIGRA < 750 W/s | - | EN ISO 11925-2 |

*Table A- 7: Ignitability test classification for construction products*

| Class | Criteria for compliance | Other classification | Other test methods |
|---|---|---|---|
| B | $F_s$ ≤ 150 mm within 60 s (Exposure = 30 s) | Smoke production and Flaming droplets / particles | EN 13823 |
| C | $F_s$ ≤ 150 mm within 60 s (Exposure = 30 s) | Smoke production and Flaming droplets / particles | EN 13823 |
| D | $F_s$ ≤ 150 mm within 60 s (Exposure = 30 s) | Smoke production and Flaming droplets / particles | EN 13823 |
| E | $F_s$ ≤ 150 mm within 20 s (Exposure = 15 s) | Flaming droplets / particles | |

*Table A- 8: Ignitability test classification for flooring products*

| Class | Criteria for compliance | Other classification | Other test methods |
|---|---|---|---|
| $B_{fl}$ | $F_s$ ≤ 150 mm within 20 s (Exposure = 15 s) | Smoke production | EN ISO 9239-1 |
| $C_{fl}$ | $F_s$ ≤ 150 mm within 20 s (Exposure = 15 s) | Smoke production | EN ISO 9239-1 |
| $D_{fl}$ | $F_s$ ≤ 150 mm within 20 s (Exposure = 15 s) | Smoke production | EN ISO 9239-1 |
| $E_{fl}$ | $F_s$ ≤ 150 mm within 20 s (Exposure = 15 s) | - | - |

*Table A- 9: Flooring Radiant Panel Test EN ISO 9239-1 classification*

| Class | Criteria for compliance | Other test methods |
|---|---|---|
| $A2_{fl}$ | CHF≥ 8.0 $Kw/m^2$ | EN ISO 1716 |
| $B_{fl}$ | CHF≥ 8.0 $Kw/m^2$ | EN ISO 11925-2 |
| $C_{fl}$ | CHF≥ 4.5 $Kw/m^2$ | EN ISO 11925-2 |
| $D_{fl}$ | CHF≥ 3.0 $Kw/m^2$ | EN ISO 11925-2 |
| s1 | $< 750\% \times minutes$ | - |

*Table A- 10: Typical properties of fused silica/quartz glass* (QSI Quartz, 2021)

| | Property | Units | Value |
|---|---|---|---|
| **General** | Chemical Formula | N/A | $SiO_2$ |
| | Density | $g/cm^3$ | 2.23 |
| **Mechanical** | Design Tensile Strength | MPa | 48 |
| | Design Compressive Strength | MPa | 1100 |
| | Young’s Modulus | GPa | 72 |
| **Thermal** | Max Use Temperature | ℃ | 950-1300 |
| | Thermal Conductivity | W/m·K | 1.4 |
| | Co-Efficient of Linear Expansion | $10^{-6}/℃$ | 055 |
| **Electrical** | Volume Resistance | $V \cdot cm$ | $10^{16}$ |
| | Dielectric Constant | - | 3.7 |
| | Dielectric Strength | kV/mm | 40 |

# Appendix B – Additional Analysis of Fire Tests

The information in this appendix describes additional testing standards that are analysed and summarised. Additionally, discussions regarding comparisons of fire tests are provided. Lastly, fire test standards are utilized to test for the same fire parameter. In accordance with Chapter 6, additional comparisons of fire testing standards are provided.

The most critical test relative to building resistance and fire safety has been discussed. Table A- 11 summarises additional tests that could be considered and the parameters they present. However, the comparative table is not the focus of this work and has been mentioned for additional information.

*Table A- 11: Common fire tests and parameters assessed*

| | Apparatus name | | | | | | |
|---|---|---|---|---|---|---|---|
| **Parameter** | **Radiant ignition test<br><br>ISO 5657** | **Glow wire test<br><br>IEC 60695-2-10-13** | **UL-64<br><br>IEC 60695-11-10** | **Laterally induced flame test<br><br>ISO 5658** | **Limiting oxygen index<br><br>ISO 4589-2** | **Smoke density chamber<br><br>ISO 5659** | **Steady-state tube furnace<br><br>ISO 19700** |
| Ignitability | ✓ | ✓ | ✓ | | | | |
| Rate of flame spread | | | ✓ | ✓ | | | |
| Rate of heat release | | | | | | | |
| Smoke production and toxicity | | | | | | ✓ | ✓ |
| Ease of extinction | | | | | ✓ | | |

## Additional Comparisons of Fire Tests

**Room Corner test**

Several Room Corner tests (ISO 9705) are used and standardized by various organizations such as the ASTM, NFPA, UBC and ISO. The test setup is all the same, but one difference can significantly impact the specimen's performance.

These differences include the size, sample mounting location, and the ignition burner's heat flux output. The primary difference between the various test methods is the ignition source. Results have indicated that the associated heat flux to the specimen and the duration of exposure influence the material's performance, which holds for thin, short burning duration materials.

The walls and ceiling have been lined in preparation for ISO 9705 tests. The interior surfaces of all walls (except the front wall) are covered with the test material for NFPA 286 tests. The burner is placed directly against the walls (ISO 9705 and NFPA 286) or 50 mm away from the walls (NFPA 265).

The flame from the burner alone only touches the ceiling in NFPA 286, which is a significant difference between the two standards. As a result, it is appropriate for evaluating the fire performance of an interior ceiling finish, an application for which NFPA 265 is ineffective. This effect is caused in part by the NFPA 286 burner's higher energy release rate, but primarily by the burner being in direct contact with the walls, reducing the area over which the flames can entrain air and increasing the overall flame height (Horrocks and Price, 2008)

The test apparatus described in the NFPA and ISO room corner test standards are nearly identical. The distinction is in the specimen configuration and the use of an ignition source, as described in Appendix C.

**Flooring radiant panel**

The two standards that will be examined are the EN 9239-1 and the ASTM E648. Firstly, differences lie with the pilot ignition sources. The European standard uses a propane gas burner, whereas the ASTM standard employs a methane burner.

The standards cannot be used to provide a "deemed-to-satisfy solution". The ASTM E648 differs from ISO 9239-1 in some test parameters, and the ASTM standard does not measure the smoke produced during the test so that no equivalency can be met. Additional testing under the performance-based design provisions may demonstrate that ASTM E648 is an acceptable alternative where a smoke index or classification is not required. (Carpet Institute of Australia Limited, 2021).

# Appendix C – Details of Fire Test Procedures

## Introduction

The details below relate to the fire test standards discussed in Chapter 5. Additional technical information is provided, especially with regards to how tests should be carried out. Since test results are highly dependent upon the manner of testing, the following helps assess the suitability of tests.

## Oxygen Comb Calorimeter Operations

The bomb is a sealed stainless-steel container with a constant volume. A small quantity of material, about one gram, is combusted at high bar pressure inside an oxygen atmosphere. The fuel inside the bomb is kept in touch by a cm fuse wire connected to two electrodes. The entire calorimeter vessel is immersed in a stirred water bath. The jacket, located between the water container and the outer can, is also filled with water. The water temperature of this outer jacket follows the inner water bath during the test to ensure no transfer of radiation.

The jacket temperature is maintained at a steady level. In contrast, as the combustion of a sample releases heat, the temperature of the calorimeter vessel (bomb and bucket) rises and is measured. The temperatures of the jacket and bucket are constantly monitored, and heat loss is corrected after the test. The embedded control computer automatically sets the outer bath temperature and indicates when the temperature of the calorimeter vessel has stabilized. The bomb is automatically detonated at this point. Two platinum resistance thermometers with high precision and resolution are used to measure the temperature. The precision equipment eliminates human error, increasing the repeatability and significantly reducing the preparation time of the next test.

## Room Corner test Operations

The details below present an overview of the operations of the room corner test and focus on differences between standards that use the same apparatus but have different experimental setups to obtain different results.

The Room Corner Test specifications differ in specimen configuration and ignition source according to a specific standard implemented by the country in question. Table 5-2 provides the test specifications for the International Standards Organization (ISO), which, as mentioned in the ISO 9705, primarily tests for wall and ceiling lining products. America adopted this test standard as the ASTM E2257. The National Fire Protection Association (NFPA) has two standards that utilise the Room Corner test, namely the NFPA 265 and NFPA 286.

These two test specifications will be provided in Table C- 1 and Table C- 2, illustrating the significant differences. A fundamental difference between NFPA 265 and NFPA 286 is that the flame from the burner touches only the ceiling as required by NFPA 286. This distinction ensures the suitability of assessing interior ceiling finishes' fire performance, an application for which NFPA 265 is unsuitable. This effect is partly due to the higher energy output of the NFPA 286 burner, but primarily because of the burner placement being in direct contact with the walls, thus increasing the overall flame height by reducing the area over which the flames can trap air (Horrocks and Price, 2001).

*Table C- 1: Test specifications for NFPA 265*

| | |
|---|---|
| **Specimens** | Sample material enough to cover all walls (except the front wall) and the ceiling of the test room. The wall containing the doorway is not covered |
| **Specimen Position** | Forms a room lining on all walls and ceiling |
| **Ignition Source** | Propane fuel burner placed in one corner, 0.05 m away from both walls. The burner heat output is 40 kW for the first five minutes, followed by 150 kW for an additional ten minutes |
| **Ignition Size** | Steel sandbox measuring 0.305 m × 0.305 m × 0.152 m |
| **Test Duration** | 15 minutes or until flashover |

*Table C- 2: Test specifications for NFPA 286 in comparison to NFPA 265*

| | |
|---|---|
| **Specimens** | As above |
| **Specimen Position** | Forms a room lining on all walls and ceiling. Suitable for ceiling finishes |
| **Ignition Source** | Propane fuel burner placed in one corner in contact with both walls. The burner heat output is 40 kW for the first five minutes, followed by 160 kW for an additional ten minutes |
| **Ignition Size** | As above |
| **Test Duration** | As above |

Based on the proposed test procedure, Williamson *et al.* (1991) conducted theoretical experiments. Based on the findings of those experiments, it was recommended that the 0.05 m stand-off distance be used in tests and experiments to assess the fire propagation potential of various wall lining materials. This distance provided exposure to the lower portion of the wall, best determining whether the wall covering material will propagate a fire under the given ignition fire. If the burner is placed too close to the wall, the exposure is too great to adequately assess the fire spread potential of a wall covering material. Exposure from too far away, on the other hand, is insufficiently intense to cause a challenge to the wall covering material. This stand-off distance is only implemented in the NFPA 265 standard, not ISO 9705 or NFPA 286.

## Lateral Ignition Flame Transport (LIFT) test Operations

In terms of measuring the lateral flame spread, the LIFT apparatus is equipped with a vertical propane-fired radiant panel in an open-air environment inclined to the specimen. Specific dimensions are required for a lateral flame spread test as well as be mounted vertically. A gradually decreasing heat flux distribution is applied along the horizontal length of the sample. A series of specimens are exposed to a nearly uniform heat flux for the ignition test. A pilot flame is used as an igniter, and the time to ignition is recorded. The specimen holder is placed into position during a test and then rapidly removed an aluminium cover (thermal shutter) from the specimen.

## Single Burning Item (SBI) Operations

The floor test specimen forming a right-angled corner is mounted on a trolley specimen. To facilitate mounting procedures, the burner is removed from the testing environment. The specimen is placed at the bottom corner where the primary burner is located and then exposed to the flames from the burner. The combustion of propane gas produces flames that are diffused through a sandbox. The testing system is installed beneath an exhaust system, which collects combustion gases in a hood and transports them through a duct. A measurement section within the duct includes a differential pressure probe, thermocouples, a gas sample probe, and a smoke measurement system for measuring heat and smoke production.

## Single Flame Source Test (Ignitability Test)

The spread of a small flame up the vertical surface of a specimen is measured to assess ignitability. For either $15$ seconds or $30$ seconds, a small flame is applied to either the surface or edge of a specimen.

To maximize its operating life, the combustion chamber is constructed of corrosion-resistant stainless steel. It has large front and side doors for easy access, and these are glazed with toughened glass to provide a full view of the specimen during testing. The assembly, along with its relevant dimensions, is shown in $50 \pm 20\%$. The hood is excluded from this view, i.e., the extraction system assembly under which the combustion chamber should be situated. The ignitibility apparatus should be placed in a draught-free environment with a relative temperature of $23 \pm 5$ ℃ and relative humidity of $50 \pm 20\%$.

## Fire Propagation Apparatus

The test section involves wide vertical silica (pure silicon dioxide) or quartz (silicon dioxide with impurities) tube containing the fire zone. The specific properties of fused silica or quartz glass are provided in Table A- 10. Notably, the most valuable property is the maximum use temperature listed as between $950 - 1300$ ℃. This property allows the tube to withstand the energy output of the ignition source.

The tube housing allows for improved control of the firing atmosphere and eliminates any contact with the heaters. A water-cooled shield may also be used to protect the specimen holder from external heat flux. The heating system consists of four halogen infrared heaters producing $190$ kW/m$^2$ of radiant flux in front of the quartz window that surrounds the tube. The sample is resting on top of a load cell system that measures the specimen's mass loss during the test duration. The ignition source is as described by the test specifications, Table 5-10. Rotated and elevated, the pilot flame tube shall be positioned such that the horizontal flame will be at specified locations near the specimen. The pilot flame shall be $10$ mm in length and anchored at the end of a stainless-steel tube which dimensions have been provided in Figure C- 1.

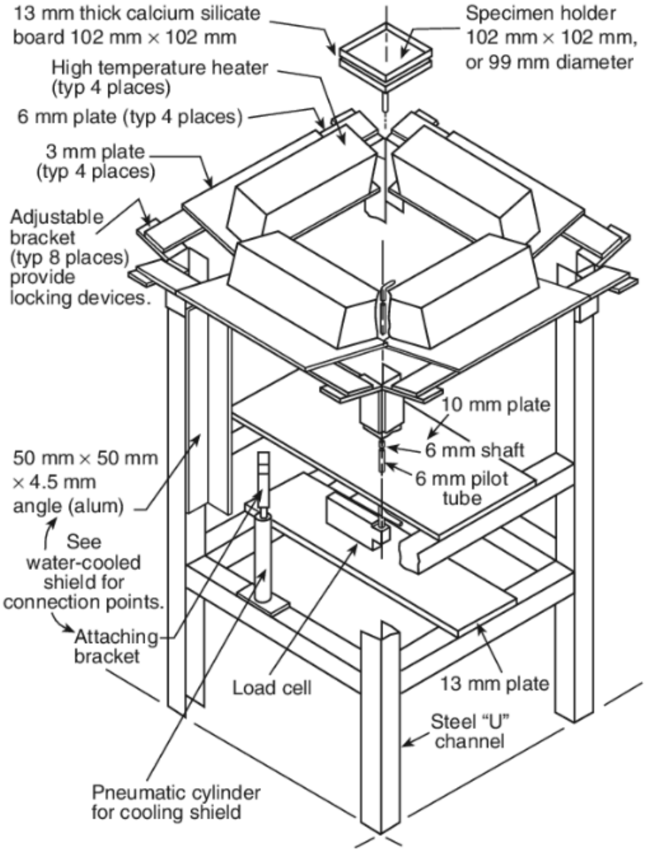



*Figure C- 1: Exploded view of specimen mounting (NFPA, 2017)*

The hood situated above the tube collects all of the combustion products, namely the CO, $CO_2$, $O_2$, soot yield, measured by shining a sampling probe through the flue gases based on the amount of obscuration. Oxygen concentration at 40 % is pumped in to create an oxygen-rich atmosphere. A sample may also be tested in the vertical configuration with the specifications provided in the NFPA 287. The exact dimensions of the apparatus and a complete layout of every component are provided in the NFPA 287. Once the pilot flame has ignited, it must be moved away; otherwise, it must be moved into contact with the sample surface 75 mm above the bottom of the specimen to initiate fire propagation.

## Non-combustibility Apparatus Operations

In order to observe flaming inside the furnace, the apparatus should not be exposed to draughts, direct sunlight, or artificial illumination. Surrounding areas should not block observation. The room temperature cannot change by more than 5°C during a test.

According to existing apparatuses in the industry, there are two types of 'furnaces' available, one which meets the requirements of the ISO 1182: 2020 standard and one which meets the previous version of ISO 1182 (ISO 1182, 2010) and other international standards. The difference between the updated and older versions is the number of furnace thermocouples that should be utilized. A second furnace thermocouple has been introduced in the new version of the standard. The thermocouple inside the furnace, specified to measure furnace temperature during testing, is replaced by the inclusions of two thermocouples, both 60° apart from the previous thermocouple.

Inserting one prepared specimen into the specimen holder, suspended on its support, is the essential operation. The holder is then placed into the furnace in the correct position as per the International

Standard, not taking longer than 5 seconds to perform this placement. The timer is started, and all the necessary temperatures are measured for the duration of the test. The specimen is then weighed, and any debris or ash located in the tube is recovered and included as part of the unconsumed specimen. The test is repeated as stated in Table 5-13.

## Flooring Radiant Panel Test Operations

The specimens are mounted in a stainless-steel test chamber with calcium silicate panels as the lining material. Specimen feeding takes place from the front where a generous opening flap is located, equipped with refractory glass to observe the test process. The front opening system allows the mounting plate for the specimen holder to be pulled out. The tests of eight specimens must be conducted in four directions (e.g., production direction) and four directions perpendicular to the first direction. The standard procedure is stipulated in Table 5-17.

In the position as described, the test specimen is exposed to a defined heat flow. The radiator, temperature-resistant up to 900℃, consists of porous refractory material fixed in a steel frame. The inclined radiant panel generates a defined heat radiation profile on the specimen. Therefore, the thermal load of the flooring in a corridor in the event of a fire is simulated. The attenuation of a laser beam integrated into the exhaust system, which includes the hood and exhaust duct, is used to calculate the flue gas density.

The temperature of the test chamber is determined by measuring the ambient temperature with a thermocouple. Directly in the flame area, the mantle thermocouples also detect the flame temperature of the pilot burner and emitter. A signal is delivered to stop the gas supply when no flame is detected.

A separate thermocouple monitors the burning status. As soon as the temperature drops below the specified set point, the gas supply is interrupted. Technical details of the setup are shown in Figure 5-17.

## Inverted Channel Tunnel Test Operations

To measure the flame spread properties of a building material, a heat flux associated with its conductive, convective, and radiative properties is produced from three adjacent surfaces, two walls and a ceiling.

The support brackets are fitted inside the channel in two locations, Figure C- 2.

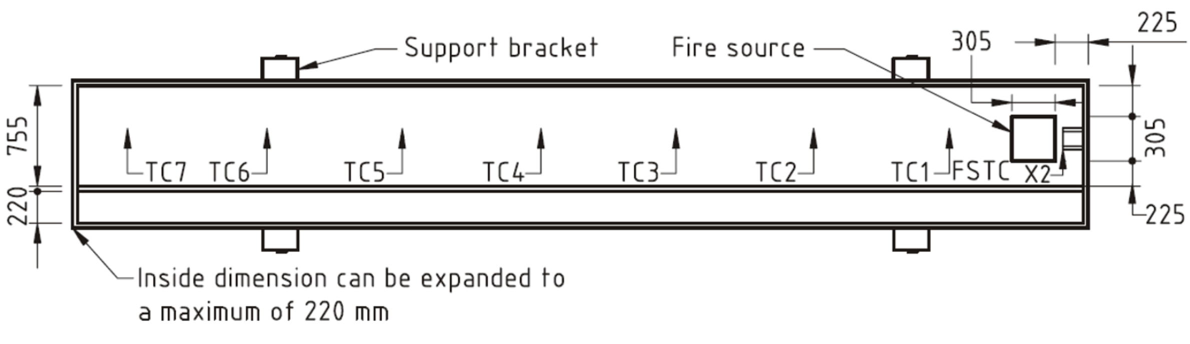



*Figure C- 2: Plan view of the inverted channel tunnel (SANS, 2007)*

The higher placed support bracket is used for insulation applications below non-combustible fire-resistant structures. At a distance of 300 mm below the channel’s ceiling, one will locate the other support bracket used for suspended ceiling applications with a ceiling void and for building envelope insulation applications with roof sheeting on top of the respective application.

## Small-scale Burning Characteristics of Building Materials Test Operations

Provided the test specifications in Table 5-23, the specimen is placed above the Bunsen burner. The burner is then ignited and placed in the centre of the test specimen's bottom edge, deemed the test position. The burner must be situated such that any molten or burning debris from the burning specimen does not fall onto the burner head.

After a 12 s and 24 s interval, observations regarding the occurrence of sustained ignition are made. For each case, the Bunsen burner is removed and returned to the test position as described. Once the test period has concluded, the extinguishment process takes place.

## Full-scale Furnace Testing (Vertical) Operations

As shown by the indicative time-temperature graph in Figure 2-1, the furnace temperature rises sharply during the test and gradually levels out but will continue until the complete test duration. During the test, thermocouples in the furnace monitor the temperature, and feedback to the burners ensures that the average temperature follows the prescribed curve. The curve is defined by Equation 2.9. The thermocouple placement in the furnace is specified in the standard for each type of specimen tested.

The furnace is constructed so that the neutral pressure plane is 1000 mm above the theoretical floor level. The pressure gradient inside the furnace should be 8.5 Pa/m height, and however, the pressure at the top of the specimen should never exceed 20 Pa during the test.

As part of the monitoring equipment, a cotton pad is used for the monitoring of permeability. It is stipulated to be 100 $mm^2 \times 20$ mm thick and weighs between 3 and 4 grams. Dried and then cooled, the cotton pad will be placed on a typical supporting frame stipulated in the testing standard (BS, 1987).

The distance between the exposed face of the specimen and the furnace lining is defined as the chamber depth. Non-separating and separating elements (required to satisfy stability, integrity, and insulation criteria) that are only required to resist fire from one side shall be tested on one specimen. Separate specimens are necessary for asymmetrical separating elements that must be tested from both sides of the specimen. The test specimen and any associated construction should be full-sized building construction elements if possible.