FIREFIGHTING DECISION MAKING ON SANDWICH PANEL CONSTRUCTION GUIDED BY TEMPERATURE DEVELOPEMENTS

A thesis submitted to the University of Manchester for the degree of Master of Philosophy in the Faculty of Engineering and Physical Sciences.

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CONTENTS

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ABBREVIATIONS

ADB = Approved Document B

ASTM = American Society For Testing Of Materials

BA = Breathing Apparatus

CEWS = Cutting Extinguishing Watermist System

CLG = Communities And Local Government

DRA = Dynamic Risk Assessment

EFR = Explosive Force Projection

EPS = Expanded Polystyrene Foam

FM = Factory Mutual

GRA = Generic Risk Assessment

HRR = Heat Release Rate

IC = Incident Commander

IACSC = International Association For Cold Storage Construction

LPC = Loss Prevention Council

LPCB =Loss Prevention Certification Board

MDT = Mobile Data Terminal

MF = Mineral Fibre

PF= Phenolic Foam

PIR = Polyisocyanurate Foam

PUR = Polyurethane Foam

RDS = Retained Duty System

SoP = Standard Operating Procedure

SW = Stone wool

TiC = Thermal Imaging Camera

UHPL = Ultra High Pressure Lance

XPS = Extruded Polystyrene Foam

University of Manchester

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Sandwich panel construction involved in fire has been of concern for UK Fire and Rescue Services for many years. Assessment of fire conditions within buildings of sandwich panel construction has largely been by using thermal imaging technology to determine temperature differences and therefore extent of fire spread.

A literature review of all guidance notes and standard operating procedures issued to UK Fire and Rescue Services revealed little advice on how to use thermal imaging technology and how to interpret the results. Temperature information may also be unreliable for many reasons including the excellent thermal insulating qualities of the sandwich panel leading to negligible temperature increase on the unexposed surface.

The objective of this thesis is a study of the temperature profiles within the core, joints and on the unexposed face of sandwich panel samples when subjected to real fire conditions. The results are then analysed to determine whether this information could be used to assist Fire and Rescue Services in better assessing temperature profiles within the fire compartments and assisting in fire fighting decision making when faced with building fires of this type.

The analysis demonstrates that it is impossible to assess compartment temperatures from outside using thermal imaging cameras other than by direct observation. However there are a number of relationships that have been identified which relates temperature development with different phases of fire development and is important in tactical firefighting decision making. An easy to use guide has been developed describing the relationships and suggesting the appropriate firefighting response.

Declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Copyright Statement

Acknowledgements

In writing this thesis, I have received great support from many friends and colleagues. However, I feel that there are certain people that should be acknowledged for the great support they have provided during the course of my studies. Without these people, and their direct support it would not have been possible to for me to complete this thesis.

Firstly I would like to thank Adele, my wife for her unending support and patience over the last three years.

Colleagues, Stuart Renshaw and Bob Birtles who assisted with the experimentation with such enthusiasm and have acted as sounding boards over the last number of years. Andrew Foster of Manchester University who is studying for a PhD and provided great academic assistance.

I would like to thank my employer Greater Manchester Fire and Rescue Service for allowing me the opportunity to undertake this course of study. I would like to thank Lancashire Fire and Rescue Service for allowing me to use their fire testing facility at Euxton without restriction.

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CHAPTER 1: INTRODUCTION

1.1 Introduction to Sandwich Panels

Sandwich panels have traditionally been used in aerospace and marine applications but have been increasingly used in building construction. In the building construction industry, cladding walls generally provide an envelope to the building for protection against the elements, thermal insulation, and fire protection and may also provide a certain architectural design to enhance the aesthetics of the building.

Cladding panels are typically non-load-bearing in the plane of the panel and are generally designed for out-of-plane loading due to wind loads. Fire safety provision within the built environment is primarily aimed at ensuring that occupant of the building can escape to a place of safety within a reasonable time. To achieve this compartment sizes are defined to ensure that fires will not grow to involve the whole of the building. Building materials are used with a specified fire resistance period and limits on surface spread of flame to ensure that occupants are able to escape safely.

Fire safety within the built environment has been extended to included property protection; this requirement has normally been driven by the insurance sector. Additional measures to ensure business continuity and continued economic prosperity have come to prominence due to the present economic climate. Facilities to ensure that fire-fighters are afforded a reasonable level of safety when firefighting within and around the building are also included as part of the overall building fire safety design.

Fire fighting in buildings made of sandwich panel construction has been a long term concern of Fire and Rescue Services (FRS) throughout the UK and the guidance varies in different FRS. A focused research study is necessary to help develop evidence based guidance for firefighting decision making. This thesis presents the background of sandwich panel construction and properties, details of experimental studies and analysis of the results and recommendations into how the information derived can be utilised to advise compartment firefighting decision making and other techniques that could be considered.

1.2 Construction

Sandwich panels are typically a core material sandwiched in between and bonded to two outer faces by means of an adhesive polymer.

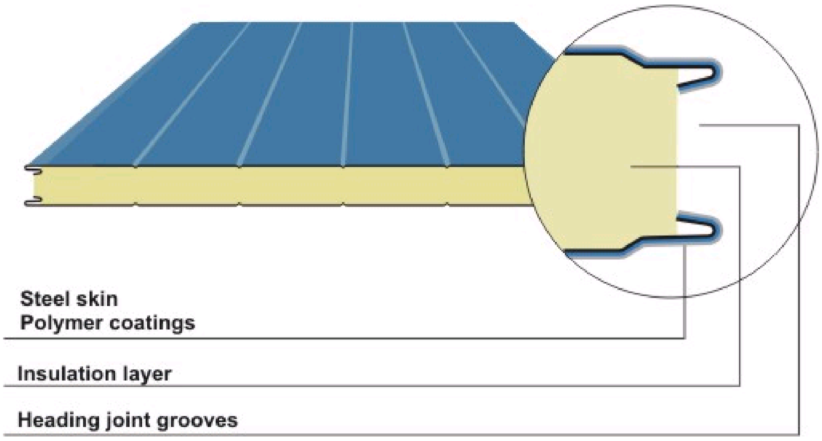


Figure 1.2 Cross section of typical sandwich panel construction. (Nottinghamshire FRS Service Order, 2011) [31].

There are many forms of construction combining different facing and core materials. Facings are normally steel or aluminium but can be wood, rigid plastic and concrete. Cores vary from cork, balsa wood, rubber, solid plastic material (polyethylene), rigid foam (polyurethane, polystyrene, phenolic foam), mineral wool slabs, or honeycomb of metal or even paper (Davies, 2001)[10]. This thesis is concerned with sandwich panels constructed of steel facing and PIR cores.

1.3 Properties

Under normal conditions sandwich panels exhibit good structural properties due to their light weight and high stiffness. The stiffness comes from the rigidity of the core which holds the outer facings and prevents shear deformation (Buchanan, 2006) [4].

There are significant favourable and less favourable properties associated with the use of lightweight sandwich panels identified as follows (Davies, 2001) [10]. Advantages include high load-bearing capacity at low weight, excellent and durable insulation, absolute air and water tightness, easy installation and replacement of damaged panels, long life at low maintenance costs and economical mass production.

Less favourable properties are behaviour in fire of elements with rigid foam cores, deformation when one side is exposed to heat, creep under unstained loads. Insulating core panel systems are used for external cladding as well as for internal structures.

The most common use of insulating core panels, when used for internal structures, is to provide a chilled enclosure for foodstuffs. However they can be used in other applications, such as hygienic environments and in storage premises.

The most common forms of insulation core material are highly flammable polystyrene and polyurethane derivatives, although they may be made up of mineral fibres. With the exception of mineral fibre cores, a flammable core panel can degrade in a fire and cause large quantities of black, toxic smoke.

Fire can also spread behind the panels and fire-fighters may not be able to track the spread of fire, even using a thermal imaging camera (TIC) due to the excellent thermal insulation properties of the core material, leading to negligible temperature rise on the unexposed side. In addition, irrespective of the type of core material, the panel will tend to delaminate between the facing and core material.

1.4 Research Objectives

A number of fires occurred in sandwich panel construction. The consequences of some of these fires were severe resulting in significant financial losses and fire-fighter deaths. As a result, they have led to different recommendations on fire fighting in sandwich panel construction. It is necessary to review these fire accidents in order to understand the objective of this research.

The specific objectives of the research are as follows:

1. Subject different thicknesses and orientation of sandwich panel to real fire conditions.
2. Measure and collect temperature data at various critical parts of the sandwich panel samples.
3. Analyse the temperature data collected and discuss implications on firefighting tactics.
4. Provide recommendations on how the analyses of the information can be utilised.
5. Provide a practical easy to use guide.

1.4.1 Background

1.4.1.1 Fire in North Carolina , USA 1991

In September 1991, a fire occurred in a chicken processing factory constructed from Insulated panel, located in North Carolina. Of the 90 staff present at the time of the blaze, 25 were killed and a further 54 injured. Firefighting was delayed while search and rescue was carried out. The NFPA identified one of the main contributor factors to be a rapid fire development to allow any initial first aid firefighting (Morgan and Shipp, 1999) [(33)].

1.4.1.2 Fire in Sun Valley Poultry Ltd, UK 1993

In the UK concerns in relation to sandwich panel construction involved in fire were expressed for some time prior to the fire at Sun Valley Poultry Ltd in September 1993 where two fire-fighters lost their lives. Following the Sun Valley fire, the Fire Research Development Group (FRDG) of the Home Office commissioned The Fire Research Stations to carry out a review of firefighting options for fires involving sandwich panels.

Burning sandwich panel construction had not been considered a significant problem prior to the occurrence of these two fires. However it was evident that several near misses had been reported in the fire press and fire-fighters were conversant with the risk that this type of construction posed to them.

The report (Shipp, 1999) [(33)] provided 31 areas of considerations where additional research was needed to assist Fire and Rescue Services when fighting fires involving sandwich panel construction. These include further investigation into jointing and fixing details, exploring alternative firefighting techniques and the use of thermal imaging technology. Thermal imaging technology was considered to be able to inform the dynamic risk assessment (DRA) carried out by the fire crews on the incident ground. The report provided no specific details on how this technology could or should be used, what information could be derived and how this information could be used to assist firefighting tactics.

1.4.1.2.1 Changes and recommendations following the Sun Valley Fire

A series of recommendations and changes followed this incident. The recommendations were categorized in relation to improvements that could be made prior to the incident, considerations en route to an incident and where the incident was developing. The main changes are summarized as follows.

There has been a duty to collect relevant information in relation to buildings since The Fire Services Act 1947 and this was reinforced in The Fire and Rescue Services Act 2004. Although Fire and Rescues Services have historically carried out the collection of risk information, the information was generally collected and stored in hard copy format and an electronic solution was sought.

Due to the dynamic nature of firefighting, the dynamic risk assessment (DRA) process was developed and required to be used by Incident Commanders in recognition of the rapid changing nature of fire situation.

Operational personnel should be given regular instruction on the hazards and risks likely to be encountered at premises where insulated sandwich panels are installed. The training should include instruction on how to recognise sandwich panels and premises in the station area that utilise insulated sandwich panels in their construction. Early investigation should be made to establish the extent of the fire and / or smoke spread within the roof voids and cavities and identification of the type, nature and location of panels should be determined as soon as possible.

Where an incident is in the developing stages the training and instruction the use of water spray pulses to cool and dilute the atmosphere within the building. The Incident Commander should consider an early enhanced attendance. Early ventilation of the building should be considered by using any available installed systems. Automatic or manual roof vents can assist in the removal of hot fire gases and improve firefighting operations. Early ventilation of the building should be considered if tactically advantageous. This should be undertaken at roof and eaves level by selective cutting away of parts of roof structure. The number of fire-fighters undertaking this work should be kept to a minimum and be supported by safety crews equipped with thermal imaging cameras and firefighting equipment. Breathing apparatus (BA) should be worn at all times and the production of burning droplets of molten polystyrene should be expected if the insulation becomes involved in fire. An additional consideration when fighting fires in cold stores, where there are extreme temperatures (-28°C) working duration is drastically reduced. The impact on a fire-fighter to work effectively at these temperatures should also be considered.

The environment impact of large fires involving sandwich panels should not be underestimated and the Environmental Agency and the Local Authority Environmental Health and Health Protection Agency should be informed of large incidents. This is due to the harmful effects of environmental pollution and water run-off and efforts should be made to avoid pollution of water courses

1.4.1.3 Fire at De Punt, Netherlands 2008

On 9 May 2008, three fire-fighters lost their lives while fighting a fire in a commercial building at De Punt in The Netherlands. The fire-fighters attempted to reach the seat of the fire by entering the building and were caught by a sudden and rapid spread of the fire. As the fire-fighters moved through the shed, the hot layer ignited, triggering an explosion that caused the fire to spread further through the structure. The three fire-fighters became fatally trapped, with initial rescue efforts hampered by the increasing size and intensity of the fire.

The sandwich panels used for the construction of the roof complied with the legal requirements of The Netherlands applied to such a building in terms of flammability and/or the spread of a fire, but at the same time they also presented a major risk.

The subsequent investigation and fire investigation report identified that if the panels were sufficiently heated, the polyurethane present would lead to gas emission, which could cause an unexpectedly rapid spread of the fire. Although the risks associated with such sandwich type constructions have been previously demonstrated in the course of fire trials and actual fires, not all fire fighting personnel at that time were familiar with the risks and hazards associated with this type of construction.

The opinion of the investigative committee was that the layer of smoke beneath the ceiling was probably not hot enough to generate a recognisable or alarming image on the infrared camera. The heat given off by the lighting fixtures at ceiling height would also have interfered with the imaging process. On such a warm day, the ceiling and walls would have been, and this would have limited the contrast of the image at any rate. In addition, the overhead door would have limited the field of view available to anyone standing at the front entrance. (I.Helsloot, 2008) [17]

1.4.1.3.1 Changes and recommendations following Fire at De Punt

The report following this incident identified a number of shortcomings that needed addressing to improve general firefighting practice and procedures within the Dutch Fire and Rescue Service. Dutch fire-fighters were primarily trained for situations in which fires suddenly expand and reach flashover conditions within relatively small compartments. In this incident they were presented with a very large compartment with high ceilings and significant ventilation and therefore they did not consider that flashover conditions could be reached within such a large compartment. For these reasons the chosen method of attack from inside the building seemed the most logical and safest approach to tackling this fire.

The primary outcomes were that the incident was poorly coordinated and there was no procedure for dealing with lost or injured firefighters. Additional recommendations were to improve hazard and risk identification measures, modify existing policies and procedures and investing in technology and training for Incident Commanders.

There were concerns about the flashover training currently being offered to Dutch fire brigades, which suggests that a fire can be safely fought from the inside, if there are no clear signals of heat accumulation in an indoor area. Improvements in knowledge of the construction elements of industrial buildings, the fire risks they can pose to fire-fighters, and how brigades can tighten up their procedures to ensure that personnel gain greater professional knowledge of the risks and to manage safety on the fire ground.

1.4.1.4 Atherstone on Stour, UK

On Friday 2 November 2007 at approximately 1720hrs, the fire alarm activated at a substantial vegetable packaging premises owned and operated by Wealmoor's in Atherstone-On-Stour, Warwickshire.

Figure 1.4.1.4 Atherstone upon Stour, 2007 (Courtesy of Warwickshire FRS (2011)[35]

The use of the premises was predominantly 'cold storage' to retain the goods fresh. A large part of the building including the storage area was constructed of a steel girder framework to which was attached sandwich panels to form walls.

Within the large storage area there were a number of internal sandwich panel walls effectively dividing this space into smaller compartments. At the conclusion of the incident four Fire-fighters were pronounced dead at the scene.

1.4.1.4.1 Changes and recommendations following Atherstone on Stour fire

All of those premises deemed to be an operational risk are subject to a risk assessment and the risk information should be collected and made available through the appliance mobile data terminals (MDT). All of this risk information is then loaded on to a database which is available to all fire engines via their mobile data terminals (MDT). This means that all incident commanders have access to risk information on scene.

The location of water supplies is available and should be made available via a mapping system used on the MDTs. In addition to pressurised supplies, all of the known open water supplies are also indicated on the mapping system e.g. lakes, ponds, swimming pools, etc. This means that all operational crews have the information they need to enable access to water supplies.

The four fighters that died at this incident were part time fire-fighters operating the retained duty system (RDS). Retained duty fire-fighters are only required to train for 2 hours a week but still expected to attend the full range of incident attended by their whole time colleagues. Fire Authorities were asked to review training requirements and determine whether an increase in core training time was required.

1.5 Scope and contents

From the short review above, it is clear that fires in sandwich panel construction can lead to serious consequences. Yet there is no evidence based guidance for firefighting decision making. The aim of the study is to provide an easy to use guidance on fire fighting in sandwich panel construction that could be utilised by Fire Incident Commanders. This research will be based on a programme of fire testing of sandwich panel samples and analysis of the fire test results. This study encompasses four parts: literature review, fire testing, analysis and interpretation of test results, and recommendations for firefighting.

This purpose of literature review is to identify information available on how different Fire and Rescue Services determine fire conditions within a building of sandwich panel construction. The main objective of fire testing and data analysis is to determine temperature profiles at different critical points, including the joints, of sandwich panel construction. The analysis results would form the basis of a new recommendation on how to use thermal imaging technology to help firefighting in sandwich panel construction.

1.6 Layout of the thesis

The thesis presents the detailed results of the author's work over a two year part- time MPhil research programme. It included a detailed literature review of technical and academic papers as well as more general and practical guidance provided to different Fire and Rescue Services in the UK. It then provides a description and methodology of experimental testing and provided an analysis of the results along with conclusions reached.

Chapter 1: Presents a brief introduction of the research problem with a statement of the aims and objectives of the research.

Chapter 2: Provides a review of existing literature relevant to the research problem and identifies guidance and policies adopted by UK Fire and Rescue Services. The main focus of this chapter is to present and discuss previous research studies within this field and identify any gaps in knowledge in order to justify the originality of the research project and devise an appropriate research methodology for this research.

Chapter 3: Presents an explanation of the methodology used in conducting the experimental programme. The main focus of this chapter is to describe the arrangements and procedures adopted when carrying out the fire test experiments.

Chapter 4: Presents the fire data results attained from the experimental programme in graphical format and explains the methods of measurement and rationale for the collection of the data.

Chapter 5: Provides an analysis of the fire data results and the implications to fire fighting decision making.

Chapter 6: Provides a summary and discussion of the main findings and identifies relationships between the analysis and stages of the fire development. An easy to use guide is provided to assist in firefighting decision making. Further work is suggested.

CHAPTER 2: LITERATURE REVIEW

This chapter aims to review traditional and contemporary literature and introduce the reader to the concept and features associated with sandwich panel construction and its use within the built environment. The chapter goes on to describe ways in which Fire and Rescue Services are able to recognise types of sandwich panels and identifies the problems, risks and hazards associated with sandwich panel construction when involved in fire.

A full review of guidance documents available to UK Fire and Rescue Services is carried out to identify the similarities and differences between the guidance and hence the approach to dealing with fires involving sandwich panelled construction.

2.1 Introduction to sandwich panel construction

Insulated sandwich panels began to take over from site assembled systems from 1980 onwards. This increase is quoted as follows:

- 10% of the market by 1990
- 40% by the end of the 1990's
- Over 60% by 2006

Modern sandwich panels consist of two metal facings either side of an insulated core. They are generally in width of 1 -3m and in lengths of up to 20m. Metal facings can be flat or profiled dependent upon aesthetic and the function they are to perform, often with a weather protective coating and faced in plastics or timber boards.

If the external face has an irregular profile with longer distance between crowns then the cladding is most likely to be an Insulated Panel. These panels are found on both roofs and walls of buildings.

The facing material generally consists of thin, high strength sheets which satisfy the functional requirements in relation to wind, water and vapour tightness but also have the ability to resist local loading, corrosion and fire.

Steel sheeting is the most commonly used facing material and is normally pre-coated with a corrosion protection layer. The steel sheeting thickness is normally 0.5mm and aluminium normally 0.7mm as 0.5mm is regarded as too thin to prevent local damage during handling.

2.1.1 Insulating Cores

The core material used in sandwich panel construction varies depending upon a number of factors and some of the fundamental properties are described below.

The density of rigid foams is important as the cost of the raw material is more significant than the cost of manufacture, so it is important to obtain the desired physical and mechanical properties with the lowest possible density.

At higher temperatures, rigid foams become softer and more viscoelastic, whereas at lower temperatures they become more brittle, stiffer and stronger. Mineral wools on the other hand are stable materials and temperature has little effect on their mechanical properties. Their strength increases with density but is more dependent upon the internal structure of the fibres (Davies, 2001) [(10)]

2.1.1.1 Polyurethane foam (PUR)

PUR is an organic insulation material made from a reactive mixture of two principal liquid components and a number of additives, to produce highly cross linked polymers with a closed cell structure.

The foam produced will not normally be ignited by a small heat source, but a larger flame will cause ignition and fire spread, with abundant smoke and toxic decomposition giving off hydrogen cyanide, oxides of nitrogen, and carbon monoxide. This is a thermosetting plastic which forms a carbonaceous char when exposed to fire. PUR starts to decompose at 150 - 200°C and becomes flammable at 300°C.

2.1.1.2 Polyisocyanurate foam (PIR)

Polyisocyanurate is made in the same way as polyurethane, but the ratio between the components and the type of additives is usually different, to produce a polymer containing chemical bonds with a higher temperature resistance.

The smoke and decomposition products are similar to PUR. This is a thermosetting plastic which forms a carbonaceous char when exposed to fire. PIR starts to decompose at 150 - 200°C and becomes flammable at 300°C.

2.1.1.3 Expanded and extruded Polystyrene foam (EPS and XPS)

Expanded Polystyrene (EPS) is an organic insulation material made by the addition of catalysts and a blowing agent (normally pentane) to a styrene monomer derived from crude oil, by a combination of ethylene and benzene. The bead is then made into a foamed product containing entrapped air. When exposed to a small flame, polystyrene melts and shrinks away from the heat source.

A larger heat source will produce flaming molten droplets and rapid emission of dense black smoke/soot. These are thermoplastic materials which begin to melt at temperatures over 100°C resulting in ignition and the formation of burning droplets.

2.1.1.4 Phenolic resin foam (PF)

These foams were introduced in a response to improving the fire resistance of PUR rigid foam cores. This is a thermosetting material which has excellent char forming properties and low smoke emissions.

It begins to decompose between 350 and 500°C and ignites between 530 and 580°C. During burning a stable char is formed releasing mainly hydrocarbons and carbon monoxide.

This is less commonly used than PIR and PUR but often used for internal walls and ceiling applications. The core is not easily ignited by a small ignition source and has the ability to self-protect; however some smouldering or glowing has been observed after the extinction of an ignition flame.

2.1.1.5 Mineral fibre (MF)

Mineral wool is produced by melting naturally occurring rock with coke and dolomite and/or slag. The molten rock is formed into stone wool by contact with spinning wheels. The woollen structure entraps air, and is bonded together with cured resin, to form non-combustible insulation in a variety of densities with very low calorific content.

2.1.2 Thermal Decomposition of Polymers

Solid polymers undergo both a physical and chemical change when heat is applied resulting in unwanted changes to the material. There are specific differences between thermal decomposition and thermal degradation as defined by the American Society for Testing of

Materials (ASTM). Thermal degradation is a process where the application of heat or elevated temperatures causes a loss of physical, mechanical or electrical properties.

In terms of fire the important change is thermal decomposition whereby the chemical decomposition of the solid material generates gaseous vapours, which then burn above the solid material (American Society for Testing of Material, 2006)[1].

The physical changes such as melting and charring can alter the burning and decomposition characteristics of a polymeric material. Many materials including thermosetting and thermoplastic polymers produce carbonaceous chars on thermal decomposition. The physical structure of these chars affect the continued decomposition process by increasing in thickness and preventing the exposure of the heat flux to the virgin material therefore reducing the decomposition rate is reduced (Hirschler, 2002)[13].

2.1.3 Joint design and fixing methods

Design of the side laps is important to ensure tight connections between adjacent panels. The most common form of joint is a ‘tongue and groove’ arrangement in which the edges of the facing members are folded back into the core thus preventing a thermal bridge. Self-tapping screws are then passed through both faces to connect the panel to the supporting structure. Other designs for cold storage use are more onerous in order to attain the thermal efficiency requirements necessary for the application.

Factory made panels are highly engineered and the edges details are designed for the panels to be interlocked to provide a complete assembly in which there is no contact between the inner and outer metal faces**.** The figures below show some typical joints for industrial external walling.

2.1.3.1 Standard Wall Panel

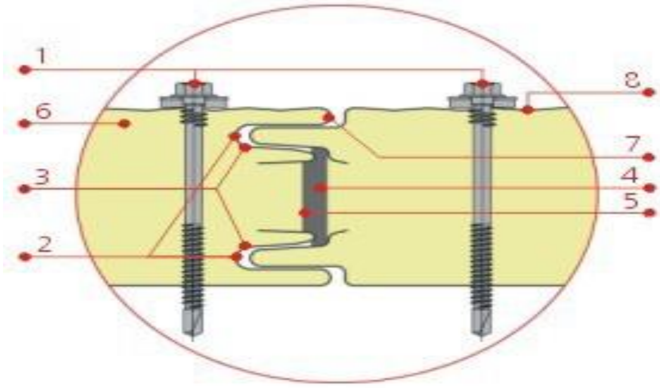


Figure 2.1.3.1 Example of standard wall panel joint (GMFRS Service Order)[29]

1. Fastening joints.

2. Same shape both-sides of panel's joint - fastener, enhancing fire integrity and facilitating the assembly.

3. Conical inclination of the interior joint' surface on the panel facilitating the assembly.

4. Continuous polyurethane seal or made of non-flammable material with aluminum foil introduced into production process, preventing the infiltration of steam and retaining high heat insulation.

5. Stiff polyurethane foam core technology with the lowest heat conduction factor of thermo - insulated materials.

6. Special shape of facings as a guarantee of the high durability of stainless coating.

7. Wide range of external coatings profiles fulfilling high architectural requirements.

8. Wide range of external coatings profiles fulfilling high architectural requirements.

2.1.3.2 Wall panel with invisible joint

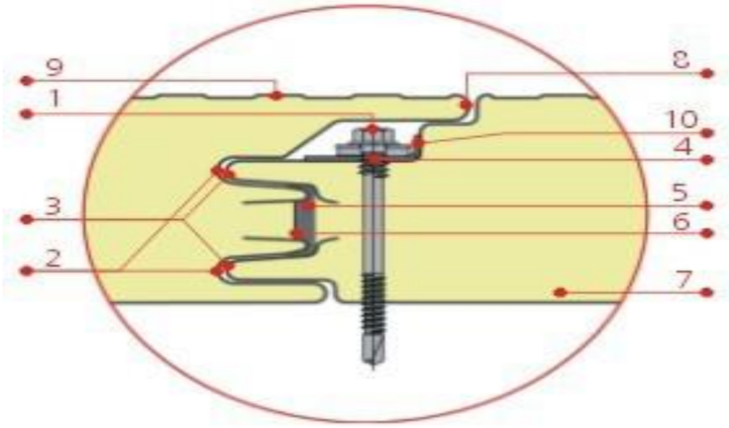


Figure 2.1.3.2 Example of wall panel with invisible joint (GMFRS Service Order)[29]

1) Invisible fastened joints guaranteed an aesthetic elevation.

2) Unique, same shape both-sides of the panel's joint – fastener, enhancing fire resistance and facilitating the assembly.

3) Conical inclination of interior joint' surface of panel facilitating the assembly.

4) Sheer rabbet facilitating the positioning of fastening joints.

5) Continuous polyurethane seal made of non-flammable material with aluminum foil introduced into production process, preventing the infiltration of steam and retaining high heat insulation.

6) Aluminum foil preventing the infiltration of steam and gas diffusion to retain the heat conduction factor.

7) Stiff polyurethane foam core technology with the lowest heat conduction factor of thermo - insulated materials.

8) Special shape of facings as a guarantee of the high durability of stainless coating.

9) Wide range of external coatings profiles fulfilling high architectural requirements.

10) Steel LB pad in the zip enhancing joint resistance.

2.1.3.3 Joint used for cold store facility

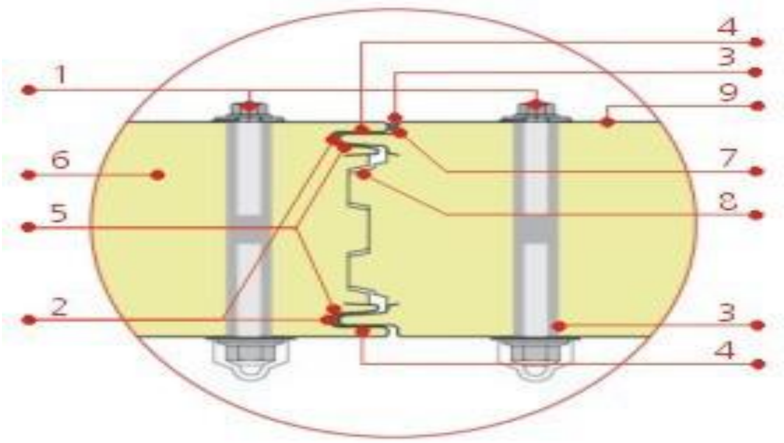


Figure 2.1.3.3 Example of joint used for cold storage facility (GMFRS Order)[29]

1) Special panel assembly system eliminating the spot – thermal Sternum.

2) Sealing mass in the lock preventing the infiltration of steam and retaining high heat insulation.

3) Permanently flexible sealing mass.

4) Unique same shape both-sides of panel - fastener joint enhancing fire integrity and facilitating the assembly.

5) Conical inclination of interior joint surface of panel facilitating the assembly.

6) Stiff polyurethane foam core produced using environmentally friendly and ozone layer technology with the lowest heat conduction factor of thermo - insulated materials.

7) Suitably shaped facings as a guarantee of the high durability of stainless coating.

8) Mill joint of core abandoning a linear thermal sternum.

9) Wide range of external coatings profiles meeting high architectural requirements.

2.1.3.4 Panel to panel joints – external

Complex joints such as those used for the external envelope are fully engineered joints that are designed to be weather tight and to prevent air leakage. Their robust interlocking nature combined with secure fixing to the building framework simultaneously gives better protection of the core from direct flame attack

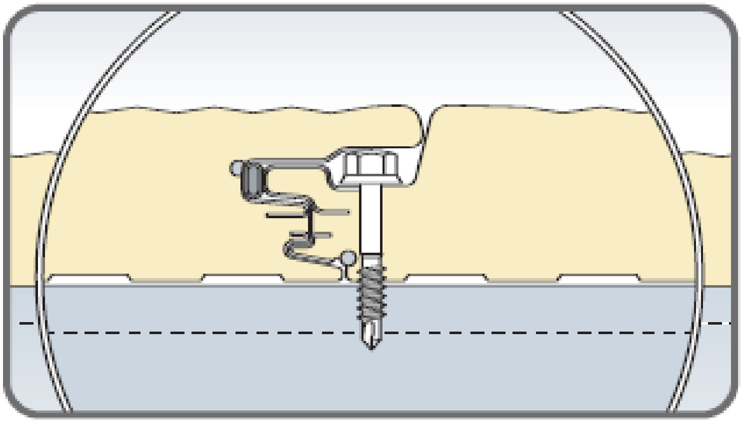


Figure 2.1.3.4 Example of secret fix joint (GMFRS Service Order)[29]

2.1.3.5 Panel to panel joints – internal

These types of panels do not have to withstand wind forces and other loads therefore a simpler joint is employed. Tongue and groove arrangement are often used which aids the demount ability and relocation of panels. They are often used in freestanding form and given the simple nature and temporary nature the fixing arrangements are not as robust and therefore more prone to early collapse.

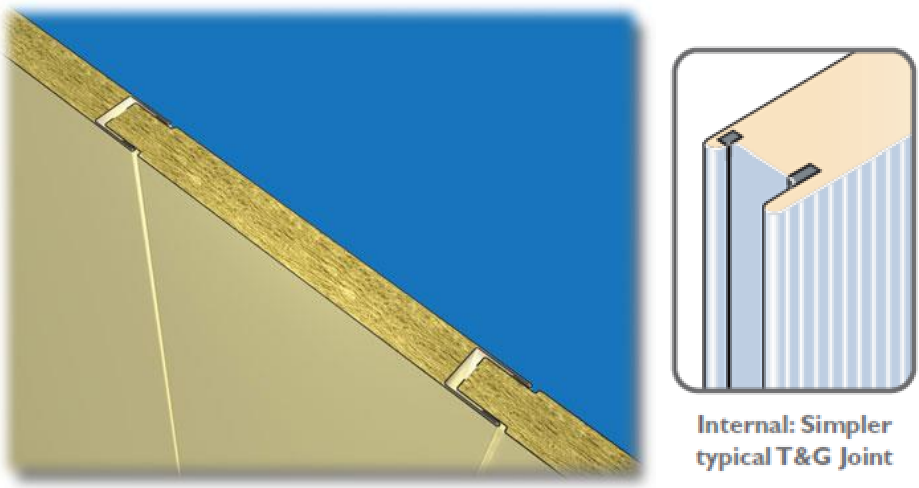


Figure 2.1.3.5 Tongue and grooved joints (GMFRS Service Order)[29]

2.1.3.6 Ceiling panel fitting

Ceiling panels are often supported by the wall panels and may have additional support of hangar systems connected to the external face of the panel or to a grid framework into which the panel is placed. As a fire develops and temperature rises the unrestrained facings

(Internal side) can buckle, delaminate and expose the core, once exposed, insulating material adds to fire loading and fire will escalate rapidly.

2.2 Fire hazards of sandwich panel construction and implication on fire fighting.

2.2.1 Introduction

Buildings constructed using insulated panels can present a major risk to operational crews when involved in fire. Insulated panels can contribute significantly to the fire loading of a building and their involvement may lead to catastrophic collapse of the structure with little or no warning. The following describes the main risks associated with sandwich panel construction involved in fire (Cooke, 2000)[9].

2.2.1.1 External/Internal Collapse of Insulated Panels

Insulated panels used externally do not form part of the structure and the cores consist of insulation materials which would be unlikely to be the principal cause of collapse. External panels are fitted to the external structure of the building are designed to withstand static forces and imposed loads from environmental conditions (e.g. wind).

2.2.1.2 Delamination of Insulating Panels

Delamination of a sandwich panel refers to the metal facing peeling or falling away and exposing the core material. Delamination is caused by heat exposure affecting the bonding adhesive, either through conductive heat being transmitted through the facings and the core or by direct exposure due to damaged panels.

The process of delamination can occur at temperatures as low as 270°C, leading to large metal sheets falling in the risk area, exposing the combustible core and increasing the fire load and fire development.

2.2.1.3 Rapid Fire Spread

Fires may reach temperatures in excess of 900°C within minutes. Every insulation core will have a level of fire resistance but once past its resistance levels the core material will be a contributing element to the fire load. A further risk may occur when fire spreads into the core and may go undetected in voids and concealed spaces. Aside from mineral fibre, all other insulating core materials will have a level of flammability, but the core with the greatest risk is polystyrene.

2.2.1.4 Large Volumes of Dense Smoke

Due to the elements within each core material, any exposure to fire and ignition will produce hot flammable products of combustion and dense black smoke that, if not cooled or ventilated, could lead to flashover at approximately 500°C.

Figure 2.2.1.4 Fire involving sandwich panels (Northamptonshire FRS (2011)) [31]

2.2.1.5 Undetected Fire Spread

Undetected fire spread in a panel's core can occur; this could then result in rapid fire-spread and potentially isolating personnel by cutting off exit routes. A further risk is generated when panels connected to each other side by side may have exposed core material on its edges. This will then enable fire to spread from one panel to another undetected.

2.2.1.6 Contribution to Fire Loading

It has been shown in both large and small scale tests that fire severity (expressed as an equivalent amount of fire exposure) can be directly related to the fire load. The fire load can be defined as the sum of the calorific energies that can be released when the combustible materials are subject to complete combustion.

The series of tables below have been replicated from (Davies, 2001)(10) and describe the contribution that sandwich panels make towards total fire loading in a building.

Occupancies	**Fire load density MJ/m² of floor area**	**Fire load density MJ/m² of floor area**
	Average	80% Fractile
Dwelling	780	870
Hospital	230	350
Hospital Storage	2000	3000
Hotel Bedroom	310	400
Offices	420	570
Shops	600	900
Manufacturing	300	470
Manufacture and Storage	1180	1800
Libraries	1500	2250
Schools	285	360

Table 2.2.1.6 Typical Fire Load Densities for occupancies

Core Material	**Density (Kg/m²)**
Polyurethane Foam	45
Expanded Polystyrene Foam	20
Extruded Polystyrene Foam	35
Stonewool	100

Table 2.2.1.6 (a) Density of various types of foam cores.

Core Material	Fire Load MJ/m² for thickness		
	50mm	**100mm**	**200mm**
Polyurethane Foam	**58.8**	**117**	**234**
Polystyrene Foam	**46**	**86**	**166**
Stonewool	**11**	**16**	**26**

Table 2.2.1.6 (b) Fire load for various thickness of foam core

The fire load density (FLD) can be derived from the following equation:
Fire load/ unity area = Calorific Value x Density x Thickness

A theoretical assessment was carried to determine the relationship between the typical fire load due to the occupancy type and that by various panel types and sizes.
To calculate the ratio of the fireload of panels to fireload of contents a ratio denoted by **R** is introduced in table 2.2.1.6(c) and some assumptions about the size and shape of the building is made (for example – a tall single storey shed of small plan area will have a larger **R** than a lower building of the same plan area because the area of the walls will be greater in the former.

Two fire load densities of contents were considered for this exercise, 300 MJ/m² was considered a low value from table 2.2.1.6 and 1000 MJ/m² was considered a high value. A comparison was made between the FLD of the panels and the contents and the results given in table 2.2.1.6(c) (Cooke, 1998)[8].

Building Geometry	Panel Thickness (mm)	Core Type	Total Panel Fire load x10-3 MJ	R(%) for low Fire load densities of 300MJ/m²	R(%) for high Fire load densities of 1000MJ/m²
H L W					
5 40 40	**50**	**PUR**	**1.404**	**29**	**9**
5 40 40	**50**	**EPS**	**1.104**	**23**	**7**
5 40 40	**50**	**SW**	**0.264**	**55**	**1.6**
10 40 40	**50**	**PUR**	**1.872**	**38**	**12**
10 40 40	**50**	**EPS**	**1.472**	**30**	**9**
10 40 40	**50**	**SW**	**0.352**	**7**	**2**
5 40 40	**200**	**PUR**	**5.616**	**117**	**35**
5 40 40	**200**	**EPS**	**3.98**	**83**	**25**
5 40 40	**200**	**SW**	**0.624**	**13**	**4**
10 40 40	**200**	**PUR**	**7.488**	**153**	**46**
10 40 40	**200**	**EPS**	**5.312**	**110**	**33**
10 40 40	**200**	**SW**	**0.831**	**17**	**5**

Table 2.2.1.6 (c) Total fire load for nominal building sizes

In conclusion, the calculation of the fire load due to panels with plastic cores needs to be carried out as part of the risk assessment for the building. Normal thickness panel cores (50mm) can be 30% and 9% of the low FLD and high FLD respectively. This is significant as in traditional buildings the fire load presented by the building is normally negligible as compared to the building contents. As has been shown above sandwich panel cores present a significant percentage of the total fire load. Following a number of high profile fires in buildings of sandwich panel construction Fire and Rescue Services have been directed to collect risk information on buildings within their respective areas. The risk rating of buildings in normally associated with building contents and processes; however the risk rating now extends to include building type.
Where the risk assessment of the building determines that the construction presents a high FLD then this would be factored into tactical fire fighting which may lead to defensive fire fighting only.

In environments using enhanced insulation the FLD can rise to 150% of the building contents.

The fire load presented by stone wool is regarded as negligible. In buildings of high fire load it is prudent to subdivide the building to reduce potential fire severity and fire loss. For panels of 200mm and greater, the fire load presented by the panels can easily exceed that of the contents.

2.2.1.7 Environmental Pollution

Due to the composite materials used within insulated panels the threat of environmental pollution is high. This pollution risk can be manifested in either airborne pollutants being released or water sources being affected by pollutants being carried in fire fighting water runoff. A balance would be made between the effect on the environment of smoke pollution as opposed to that caused as a result of contaminated fire fighting water entering the drains and water courses. It is easier to control fire fighting water run off rather than smoke pollution. Fire fighting water can be prevented from entering drains and other water courses by using dams and other barrier techniques as well as recirculating fire fighting water.

2.3 Guidelines available to Fire and Rescue Services

2.3.1 Building Regulations Guidance

The building regulations in England and Wales provide functional requirements in relation to building design.

A suite of documents called ‘Approved Documents’ are published and reviewed regularly to support the requirements of Schedule 1 to and Regulation 7 of the Building Regulations 2000 (SI 2000/2531). These documents offer practical guidance on how the functional requirements of the Building Regulations can be met and Approved Document B (CLG, 2000)[(7)] provides guidance on fire safety and particularly in relation to life safety within the built environment.

In the 2000 edition and subsequent revisions of Approved Document B Appendix F (CLG, 2000)[(7)] provides guidance on the ‘Fire behaviour of insulating core panels used for internal structures’ and in particular the following areas:

- fire behaviour of the core materials and fixing systems
- fire fighting
- design recommendations
- specifying panel core materials
- specifying materials/fixing and jointing systems.

This document (Secretery of State, 2006)[26] recognises the risks associated when panel cores of polystyrene or polyurethane foam pose a unique combination of problems for fire-fighters namely:

- Hidden fire spread within the panels.
- Production of large quantities of black toxic smoke.
- Rapid fire spread leading to flashover.
- Hidden fire behind lining systems.

This report also highlights and recognises the stability problems associated with panels systems of this type, delamination of the facing materials and potential for total collapse when fire spreads undetected behind the system irrespective of type of core material.
In addition to the concerns highlighted above the report states:

'*This can prove to be a particular problem to fire-fighters as, due to the insulating properties of the cores, it may not be possible to track the spread of fire, even using infra-red detection equipment. This difficulty, together with that of controlling the fire spread within and behind the panels, is likely to have a detrimental effect on the performance of the fixing systems, potentially leading to their complete and unexpected collapse, together with any associated equipment.*'

Appendix F provides awareness of the issues but does not offer any solutions. Instead it refers the reader to a document produced by the International Association of Cold Storage Contractors (European Division) entitled *Design, construction, specification and fire management of insulated envelopes for temperature controlled environments. Association of Cold Storage Contractors (European Division) entitled Design, construction, specification and fire management of insulated envelopes for temperature controlled environments.* This document discusses good practice in relation to construction and fire management of insulated envelopes. One of the recommendations in the document is in relation to a voluntary scheme for labelling and marking of panels which is discussed in section 2.3.2.2.1.

2.3.2 Identification of sandwich panels

There are two distinct categories of panel that could be encountered by fire-fighters. An authentic insulated sandwich panel is one which is factory made and delivered to site ready for fixing. Alternatively a system that is assembled on site, visually similar but displaying different characteristic exist in older buildings.

2.3.2.1 Site assembled cladding system

Metal clad industrial buildings built prior to 1980 were mainly constructed using this method for external roofs and walls. The external weather sheets are heavily profiled and insulated with mineral felt material which generally offers good levels of fire resistance. Lining systems usually comprise of plasterboard in ‘T’ bar configuration or occasionally a flat faced metal lining sheet.

Due to the fixing methods delamination is unlikely as is unseen fire spread due to the fire resisting qualities of the insulating material. If the external facing is a regular deep profile typically 35-40 mm, it is most likely to be a site assembled system with a glass or mineral fibre quilt insulation.

A hollow sound when tapping the crown of the profile should indicate this type of system. This type of system is found on roofs, and walls of older buildings. Roof systems where the external sheet has a narrow raised rolled seam at the joints is most likely to be a site assembled

2.3.2.2 Insulated Sandwich Panels

2.3.2.2.1 Identification labels for core materials used in insulation panels

The International Association for Cold Storage Construction (IACSC) developed a voluntary for marking and labelling scheme to enable fire-fighters to gain immediate information on the type of insulated panels used in the premises. The labelling system was driven from Fire and Rescue Services to provide additional information that could be used in pre-planning for firefighting in cold storage facilities. (International Association For Cold Storage (IACSC), 2003)[(19)].

The labelling system evolved in response to a request from the Fire Service for there to be greater information available in respect of insulated panels used in the construction of buildings. Even though the guidance is voluntary it is recognised with Approved Document B, a supporting document of the Building Regulations. The main component of the labelling system is designed around providing labelling at doorways and walls into areas into which fire-fighters may need to enter to extinguish a fire.

The labels give information of the fire performance of the panels enclosing the space to be entered with a choice of firefighting options for consideration by the Incident Commander. The labels are in A5 format and attached to the relevant walls to give information on the wall panels and attached to the door to give information on the ceiling panels.

A secondary enhancement to the labelling scheme is an enhanced fire plan of the building which clearly identifies the materials from which the panels are constructed and other fire safety information that may be relevant. The A3 plan in mounted adjacent to the fire control panel and is portable so that it can be positioned in the most appropriate place on the incident ground.

Key information regarding the type of core material is displayed as large lettering on the label. As an example, the lettering 'EPS' designates that expanded polystyrene is used. The main information displayed in a code letter clearly identifying the core material as follows below:

Symbol	Core Material
Pu	Polyurethane
pIr	Polyisocyanurate
PH	Phenolic
EPS	Expanded Polystyrene
XPS	Extruded Polystyrene
MRF	Mineral rock fibre
MGF	Mineral glass fibre
FG	Foamed glass
COM	Composite (calcium silicate)
B	Block work (faced with metal lining)

Table 2.3.2.2.1 Designation of sandwich panel core materials

In addition to the core material the label carries additional information in respect of fire stability of the insulated panels. Compliance with the fire stability criteria is identified by a green and white striped flash to the left hand side of the main core code letters.

If the panel has fire resistance **in addition** to the fire stability criteria is that it complies with BS476 part 22 or LPS 1208 (LPCB, 2005)[(21)] then the striped flash is replaced by a solid green flash. If the panels comply with LPS 1181 (LPCB, 2005)[(22)] then this is indicated by a solid red flash on the right hand side of the code which states 1181.

In order to provide additional safety to fire-fighters the scheme promotes the construction of 'fire stable structures'. Fire stability can be achieved if the construction methods make the construction stable. LPS 1181 do not ensure stability and additional fixings may be required to achieve the LPC accreditation (International Association For Cold Storage Construction (IACSC), 2003)[19]

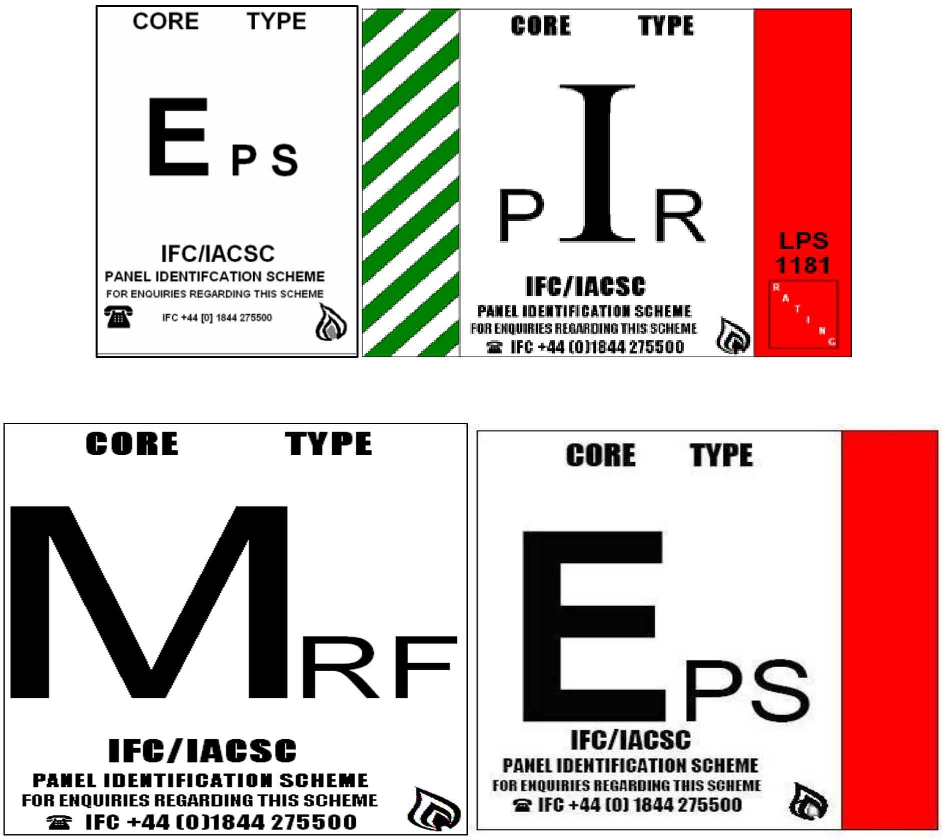


Figure 2.3.2.2.1 Examples of markings under the scheme (Courtesy of IACSC)[19]

2.3.3 Guidance on fire fighting in sandwich panel construction buildings.

2.3.3.1 Traditional guidance provided by UK Fire and Rescue Services

Guidance documents and publications have been reviewed to determine the extent that the risks and hazards of firefighting operations within buildings of sandwich panel construction have been identified. This has included both centrally produced guidance and also bespoke arrangements developed by individual Fire and Rescue Services.

The literature reviewed generally identifies the risk and hazards associated with fires of this nature and adopt a consistent generic advice and direction. However there are some minor variations adopted by individual Fire and Rescue Services to their own standard operation procedures (SOPs).

Traditional guidance supplied by the UK Fire and Rescue Services in 1970 describes risk and hazards associated with fighting fires in refrigerated plant and cold store facilities. The guidance concentrates on the risk of the refrigerated gases rather than that posed by the insulated cores.

Given that the guidance was written in 1970 the majority of these facilities used granulated or pressed cork to insulate the boundary but does give some acknowledgement to the possibility of hidden fire spread and difficulty of access due to limited ventilation.

There is recommendations within the guidance on extinguishment techniques but the only advice on determination of compartment conditions or assessment of fire spread within the core is by 'cutting away' of the affected panels (Home Office (Fire Department), 1970)(15). Although there are significant differences between burning cork and modern insulated cores the fundamental risks and hazards associated with dealing with fires within these types of buildings are the same.

Updated centrally produced guidance in 1992 introduces modern methods of construction and within that external cladding systems with polyisocyncyanurate or polyurethane foam insulated cores (Home Office (Fire Department), 1992)(16). However there is no guidance on firefighting or assessing fire conditions or degree of fire spread within the core and refers the reader to the previous 1970 guidance described in the previous paragraph.

A further revision was published (HM Fire Service Publications Section, 2001)(14) which mirrors the previous 1992 guidance with the exception that it provides a more detailed description of the properties of plastics and their derivatives. Again there is limited discussion on hazards and risks associated with fire fighting in sandwich panel construction and no advice or guidance in relation to firefighting techniques or determination of compartment conditions.

2.3.3.2 Contemporary guidance provided to Fire and Rescue Services

A Generic Risk Assessment (GRA) document was produced for Fire and Rescue Services in 2011 to examine the hazards, risks and control measures relating to Fire and Rescue Service personnel when fighting fires within the built environment. It assesses the issues which may be present from the building structure itself, to the contents and the tasks undertaken by fire fighting crews. However as this only addresses the generic risks and hazards there is still a requirement for Fire and Rescue Services to conduct their own assessments and produce their own safe systems of work including Standard Operating

Procedures (SOPs), training programmes, provision of equipment, appropriate levels of response.

The general risk and hazards associated with sandwich panels are identified as well as pollution risks and highlights that fuel in the panels will contribute to the fire development, and the fire can spread quickly and unseen, both within the panels and within the voids behind and above the panels.

In addition, the nature of the panels themselves, which are intended to provide a watertight surface for hygiene purposes, makes it extremely difficult for fire-fighters to get fire fighting water onto such fires.

There is recognition that it is difficult to identify the core material once the panels are in place and some difficulty in identifying the different types of panel once they are in place and the core hidden and recommends the use of a labelling scheme as a benefit to both building owners and the Fire and Rescue Services.

The document provides an assessment of what the risk are, who is at risk and some control measures but there is no guidance of assessing the extent of the fire conditions within a compartment or the extent of fire spread (CLG Fire and Rescue Adviser, 2011)[(6)].

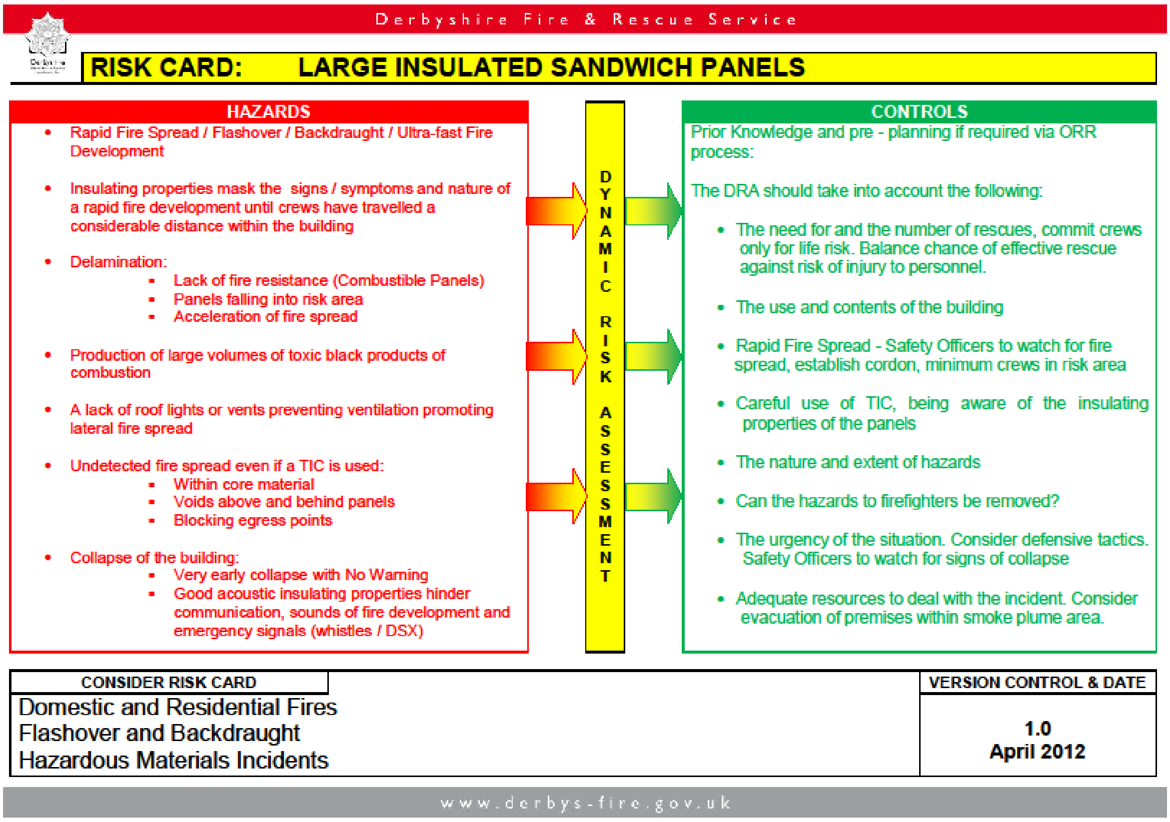
2.3.3.3 Fire and Rescue Service Standard Operating Procedures (SOPs)

The 46 Fire and Rescue Services in England and Wales are required to develop generic risk assessments provided centrally and develop SOPs which are pertinent and relevant to their own geographical areas.

Although much of the literature reviewed from the various Fire and Rescue Services is broadly similar in content there are a number of differences in approach and guidance highlighted below.

2.3.3.3.1 Derbyshire Fire and Rescue Service

Derbyshire Fire and Rescue Service provide an aide memoire for their Fire Officers as shown in Figure 2.3.3.3.1. They advise that a thermal image camera (TIC) could be utilised to detect fire spread within the core material, above or behind panels. However there is acknowledgement that this may not give a reliable indication due to the insulating properties of sandwich panels (Derbyshire FRS Service Order, 2010)[28].



Derbyshire Fire & Rescue Service

RISK CARD: LARGE INSULATED SANDWICH PANELS

HAZARDS

- Rapid Fire Spread / Flashover / Backdraught / Ultra-fast Fire Development
- Insulating properties mask the signs / symptoms and nature of a rapid fire development until crews have travelled a considerable distance within the building
- Delamination:
  - Lack of fire resistance (Combustible Panels)
  - Panels falling into risk area
  - Acceleration of fire spread
- Production of large volumes of toxic black products of combustion
- A lack of roof lights or vents preventing ventilation promoting lateral fire spread
- Undetected fire spread even if a TIC is used:
  - Within core material
  - Voids above and behind panels
  - Blocking egress points
- Collapse of the building:
  - Very early collapse with No Warning
  - Good acoustic insulating properties hinder communication, sounds of fire development and emergency signals (whistles / DSX)

DYNAMIC RISK ASSESSMENT

CONTROLS

Prior Knowledge and pre - planning if required via ORR process:

The DRA should take into account the following:

- The need for and the number of rescues, commit crews only for life risk. Balance chance of effective rescue against risk of injury to personnel.
- The use and contents of the building
- Rapid Fire Spread - Safety Officers to watch for fire spread, establish cordon, minimum crews in risk area
- Careful use of TIC, being aware of the insulating properties of the panels
- The nature and extent of hazards
- Can the hazards to firefighters be removed?
- The urgency of the situation. Consider defensive tactics. Safety Officers to watch for signs of collapse
- Adequate resources to deal with the incident. Consider evacuation of premises within smoke plume area.

CONSIDER RISK CARD	VERSION CONTROL & DATE
Domestic and Residential Fires Flashover and Backdraught Hazardous Materials Incidents	1.0 April 2012

www.derbys-fire.gov.uk

Figure 2.3.3.3.1 Risk information card (Courtesy of Derbyshire FRS (2010)[28]

2.3.3.3.2 Gloustershire Fire and Rescue Service

They provide guidance on identification of identifying site assembled cladding systems as opposed to ‘authentic sandwich panel’ which are factory made and delivered to site ready for fixing stated below (Gloustershire Fire and Rescue Service Order, 2012)[12].

If the external facing is a regular deep profile typically 35-40 mm, it is most likely to be a site assembled system with a glass or mineral fibre quilt insulation. A hollow sound when tapping the crown of the profile should indicate this type of system. This type of system is found on roofs, and walls of older buildings.

If the external face has an irregular profile with longer distance between crowns then the cladding is most likely to be an Insulated Panel. These panels are found on both roofs and walls of buildings. Roof systems where the external sheet has a narrow raised rolled seam at the joints is most likely to be a site assembled

Wall claddings that run vertically from ground which have a micro-rib or flat profile will be an Insulated Panel System. Similarly cladding running in a horizontal format between columns will be Insulated Panels.

Wall cladding systems that are a multiplicity of small panels i.e. 2.5 x 1.2 m tightly supported in a support frame or grid are likely to be panels. Buildings post 1995 building owner will have copies of construction design health and safety file – details type of panel. Check longitudinal edge of the panel, if accessible – some manufactures use a printed identification tape

In addition to the normal precautions and practices adopted when fighting a fire within the built environment this guidance recommends that Safety Officers are appointed with the sole remit of watching for fire spread and collapse by using thermal imaging technology. However there is no caution about the insulating properties of sandwich panels and that a negative result given by thermal imaging technology may be misleading.

2.3.3.3.3 Warwickshire Fire and Rescue Service

Warwickshire FRS guidance acknowledges that the insulating panels may also protect the structure of the building for some time; preventing rapid collapse and that signs of a developing fire inside the building may not be obvious to personnel outside of the building, even if a thermal image camera is used. The highly insulated fire resistant properties of these panels may mask the rapidly developing nature of a fire until crews have travelled a considerable distance inside the building, or until the fire has become very well developed.

Signs and symptoms of fire phenomenon that would normally trigger crews to consider withdrawal may not be evident if a fire is growing within a very large compartment. The insulating properties of these panels may make the use of thermal imaging cameras ineffective for identifying fire location or fire spread inside the building (Warwickshire FRS Service Order, 2011)[(34)].

Warwickshire FRS published a second guidance note to supplement the initial guidance. The note advises on the issues of sudden and rapid fire development when plastic products are involved and gives examples of ultra-fast fire development reaching 7MW within 3 minutes and continuing to increase at an ever increasing rate after that. The graph below supplements the guidance note.

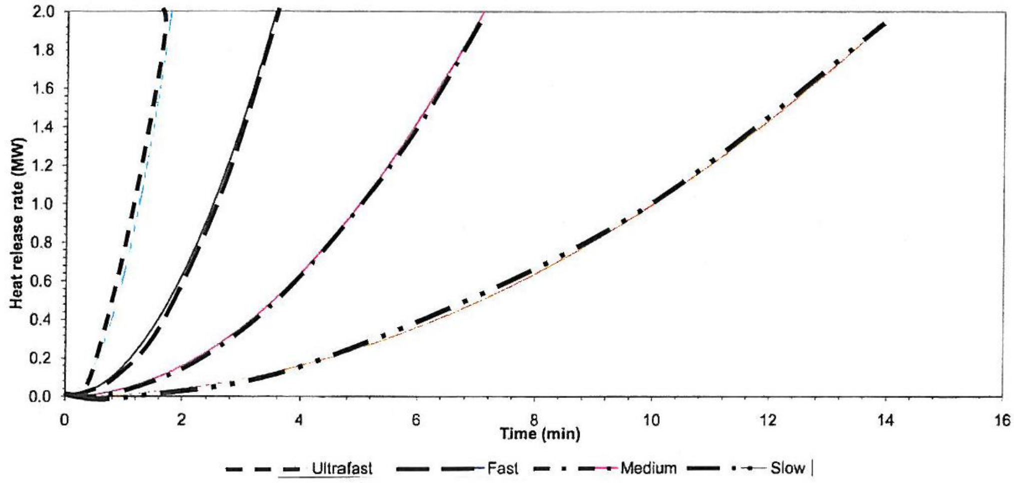


Figure 2.3.3.3.3 HRR for variety of fire growth. (Warwickshire FRS Bulletin)[35]

The document also makes that point that it is extremely likely that a fire will start on a slow fire growth because relatively low energy fuels are involved and then encounter an ultra-fast growth curve as higher energy fuels are met. The hazards to building occupants and fire-fighters arising from this may be increased with extended travel distances, high levels of insulation and limited ventilation.

2.3.3.3.4 Royal Berkshire Fire and Rescue Service

Royal Berkshire Fire and Rescue Service recommend a minimum of three man breathing apparatus and all teams will be equipped with a thermal imaging camera (Royal Berkshire FRS Service Order, 2005)[32]. The role of the third team member is to solely monitor conditions, especially above and behind the team for indicators of rapid fire spread and indicators of structural collapse. The TIC will generally be carried by the third BA team wearer but should not be regarded as a definitive indicator of safety in sandwich panel buildings but may assist.

2.3.3.3.5 Avon and Somerset Fire and Rescue Service

Avon and Somerset Fire and Rescue Service advise that thermal imaging cameras should be given a high priority but no direction is given into its use or caution in any results obtained. However consideration to ventilate the building including the removal of roof panels in recommended in order to slow the progression of the fire (Avon and Somerset Service Order, 2005)[27].

2.3.3.3.6 Nottingham Fire and Rescue Service

The thermal and acoustic insulation of sandwich panels may mask the signs and sounds of a developing fire, and make the use of thermal image cameras ineffective for identifying fire location or fire spread inside the building (Nottingham FRS Service Order, 2011)[31]

Different types of sandwich panel burn in different ways. Mineral fibre panels are non-combustible, and developments in the formulations of some types of modern core material will limit fire growth. However, the type of core will not be apparent; and where the structure of the building contributes to the fire spread, the fire may spread rapidly.

Signs and symptoms of fire phenomenon that would normally trigger crews to consider withdrawal may not be evident if a fire is growing within a very large compartment.
Because of their design sandwich panels can delaminate during a fire which will lead to the acceleration of the fire.

The fuel loading is disproportionate to the building; and the evolution of large quantities of hot smoke, hot fire gases can gather in the voids behind and above the panels. Once the buildings collapse the voids are open to a fresh source of air which can when mixed with the hot fire gases; explode as in a backdraught.

2.3.4 Summary of standard operating procedures

	Generic Risk Assessment (GRA)	Standard Operating Procedure (SOP)	Variation from GRA	Summary of variation
Avon Fire and Rescue Service	Yes	Yes	Yes	Advises on removal of roof panels to limit progress of fire.
Bedfordshire & Luton Fire and Rescue Service	Yes	Yes	No	N/A
Buckinghamshire Fire & Rescue Service	Yes	Yes	No	N/A
Cambridgeshire Fire & Rescue Service	Yes	Yes	No	N/A
Cheshire Fire & Rescue Service	Yes	Yes	No	N/A
Cleveland Fire & Rescue	Yes	Yes	No	N/A
Cornwall County Fire Brigade	Yes	Yes	No	N/A
Cumbria Fire & Rescue Service	Yes	Yes	No	N/A
Derbyshire Fire & Rescue Service	Yes	Yes	Yes	Provision of a risk card aide memoir for Incident Commanders
Devon and Somerset Fire & Rescue Service	Yes	Yes	No	N/A
Dorset Fire and Rescue Service	Yes	Yes	No	N/A
Durham and Darlington Fire & Rescue Service Headquarters	Yes	Yes	No	N/A
East Sussex Fire & Rescue Service	Yes	Yes	No	N/A
Essex County Fire & Rescue Service	Yes	Yes	No	N/A
Gloucestershire Fire & Rescue Service	Yes	Yes	Yes	Recommend the provision of Safety Officers with sole responsibility for observing the building structure.
Greater Manchester Fire &	Yes	Yes	No	N/A

Rescue Service				
Hampshire Fire & Rescue	Yes	Yes	No	N/A
Hereford & Worcester Fire & Rescue Service	Yes	Yes	No	N/A
Hertfordshire & Fire Rescue Service	Yes	Yes	No	N/A
Humberside Fire & Rescue Service	Yes	Yes	No	N/A
Kent Fire & Rescue Service	Yes	Yes	No	N/A
Lancashire Fire & Rescue Service	Yes	Yes	No	N/A
Leicestershire Fire & Rescue Service	Yes	Yes	No	N/A
Lincolnshire Fire and Rescue Service	Yes	Yes	No	N/A
London Fire Brigade Merseyside Fire & Rescue Service	Yes	Yes	No	N/A
Mid and West Wales Fire & Rescue Service	Yes	Yes	No	N/A
Norfolk Fire & Rescue Service	Yes	Yes	No	N/A
North Wales Fire and Rescue Service	Yes	Yes	No	N/A
North Yorkshire Fire & Rescue Service	Yes	Yes	No	N/A
Northamptonshire Fire & Rescue Service	Yes	Yes	No	N/A
Northern Ireland Fire & Rescue Service	Yes	Yes	No	N/A
Nottinghamshire Fire & Rescue Service	Yes	Yes	Yes	Advises on increased fire load due to building materials and options when considering firefighting tactics.

Oxfordshire Fire & Rescue Service	Yes	Yes	No	N/A
Royal Berkshire Fire & Rescue Service	Yes	Yes	Yes	N/A
Scottish Fire and Rescue Service	Yes	Yes	No	N/A
Shropshire Fire & Rescue Service	Yes	Yes	No	N/A
South Wales Fire & Rescue Service	Yes	Yes	No	N/A
Staffordshire Fire & Rescue Service	Yes	Yes	No	N/A
Suffolk Fire & Rescue Service	Yes	Yes	No	N/A
Surrey Fire & Rescue Service	Yes	Yes	No	N/A
Tyne and Wear Fire & Rescue Service	Yes	Yes	No	N/A
Warwickshire Fire & Rescue Service	Yes	Yes	Yes	Advises of the limitations of thermal imaging camera and provision of aide memoir on heat release rates (HRR).
West Midlands Fire & Rescue Service	Yes	Yes	No	N/A
West Sussex Fire & Rescue Service	Yes	Yes	No	N/A
West Yorkshire Fire & Rescue Service	Yes	Yes	No	N/A
Wiltshire Fire & Rescue Service	Yes	Yes	No	N/A

Table 2.3.4 Summary of UK Fire and Rescue SOPs

Table 2.3.4 provides a summary of the guidance that has been developed by different Fire and Rescue Services within the UK. It is evident that all use the centrally prescribed Generic Risk Assessment as a base line to develop their own SOPs. The SOPs are generally standardised with only a few that have provided additional guidance or adapted procedures accordingly. The differences have been described in section 2.3.3.3.

2.4 Fire behaviour and sandwich response and their fire signature

Effective fire fighting in sandwich panel construction requires an understanding of sandwich panel fire performance and methods of onsite assessment. This section will provide a review.

Fire fighting within compartments provides a challenging environment and some of the most important considerations for fire-fighters are whether the internal compartment will reach flashover conditions presenting serious safety concerns to those inside. In addition concealed burning may impact on the stability and integrity of the compartment and posing a threat of fire spread beyond that compartment.

During fire fighting operations it would be difficult to determine which particular test regimes panels have satisfied. However an understanding of the test performance criteria that would need to be satisfied and an awareness of general on site assessment of the panel condition and installation standards may allow fire-fighters to make a judgement on whether flashover conditions are likely to occur or the effect on the stability or integrity of the compartment.

2.4.1 Fire Response Tests for Insulated Panels

These tests establish the response of the building elements to certain pre-set objectives. They may form part of a building specification to achieve a certain performance to satisfy the requirements of the insurance industry or to provide additional protection to assist in fire fighting.

2.4.1.1 Loss Prevention Council (LPC) LPS 1181test

One of the test methods developed by the Loss Prevention Council (LPC) is LPS 1181 (LPCB, 2005)[21] and was designed to identify those buildings where elements could increase fire severity and therefore result in greater losses in the event of fire. The test uses a small fire source of either a timber crib or fluid bed gas burner.

The source is placed in the corner of an open fronted type structure 10m long, 3m high and 4.5m wide and produces a maximum heat output of 1MW at about 4 minutes. Where a standard thermal exposure is required a timber crib is constructed from 70 No lengths of Type V Redwood/ Scots Pine with nominal dimensions of 50mm x 25mm x 750mm

Following the tests the extent of the damage both internally and externally is measured and recorded. All internal faces are removed and the damage to the insulation and the depth of the char measured and recorded.

The performance is assessed against 7 criteria as follows:

1. Flashover: There shall be no flashover at the ceiling and will have deemed to have occurred if the average temperature of the hot layer below the ceiling exceeds 600°C at any time throughout the test.
2. Internal Surface Flaming: There shall be no sustained flaming beyond 1.5m from the perimeter of the crib in both horizontal directions. There shall be no sustained flaming through any joints on any of the walls or ceiling outside of the burn area of the crib.
3. External Surface Flaming: There shall be no flame spread at any location on the external surface of the test building. No flame / fire penetration to the exterior from any of the joints.
4. Concealed Burning: Determined in the post test survey and judged on the extent of the damage.
5. Burning Brands: There shall be no fall of burning brands from the ceiling outside the vicinity of the crib area.
6. Damage: No part of the insulation shall be completely destroyed so that a the external skin could be completely exposed to heat transfer from the fire unless the total aggregate area is not more than $0.5m^2$.
7. Stability: This will be achieved if no part of the test building collapses for the duration of the test. Failure will be deemed to have occurred where deformation exceeding 1/30 of the distance between the ceiling support centres. Delamination is not judged within this criterion.

2.4.1.2 Loss Prevention Council (LPC) LPS 1208 test

LPS1208 Fire resistance requirements for elements of construction used to provide compartmentation is a two stage test method for evaluating cladding and panel systems that do not contribute to the severity of a fire (LPCB, 2005)[21].

To satisfy this standard the panel must achieve a Grade A rating to the LPS 1181 method and achieve a designated fire resistance rating in respect of integrity and insulation against the BS476: Part22 test.

2.4.1.3 Association for Cold Storage Construction (IACSC) FST1 test

The International Association for Cold Storage Construction (IACSC) FST1 test was developed following concerns expressed by the UK Fire and Rescue Service to develop panels that are inherently more stable in fire and reduce disproportionate damage to the facility. This test uses a centrally positioned timber crib with an approximate heat output of 1.1 MW which maintains steady for an excess of 25 minutes.

The chamber is 8m in length, 3m high and 3.6m wide. The test is deemed to have failed if the ceiling or any of the vertical walls deflect by more than pre-determined criteria or if the chamber suffers is breached by fire. The result of the test determines panels and systems to be 'fire stable' or not.

2.4.1.4 Factory Mutual (FM) FM 4880 corner wall test

Factory Mutual (FM) has developed their own tests to establish the hazards to establish the hazards represented by sandwich panels. The FM 4880 (Corner Wall Test) is similar in objectives to the LPS 1181 but is considerably larger and open on two sides of the test facility. The length of the largest wall is 15.2 m and the shortest 11.5m with a height of 7.6m (FactoryMutual, 2010) [(23)]

The heat source is a larger timber crib, 1.5m in high and the rig can incorporate a sprinkler system to control the fire development, making it a condition of approval. Both the FM 4880 and IASCS Fire Stability Tests are used for sandwich panel construction where the systems are to be used in the vertical and horizontal geometry forming an insulated envelope.

2.4.2 Reaction to Fire Tests

Reactions to fire tests are generally smaller scale tests designed to evaluate material properties rather than the behaviour of a building element for specific properties of the product.

2.4.2.1 The BS476: Part 6: 1989 Fire Propagation Test

The BS476: Part 6: 1989 Fire Propagation Test was developed to permit combustible materials to be used as linings to rooms providing that the contribution to the development of the fire was minimal. Materials are categorised by dimensionless values which relate to maximum values of fire propagation. Class ‘0’ is the lowest accepted level of flame spread that can be used in escape routes and circulation spaces and more comparable to a rate of heat release rate rather than a surface spread of flame test.

2.4.2.2 The BS476: Part 7:1997 Surface Spread of Flame Test

The BS476: Part 7:1997 Surface Spread of Flame Test was developed to establish the level of flame spread exhibited by a particular lining during the late stages of fire development. The test specimen under evaluation is positioned at right angles to a 1m x 1m radiant panel and a small pilot flame is applied to the lower corner of the specimen for 60 seconds. The flame spread characteristics are categorised and the material designated from class 1 to class 4 , with class 4 providing the highest risk.

2.5 Methods of assessing fire conditions in sandwich construction and their effectiveness

This section evaluates the methods available to UK Fire and Rescue Services to allow fire conditions within sandwich panel construction to be assessed. The primary method is by using thermal imaging technology but less used methods are also considered.

2.5.1 Thermal Imaging Technology

All objects emit infrared energy (heat) as a function of their temperature. The infrared energy emitted by an object is known as its *heat signature*. In general, the hotter an object is, the more radiation it emits. A thermal imager (also known as a thermal imaging camera) is essentially a heat sensor that is capable of detecting differences in temperature.

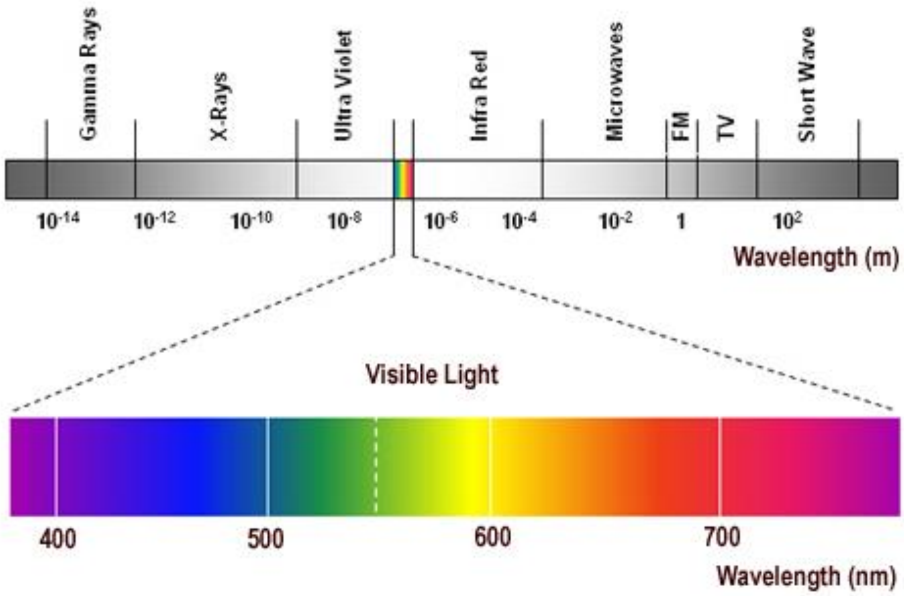


Figure 2.5.1 The electromagnetic spectrum

The device collects the infrared radiation from objects in the scene and creates an electronic image based on information about the temperature differences. Because objects are rarely precisely the same temperature as other objects around them, a thermal camera can detect them and they will appear as distinct in a thermal image.

There are many varieties and types of thermal imaging equipment used by UK Fire and Rescue Services. The hand held type shown in Figure 2.5.1(a) below is one of the most commonly used hand thermal scanning devices.

Figure 2.5.1(a) Example of hand held thermal imaging camera used in UK [30]

2.5.1.1 Limitations of Thermal Imaging Devices

Thermal imaging devices only display surface temperatures of solid objects and not fluids. These devices detect temperature based upon wavelength of the light emitted by the object (longer wavelength, colder). Infrared technology, therefore, does not show the temperature of objects that reflect light, (glass, shiny metal, light colour objects in direct sunlight) and in a two dimensional image only.

Another limitation includes a poor depth perception and therefore the user will have difficulty in determining how far objects are from thermal imaging camera. In addition, since materials at the same temperature show the same colour, the display may not depict many details normally viewable in visible light.

Thermal imaging technology will not penetrate glass or, however heated glass typically appears lighter in colour and some penetration may occur in a fog or mist. Depending upon the density steam may or may not be penetrated.

Figure 2.5.1.1 Thermal imaging camera in use during the tests.

2.5.2 Ultrasound Investigation equipment

Ultrasound is the most widely used technique for inspecting composite structures. There are a large variety of appropriate ultrasonic instruments available. Typically, ultrasound travels very well in composite laminated structures and it can detect anomalies quite easily.

In a manufacturing environment, large sandwich panels are inspected with through transmission methods in which a relatively high amplitude ultrasound beam travels through the part and a receiving transducer located on the other side measures attenuation of the signal. Results are typically presented as C-scan images. That technique is widely used and is very reliable. But it is impossible to use this technique in a maintenance environment as the required access from both sides of the aircraft structure is impossible.

The aircraft and marine industries utilise ultrasonic investigation equipment to determine condition of sandwich panel. This inspection technique can be used to determine failure including de-lamination and dry areas in the skin laminates and de-bonding between the skin and the core.

Large scale inspection of sandwich structures applied in the marine industry utilise special high damped broadband transducers in the frequency range from 0,1-2 MHz (Wulf, 2011)[36]

The method works in pulse-echo mode which means that once access to one side of the structure is required.

2.5.2.1 Limitations of ultrasound equipment

In sandwich structures the ultrasound is extremely attenuated due to the inhomogeneity and low density of the core structure. Therefore, the use of ultrasound for sandwich structures requires more specialized features in instruments.

That technique is widely used and is very reliable. But it is impossible to use this technique in a maintenance environment as the required access from both sides of the aircraft structure is impossible. Clearly in a dynamic and fast moving fire situation the use of this equipment would prove impractical.

2.5.3 Cutting-Extinguishing Watermist Systems (CEWS)

Cutting Extinguishing Watermist Systems (CEWS) technology is being trialled and utilised by Fire and Rescue Services throughout the UK. The system comprises of two separate functions. The first is an abrasive high pressure water stream which penetrates a compartment and the second is a separate device with a lance which applies a water mist into the compartment (Netherlands Institute for Safety, 2012)[25].

The fire compartment is accessed from outside by creating a hole of approximately 5 millimetre by applying an abrasive under high pressure (300 bar). Once the abrasive has cut through the wall material, a very fine water mist is released into the room. The water mist acts more or less like a gas, due to the very fine atomization and reduces the temperature within the compartment before fire-fighters are committed into the risk area.

The Ultra High Pressure Lance (UHPL) has the ability to pierce various surfaces including wood, metal and even stone cavity walls to deposit a fine water mist into a compartment fire, reducing the temperature inside from around 500 degrees to 85 degrees in just 20 seconds. Temperature probes can be inserted into the openings to gauge the internal compartment temperatures before fire-fighters are committed into the risk area.

Figure 2.5.3 CEWS equipment in use (GMFRS, 2012)[30].

Fire and Rescue Services have found that the speed at which cold cutting technology can be introduced is incomparable to traditional techniques. When considering traditional fire fighting techniques expose fire-fighters to extreme heat for up to 20 minutes to deal with similar types of incidents. The lance makes the environment much safer for fire-fighters entering a building and can also limit the water damage normally caused by traditional techniques.

Effecting an early entry into a building and cooling of fire gases reduces the need for firefighters to enter compartment fires. Fires can be better controlled from outside the compartment, improving Firefighter safety as the fire is combated from a safe position outside a building/construction avoiding the risk of injury due to intense heat radiation and/or explosion of fire gases.

Northamptonshire Fire and Rescue Service have been progressive in encouraging cold cutting technology in fire fighting and their spokesperson, (Emberson CM, 2011)[11] stated that:

By challenging the conventional ways of tackling property fires, on-going research and development has allowed NFRS to incorporate this new technology with advanced tactical ventilation techniques and a much greater use of thermal image technology by the Incident Commander.

From this position, a completely new ‘Cobra Extinguishing Concept’ has been developed producing numerous operational, economic and environmental benefits to NFRS and the communities within Northamptonshire. These include improved fire-fighter safety and enhanced operational response. The environmental impact resulting from fire incidents has also been substantially reduced in several areas, says the brigade.

The ability to have an earlier intervention using Cobra reduces property damage, minimising the economic impact to an individual, business or community and limits the quantities of fire gas emissions into the atmosphere. The reduced quantities of water used by the Cobra system ensure contaminated water runoff from an incident is also limited.

On 24 March 2011 Northamptonshire Fire and Rescue Service attended a fire in a high bay warehouse at Corby, Northamptonshire. It involved a significant fire in a high bay warehouse of sandwich panel construction with a high fire loading. Multiple high pressure lance units were deployed and 80% of the building and contents were saved. As part of the fire fighting tactics, five cold cutting units were deployed to maintain the integrity of the internal walls and contain the fire within the area of ignition.

2.5.3.1 Limitations of Cutting-Extinguishing Watermist Systems (CEWS)

The limitations of this type of system relate to the water mist function rather than the abrasive cutting function. Potential risks include rapid steam expansion will act to mix up the contents of the enclosure driving smoke and heat to the floor into locations that might be forming refuge for occupants.
In addition there is the added concern of the increased burn potential from low pressure steam as opposed to hot/ dry gases due to the latent heater of vaporisation / condensation of the water.

These systems are most effective when used in conjunction with other modern methods such as thermal imaging technology, positive pressure ventilation fans. This clearly leads to additional resource and training requirements. As this technology is relatively new not widely used By UK Fire and Rescue Services limited evidence exists into its practical effectiveness within the fire fighting sector.

2.5.4 Explosive Charges

The Swedish Fire Service has developed a technique to gain entry to a building to aid smoke ventilation of steel clad buildings using an explosive cutting technique. The system involves using a hollow frame into which is placed an explosive charge. The frame is normally attached to the roof to aid smoke ventilation within the building. The explosive charge is an EFR (explosive force projection) which can travel hundreds of metres (Shipp, 1999)[33].

2.5.4.1 Limitations of using explosive charges.

The use of explosives would provide challenges for Fire and Rescue Services in terms of storage and licensing arrangements as well as training of personnel. Activation of explosive charges would also impact upon persons within the risk area and operational procedures would need to be changed to reflect the use of explosive devices. In general terms cordons of 150m would need to be in place to mitigate any of the risk associated with detonation.

2.5.5 Robotic Technique

Robots developed for military use in disposal of explosives and other remote activities have been in operation for a number of years. This technology is now being extended to fire fighting. Figure 2.5.5 below (Blogspot, 2012)[3] is an example of robotic technology being trialled by UK Fire and Rescue Services.

A number of functions are being developed in collection of building information without committing fire-fighters. One of the key areas being developed is the use thermal imaging technology which would allow temperature profiles within the building to be communicated back to a central point to inform fire fighting decisions.

Figure 2.5.5 Example of robot technology in use (Courtesy of Blogspot)[3]

This approach to collection of temperature profiles is relevant when analysing fire spread within cavities, sandwich panels. This information can be utilised to inform fire fighting tactics and predict building collapse.

2.5.5.1 Limitations

Robotic techniques are the newest development in fire fighting activity and have not been fully tested. Clearly initial costs are a limiting factor and many Fire Services within the UK are testing and purchasing robotic facilities on a shared or regional basis.

Committing and manoeuvring a robot within a building is difficult as the operator will be remote from the building.

2.5.6 Other Techniques

Other more fundamental techniques are based upon establishing whether the panel is an insulated sandwich panel with combustible core or site assembled low product. If the panel can be tapped and determined as ‘hollow’, then this would indicate that this is a site assembled product with limited combustible core. Again if the edges of the panel can be revealed by peeling back, this would give the same confirmation of the inherent qualities of the panel.

2.5.7 Summary of different techniques

The review identifies different techniques available. It is clear that although some of the techniques would provide a theoretical solution they are not suitable for the rigours of fire fighting within the built environment. The most practical and commonly used technique is the use of thermal imaging cameras. Thermal imaging cameras have been used by UK Fire and Rescue Services for many years and have been easy to use. However more information is required to show how this data can be interpreted and used to help fire fighting decision making.

2.6 Originality and methodology of this project

The literature reviewed has revealed little research into the study of temperature profiles within sandwich panel structures exposed to fire and this is reflected in the generic guidance provided for UK Fire and Rescue Services. The guidance provided is often an alert to the risk and hazards to consider when fire fighting in buildings of this type rather than specific interpretation of the information available. The guidance often refers to the use of thermal imaging cameras to determine the temperature differences on sandwich panel surfaces which can then be used to assess extent of fire spread. However there was no evidence that linked temperature with likely phase of fire development.

One of the main tools used by most Fire and Rescue Services to determine fire spread within buildings is the thermal imaging camera (TIC). Much of the guidance provided advises that TICs should be used when fire fighting in sandwich panel construction buildings but no reference is made to how this information may be used to inform firefighting decisions.

This research seeks a solution to of how the temperature information measured by thermal imaging cameras can be analysed to provide reliable information that could be used to inform firefighting decision making. The fire tests will be carried out using a number of samples of sandwich panels of varying thicknesses and joint orientation. One face of the sandwich panel will be exposed to real fire conditions and the temperatures within the body of the panel and at the joint will be measured using thermocouples and thermal imaging cameras to determine the temperature profile throughout the duration of the fire.

In addition to the comprehensive review presented in this chapter, the main parts of this research are the fire tests and the analyses of the fire test data. The results of the analyses are then used to recommend firefighting guidance in sandwich panel construction, with particular reference on how to utilise thermal imaging camera data.

This methodology used in this research is the exposure of varying thicknesses and orientation of sandwich panels to real fire conditions. Temperature information is taken at different parts of the sandwich panel core and joint as well as at the unexposed face with thermal imaging camera. The results are then analysed and easy use guidance proposed that could assist firefighting decision making.

2.7 Summary

2.7.1 Introduction to sandwich panel construction.

Sandwich panels have been used extensively within the built environment and have taken over from site assembled systems from the 1980s onwards. The panels that contain polymeric cores are highly efficient insulators and are easy to install but cause significant problems when involved in fire. The panels are formed in large sheets with complex joint arrangements to ensure that the insulation qualities are maintained.

2.7.2 Fire hazards associated with sandwich panel construction and implication on fire fighting.

Buildings constructed with sandwich panels can present a significant risk to Fire-fighters when involved in fire. Due to the excellent insulation qualities of the polymeric foam cores, fire spread can be difficult to detect and delamination of the metal facings from the core can occur at temperatures as low as 270°C.

Once the sandwich panel core becomes involved rapid fire spread can occur through the panel, voids and concealed places. Prolonged exposure to fire conditions can result in catastrophic failure and collapse of the panels.

Due to the elements within the core material any exposure to fire will cause ignition of the core materials, increasing the temperatures of the compartment and producing large quantities of dense black smoke. All of these factors will adversely affect the tenability conditions within the compartment and pose an increased risk to Fire-fighters.

2.7.3 Guidelines available to Fire and Rescue Services.

There is no statutory guidance in the design and installation of sandwich panels within the built environment. The International Association for Cold Storage Construction (IACSC) have produced good practice guidance which includes a voluntary marking scheme for the cold storage sector to assist Fire-fighters identify panel core materials in buildings. This scheme is recommended in a supporting document to the Building Regulations, Approved Document B 2000[7].

Traditional guidance produced by the Home Office Fire Department in 1970[15] provides advice and guidance on tackling fires within insulated environments. However the insulation material at that time was typically compressed cork or other similar material which has significantly different properties to modern insulated cores.

Modern guidance produced for Fire and Rescue Services are published as Generic Risk Assessments (GRA) which highlights the risks, hazards and control measures in relation to fire fighting in buildings with sandwich panel construction. Based on the information within the GRA, Fire and Rescue Services will translate the guidance into a Standard Operating Procedure (SOP) which will be tailored to the specific requirements of that Fire and Rescue Service.

The majority of the SOPs reviewed are broadly similar in content and the literature review identifies those Fire and Rescue Services that have adapted or amended existing protocols.

CHAPTER 3: SANDWICH PANEL FIRE TESTING METHODOLOGY

3.1 Introduction and general description

3.1.1 Background

The literature review identified a number of tests methods common test methodologies that are adopted tests used to determine levels of and reaction to fire. The Loss Prevention Council (LPC) is LPS 1181 test uses either a timber crib or fluid bed gas burner to achieve 4MW at about 4 minutes. Where a standard thermal exposure is required the timber crib is constructed from 70 No lengths of Type V Redwood/ Scots Pine with nominal dimensions of 50mm x 25mm x 750mm.

LPS1208 Fire resistance requirements for elements of construction used to provide compartmentation is a two stage test method for evaluating cladding and panel systems that do not contribute to the severity of a fire. To satisfy this standard the panel must achieve a Grade A rating to the LPS 1181 method and achieve a designated fire resistance rating in respect of integrity and insulation against the BS476: Part22 test.

The International Association for Cold Storage Construction (IACSC) FST1 test was uses a centrally positioned timber crib with an approximate heat output of 1.1 MW which maintains steady for an excess of 25 minutes. Factory Mutual (FM) has developed their own tests to establish the hazards to establish the hazards represented by sandwich panels.

The Factory Mutual FM 4880 (Corner Wall Test) is similar in objectives to the LPS 1181 but uses a heat source of a timber crib 1.5m in height.

Many tests rely on the ISO 834 standardised test curve which can be achieved by precisely designed and regulated furnace conditions. However the temperature – time curve used in the standard fire resistance test and reaction to fire tests does not relate to any specific or realistic fire condition and is simply used to compare a product against the same replicated conditions.

3.1.2 Experimental Options

Consideration was given to the appropriate scale of testing that could be carried out. Although there is no definition of sample sizes in relation to small, medium and large scale testing the facilities available could have been adapted to test both small and medium scale samples.

Medium and large scale testing could have provided a more complete and realistic evaluation of other aspects of the performance of the panel sample under test. However medium and large scale testing is more expensive and the test facilities available are limited in terms of access and finances.

Given that this study focuses on the temperature profiles throughout a panel section and specifically at critical areas within and around the joint, bench scale testing was deemed to be the most appropriate scale of testing to carry out. Small scale testing is often used as a pre-cursor to medium and large scale testing where small scale tests have revealed a trait. As this study provides a unique analysis of temperature profiles as described above, small scale testing is appropriate and future work could include the use of larger sample sizes.

3.1.3 Small scale testing methodology

A detailed experimental programme was developed to conduct real fire testing on small sample of sandwich panels. The tests would be carried out on samples with the joints in the horizontal and vertical geometry. The chosen thicknesses were 95mm and 120mm and these are most commonly used in external wall applications. The 95mm thickness is the most commonly used and the 120mm product is the newest product type.

Test Number	Thickness (mm)	Joint orientation
1	95	Vertical
2	95	Vertical
3	95	Horizontal
4	95	Horizontal
5	120	Vertical
6	120	Vertical
7	120	Horizontal
8	120	Horizontal

Table 3.1.3 Summary of the test samples thickness and orientation

3.1.4 Fire Source Options

3.1.4.1 Crib fires (Regular Array of Sticks)

Crib fires are often used as the fire source when carrying out reaction to fire testing and reaction to fire tests. The cribs are set out in a regular three dimensional geometry with the length of the stick longer than its thickness. The sticks are placed in alternating rows with an air space separating the arrays horizontally. For a uniformly ignited crib it is observed that the burning rate is governed by one of the following below (National Fire Protection Association, 2002) [(2)].

1. The natural limit of the stick surfaces burning freely.
2. The maximum flow rate of air and combustion products through the air holes in the crib.
3. The maximum oxygen that can be supplied to the room.

3.1.4.2 Pallet fires

In concept wooden cribs and stacked pallets are similar. However the stack geometry is different in that cribs are constructed of regular arrays of sticks and pallets are made up from rectangular elements in a traditional configuration. It has been observed that similar to a wooden crib fire a constant plateau of burning can be seen if the stack size is reasonably high (National Fire Protection Association, 2002) [(2)].

There has been a good correlation observed between experimental data and developed equations over a good range of pallet heights. However the expression show an over prediction of burning rates when applied to short stacks (<0.5m).

3.1.5 Compartment Fire Development

Enclosure fires are often described in terms of temperature development within a compartment and divided into separate stages of development described below (Quintiere, Karlsson and, 2000)[(24)].

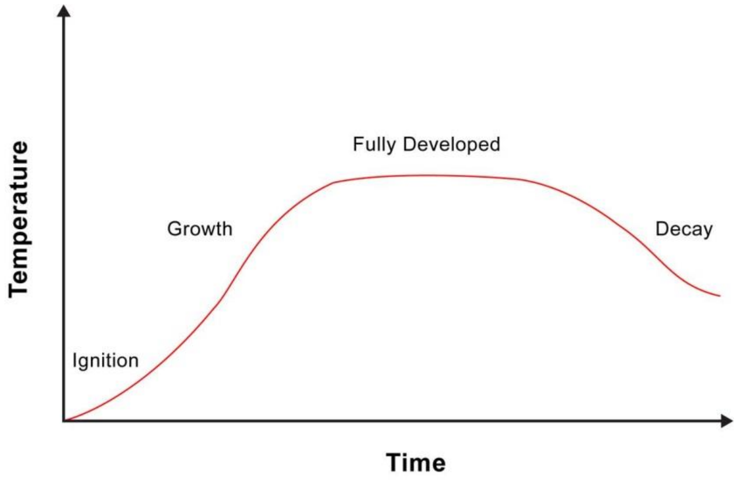


Figure 3.1.5 Fire development within compartment (Quintiere, 2000)[(24)]

3.1.5.1 Incipient Phase

Once combustion begins, development of an incipient fire is largely dependent on the characteristics and configuration of the fuel involved (fuel controlled fire). Air in the compartment provides adequate oxygen to continue fire development. During this initial phase of fire development, radiant heat warms adjacent fuel and continues the process of pyrolysis.

A plume of hot gases and flame rises from the fire and mixes with the cooler air within the room. This transfer of energy begins to increase the overall temperature in the room. As this plume reaches the ceiling, hot gases begin to spread horizontally across the ceiling. Transition beyond the incipient stage is difficult to define in precise terms. However, as flames near the ceiling, the layer of hot gases becomes more clearly defined and increases in volume, the fire has moved beyond its incipient phase and (given adequate oxygen) will continue to grow more quickly.

3.1.5.2 Growth Stage

If there is adequate oxygen within the compartment additional fuel will become involved and the heat release rate from the fire will increase. Gas temperatures within the compartment can be broadly defined as an upper hot layer extending down from the ceiling to a lower cooler layer down towards the floor. Convection resulting from plume and ceiling jet along with radiant heat from the fire and hot particulates in the smoke increases the temperature of the compartment linings and other items in the compartment.

As gases within the compartment are heated they expand and when confined by the compartment increase in pressure. Higher pressure in this layer causes it to push down within the compartment and out through openings. The pressure of the cool gas layer is lower, resulting in inward movement of air from outside the compartment. At the point where these two layers meet, as the hot gases exit through an opening, the pressure is neutral and referred to as the neutral plane.

The fire can continue to grow through flame spread or by ignition of other fuel within the compartment. As flames in the plume reach the ceiling they will bend and begin to extend horizontally referred to as ceiling jets. Pyrolysis products and flammable by-products of incomplete combustion in the hot gas layer will ignite and continue this horizontal extension across the ceiling. As the fire moves further into the growth stage, the dominant heat transfer mechanism within the fire compartment shifts from convection to radiation. Radiant heat transfer increases heat flux (transfer of thermal energy) at floor level.

3.1.5.3 Flashover

Flashover is the sudden transition from a growth stage to fully developed fire. When flashover occurs, there is a rapid transition to a state of total surface involvement of all combustible material within the compartment. Conditions for flashover are defined in a variety of different ways. In general, ceiling temperature in the compartment are in the order of 500°C - 600°C or the radiation to the floor of the compartment is 15 to 20 kW/m² (Quintiere, Karlsson and, 2000)[(24)].

When flashover occurs, burning gases will push out openings in the compartment with an increased velocity. Flashover will not always occur as there must be sufficient fuel and oxygen within the compartment and the item ignited must contain sufficient energy and release it at a quick enough rate for flashover to occur.

3.1.5.4 Fully Developed Stage

At this post-flashover stage, energy release is at its greatest, but is generally limited by ventilation. Unburned gases accumulate at the ceiling level and frequently burn as they leave the compartment, resulting in flames showing from doors or windows. The average gas temperature within a compartment during a fully developed fire ranges from 700°C – 1200°C

3.1.5.5 Decay Stage

A compartment fire may enter the decay stage as the available fuel is consumed or due to limited oxygen. As discussed in relation to flashover, a fuel package that does not contain sufficient energy or does not have a sufficient heat release rate to bring a compartment to flashover, will pass through each of the stages of fire development (but may not extend to other fuel packages). On a larger scale, without intervention an entire structure may reach full involvement and as fuel is consumed move into the decay stage.

However, there is another, more problematic way for the fire to move into the decay stage. When the ventilation profile of the compartment or building does not provide sufficient oxygen, the fire may move into the decay stage. Heat release rate decreases as oxygen concentration drops, however, temperature may continue to rise for some time. This presents a significant threat as the involved compartment(s) may contain a high concentration of hot, pyrolized fuel, and flammable gaseous products of combustion.

3.1.6 Factors influencing Fire development in an enclosure

There are a number of factors which affect fires within enclosures and can be categorised into those to do with the enclosure and those to do with the fuel. The type and amount of combustible material is one of the main factors but also the positioning of the fuel package.

Where fuel package in placed away from the walls then cool air is entrained from every direction whereas when placed against a wall or corner the amount of entrained air is reduced causing higher temperatures and increased flame height. The spacing and orientation of the fuel package is also important as the spacing determines how quickly the fire spreads within the fuel package. Upward flame spread on a vertical surface occurs more rapidly than lateral spread along a horizontal orientated surface (Quintiere, Karlsson and, 2000)[(24)].

3.1.7 Heat Release Rates

The rate at which energy is released in a fire depends mainly on the type, quantity and orientation of the fuel package. The energy release rate will vary with time as shown in the below graph.

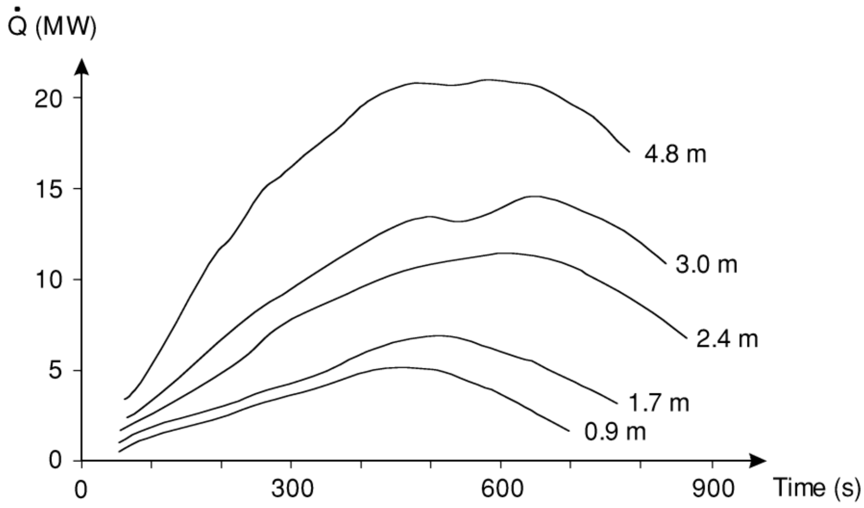


Figure 3.1.7 Energy release rate measured when burning 1.2 m by 1.2 m wood pallets, stacked to different heights (SFPA Handbook 2002) [(2)].

There are also enclosure effects to consider. Hot gases collect at ceiling level heating the walls and ceiling. This has the effect of radiating energy back to the surface of the fuel package thus increasing the burning rate. Additionally the enclosure vents may restrict the amount of oxygen available for combustion. This has the effect of decreasing the amount of fuel burnt, leading to a decrease in energy released and an increase in the production of un-burnt gases. If the ventilation openings are relatively small there is limited oxygen causing incomplete combustion, a decrease in energy release rates, lower gas temperatures and therefore lower radiative feedback to the fuel surface.

3.1.8 Ventilation conditions

Consideration was given to the benefits to exposing the sample panels to different fire growth sizes and different coinfiguarion. It would have been possible to expose the panels to a smouldering fire and fully develpoed fire. Flashover is the sudden transition from a growth stage to fully developed fire. When flashover occurs, there is a rapid transition to a state of total surface involvement of all combustible material within the compartment.

Literature determines that conditions for flashover are defined in a variety of different ways. In general, ceiling temperature in the compartment must reach 500^{o}-600^{o} C (932^{o}-1112^{o} F) or the heat flux (a measure of heat transfer) to the floor of the compartment must reach 15-20 kW/m^2. When flashover occurs, burning gases will push out openings in the compartment (such as a door leading to another room) at a substantial velocity.

It was considered that achieving flashover conditions and exposing the panel and joint to the maximum amount of radiative heat would be of benefit and therefore the ventilation conditions were designed to ensure that the wooden cribs produced a fully developed fire.

A fully developed fire will create pressurization due to the production of fire gases of the compartment which could potentially dislodge the panel samples or introduce fire gases that could be of different volumes and pressures and therefore creating different fire conditions within the compartment.

In order to alleviate this problem the ventilation conditions were arranged to confirm that sufficient air could be entrained to ensure a fully developed fire within the crib and also sufficient ventilation to ensure that fire gases could escape from the compartment without

3.1.9 The chosen option

Given the options available and the limitations of the facilities it was decided that the most appropriate fire source was a wooden crib fire constructed from wooden pallets. Although it is acknowledged that it would be difficult to perfectly replicate the same fire conditions in each test, the structure and size of the crib would be identical in all cases.

3.2 The Research Site

3.2.1 Introduction

A number of research sites were considered for conducting these tests. Clearly given the expected volume and nature of smoke given off when subjecting sandwich panels with combustible cores to a fire source this limited the amount of options available. Fire and Rescue Service test facilities within city centre locations were eliminated due to limitations on licence conditions.

The test facility chosen to conduct the experiments is a fire behaviour demonstration and training facility maintained by Lancashire Fire and Rescue Service at their training facility in Euxton, Lancashire. The facility occupies a location remote from a town or city and has the appropriate permit to allow fire testing of this nature.

3.2.2 The test facility

There were a number of test facilities that could be utilised each with slightly different geometries and internal configurations. A greater number of experimental tests could have been carried out by using the other test facilities at the same time. However as the other facilities had slightly different geometries and bespoke features it would have been impossible to compare results given the other variables.

It was therefore decided to utilise the same facility for each of the tests to ensure a degree of uniformity in each of the test conditions. The facility chosen is 13.2m in length, 2.4m in width with an average internal height of 2.42m in height.

Figure 3.2.2 Overview of the test facility

The test container is formed from an external layer of corrugated steel sheeting of 6mm thickness. The internal layout comprises of a fire compartment which houses the fire source, normally a burning crib. This compartment is further reinforced with an additional internal layer of corrugated steel sheeting bolted to the external skin. Given the extreme temperatures and frequent use of the facility this additional layer ensures the prolonged integrity of the container.

The floor to the container is formed from concrete flag stones to withstand the high temperatures developed within the compartment.

The roof of the container is formed from thin steel sheeting secured by bolts to the internal frame. A ventilation chimney is positioned 6.66m from the front of the container. The geometric free area of the ventilation chimney can be altered via a manually operated mechanism on the external face of the container. The geometric free area can be altered between zero and up to a maximum of $0.25m^2$.

The front face of the container contains two apertures both of nominal size 1010mm in length and 510mm in height. The apertures are separated from each other by a vertical box steel section.

Figure 3.2.2 (a) Position of sandwich panel samples under test

At the rear of the container are two full externally opening doors, each of 1.2m width and 2m in height. Within the container to the rear are another set of externally opening doors each 800mm in width and 2m in height.

At one side of the container adjacent to the manual control mechanism for the ventilation chimney is positioned a single externally opening door 800mm in width and 1.9m in height. The single door is positioned 7m from the front of the container.

The apertures where the samples were secured were of nominal size 1010mm in length and 510mm in height. The gaps between the samples and the boundary of the apertures were then filled with mineral wool to create a seal around the periphery. The joint was made by pushing both parts of the sample together and no other fixing or securing method was used. The samples were held in place by securing steel plates in the vertical plane at the extreme edges of both samples under test. The steel plates were secured to the panels by way of a series of clamps to ensure the panels would remain within the aperture for the duration of the test as shown in figure below.

Figure 3.2.2 (b) Sandwich panel samples in test position with lateral restraints.

Care was taken to ensure that the fixing methods at the edges were sufficient to hold the samples within the apertures and not able to be dislodged due to thermal expansion of the panel or internal pressure caused by the fire gases within the compartment.

In addition if the panels were secured into the apertures too rigidly then any expansion of the sandwich panel could create distortion and opening up of the joint. The purpose was to ensure that the panel remained restrained but the integrity of the joint remained intact and to minimise the effect of expansion and compressive forces.

It was important to ensure that the ventilation remained constant throughout each test. The ventilation to the contained was provided by a side door and a door at the rear of the container. The side door 1.9m high and 0.8m wide and remained in the fully open position for the duration of the test. The door at the rear of the contained was 2m in height and 800mm wide and remained fully opened for the duration of the test.

In addition to the ventilation provided by the doors to the container ventilation chimney was positioned within the roof of the container 6.66m from the front of the burn chamber. The geometric area of the chimney is variable but remained fully open throughout the duration of the test with the total geometric free area of 0.5m x 0.5m.

Figure 3.2.2 (c) View of ventilation chimney

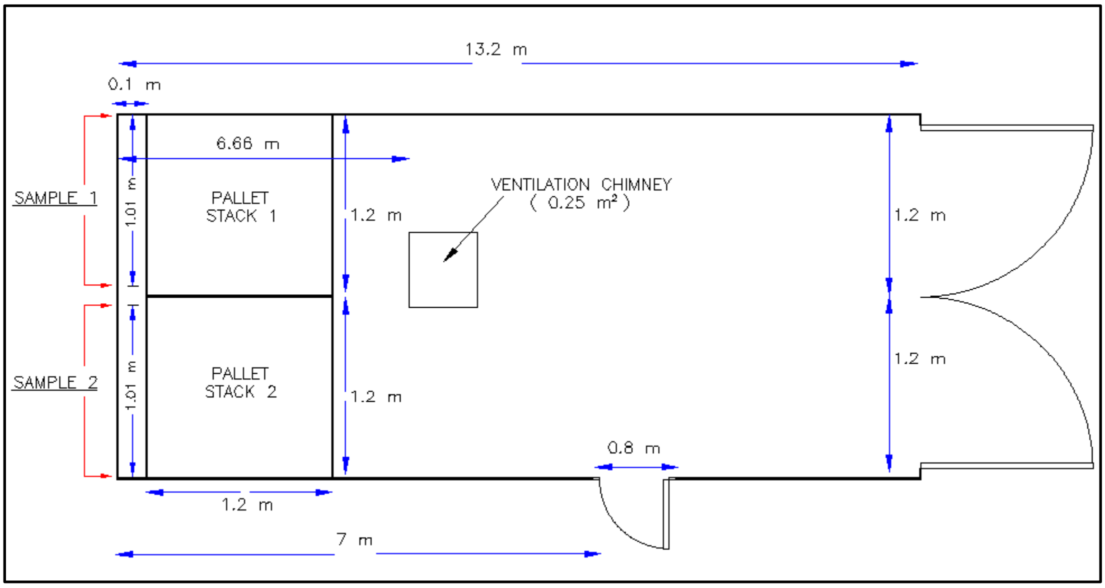


Figure 3.2.2 (d) Plan view of the test facility

3.3 Fire test arrangement

3.3.1 The Selected Product

The product selected for these test are utilised for external wall construction and have a polyisocyanurate (PIR) core with fire performance approved by the LPCB. These panels are of a secret fix design system which allows the primary fixings to be hidden from view together with an external micro rib (MR) with tongue and groove edges. The stated fire performance of the test samples are 15 minutes insulation and 4 hours integrity which is achieved with the prescribed fixing methods. The design of the panels allows the products to be used in both vertical and horizontal geometry.

The external face of the panel has a nominal 0.7mm thickness based on the proportions of zinc (95%) and aluminium (5%) eutectic alloy. The internal facing material has a nominal thickness of 0.4mm with a planked profile.

3.3.2 Samples and positioning

The selected panel samples were 495mm in height and 1030mm in length with thicknesses of 95mm and 120mm being subject to testing. The apertures where the samples were secured were of nominal size 1010mm in length and 510mm in height. Any gaps between the samples and the boundary of the apertures were then filled with mineral wool to create a seal around the periphery. The joint was made by pushing both parts of the sample together and no other fixing or securing method was used.

The samples were held in place by securing steel plates in the vertical plane at the extreme edges of both samples under test. The steel plates were secured to the panels by way of a series of clamps to ensure the panels would remain within the aperture for the duration the test.

Care was taken to ensure that the steel plates and clamp arrangement were secured solely to ensure that the panels remained in situ for the duration of the test and not to create any rotational force at the vertical edges which would create stress within the panel or at the joint.

The methods of securing the samples in a lateral position are shown in Figure 3.3.2 and Figure 3.3.2(a) below.

Figure 3.3.2 Samples positioned with joints in vertical configuration

Figure 3.3.2 (a) Samples positioned with joints in horizontal configurations

3.4 The equipment and materials used

3.4.1 Fire Source

A number of options were considered in relation to the fire source for the tests. A crib arrangement similar to that used for the Loss Prevention Council (LPC) LPS 1181 standard was considered and eliminated as it would prove too onerous and it would be impossible to ensure consistency in each test due to the facilities available. In addition these tests were not designed to replicate or compare any results from any previous tests and therefore it was important to ensure that fire sizes and fuel load configurations were consistent in each of these tests.

For consistency it was decided that the fire load was to utilise two uniformly stacked pallets which were positioned to maximise the exposure of each joint to the fire source. The stacks were positioned 100mm from the face of the sandwich panels to ensure that when the pallet stacks collapsed they did not interfere with sandwich panel samples. In addition this ensured that the burning pallets remained a uniform distance from the panel's faces and did not interfere with the joints or any of the thermocouples.

Figure 3.4.1 Example of the fire source used for each test.

The pallets utilised were of uniformed sizes and 1.2m x 1.2m and stacked to a height of 1.5m. The pallets were of uniform standard construction with an average weight of 30 Kg each. The configuration of the fire load was two identical pallet stacks each stacked 9 pallets high, giving a total fuel load of 540 Kg. Given the facilities available it was difficult to control the moisture content of the pallets. The pallets were all kept within the same facility and were covered to prevent excessive moisture ingress. All of the pallets used were kept at the facility for the same length of time so subject to the same degree of moisture and seeing as these tests were not designed to replicate any other test the moisture content was considered irrelevant for the purposes of the tests. The pallets were ignited by using a hand held butane burner and the flame was applied to the lowest pallets in the stacks until flaming ignition was observed and at this time the data recorder was activated. Four plate thermocouples were positioned at varying positions just above the sandwich panel samples.

Figure 3.4.1 (a) Fully developed fire in pallet stack

3.4.2 Plate thermocouples

In order to measure the radiative temperature from the fire source, four plate thermocouples were used. Each thermocouple had a relatively large surface area exposed to the furnace, but insulated from the test specimen. Literature states that the use of this type of arrangement for furnace conditions gives a more representative measurement of heat received by the specimen, especially in the early stages of a test. The plate thermocouples are less affected by convected heat, or other factors connected with the furnace construction.

Figure 3.4.2 Arrangement of plate thermocouples within compartment

The figure above shows the arrangements of the plate thermocouples within the fire compartment. They were positioned at different heights to get a better representative sample of the temperatures generated from the fire source.

The plate thermocouples were secured to a mounting tube which were fixed to a square bar. All elements of the arrangement were secured in such a way to ensure that the plate thermocouples remained facing the fire source for the duration of the test and were not subject to any movement due to the fire conditions.

Each of the plate thermocouples were 100mm x 100mm x 10mm in dimension with the front face covered in ceramic insulation. The thermocouple wires were then fed up through the mounting tubes and connected to the data logger outside of the compartment. Any thermocouple wires that were exposed to the furnace were protected with mineral wool insulation.

The advantages of using a plate thermocouple are that they are simple and rugged but more precise temperature measurement due to the wide surface area at the measuring tip. There are no concerns over electrical resistance in the lead wire and provide a fast response to changes in temperature. Disadvantages include sensitivity, repeatability and susceptibility to electrical noise especially if insulation fails. However given the nature of the test and the harsh furnace conditions plate thermocouples are appropriate for the type of measurement required.

3.4.3 Bead Thermocouples

Thermocouples have become the industry-standard method for cost-effective measurement of a wide range of temperatures with reasonable accuracy. They are used in a variety of applications up to approximately +2500C in boilers, water heaters, ovens, and aircraft engines—to name just a few. The most popular thermocouple is the type *K*, consisting of Chromel® and Alumel® (trademarked nickel alloys containing *chromium*, and *aluminium*, manganese, and silicon, respectively), with a measurement range of –200°C to +1250°C.

3.4.3.1 Advantages of using thermocouples to measure temperature.

Thermocouples are able to measure the most practical range of temperatures from cryogenics to jet engines. This is dependent upon the type and combination of wires used, but given the correct combination thermocouples are capable of measuring temperatures in the range of –200°C to +2500°C. As thermocouples are passive measuring devices with no moving or mechanical parts they are immune to shock and vibration and suitable in hazardous environments.

As thermocouples are small and have a low thermal capacity they respond rapidly to temperature changes, especially if the sensing junction is exposed. They are extrinsically safe as there is no requirement for excitation power and are not prone to any self-heating

3.4.3.2 Disadvantages and limitations of using thermocouples to measure temperature.

Thermocouples are reliant upon substantial signal conditioning to convert thermocouple voltage into a usable temperature reading. Traditional methods of converting from voltage signal to a temperature reading require a significant investment in the appropriate software and hardware.

The metallurgical properties of the thermocouples provide inherent inaccuracies and the measurement is only as good as the reference junction temperature can be measured, traditionally within 1°C to 2°C. Thermocouples are susceptible to corrosion and because they consist of two dissimilar metals may need protection and clearly care and maintenance is essential.

Thermocouple Type	Positive	Negative	Temperature Range
E	Chromel	Constantan	-270° to 1,000°
J	Iron	Constantan	-210° to 1,200°
K	Chromel	Alumel	-270° to 1,372°
T	Copper	Constantan	-270° to 400°
S	Platinum	10% Rhodium Platinum	-50° to 1,768°
R	Platinum	13% Rhodium Platinum	-50° to 1,768°

Table 3.4.3.2 Temperature ranges of various thermocouple types

3.4.4 Linear Displacement Transducers

Linear displacement transducers were used to measure the displacement of the panel around the joint. Two transducers were used for each panel under test and were positioned 10mm either side of each joint at the centre position of the panel, shown in figure .below.

The displacement transducers were attached to a ‘ball and socket’ joint to allow it to be positioned at 90° to the exterior face of the panel. The transducers were clamped to a free standing frame and connected to a data logger via a PC. Once the probe was positioned at 90°C to the face of the panel the data logger was recalibrated to show the same starting value.

Figure 3.4.4 Arrangement of linear displacement transducers

Figure 3.4.4 (a) Arrangement of linear displacement transducers

<u>3.4.4.1 Advantages and disadvantages of using linear displacement transducers</u>

Linear displacement transducers are relatively robust and simple to use. However due to moving part and low technology they offer limited accuracy. In addition they can measure limited displacement and it can be difficult to ensure that the probe is 90° to the face of the sample under test which will affect the final results. It is acknowledged that it would be impractical to arrange linear displacement transducers to a building involved in fire and interpretation of the results would be difficult without knowing the initial start point.

3.4.5 Data Logger

Consideration was given to utilising a recorder or data logger to record the data from the experimental tests. Following discussions with technical staff it was decided that a data recorder would be the most suitable instrument for these experiments. Given the number of channels that were required to record the thermocouple temperature and also that the instrument was required to have a diverse capability the data logger was selected.

As the data logger is a self-contained unit it allowed the flexibility to be used and installed in various locations, left unattended and not require any other operation once set up. The data logger has an advantage over other interface devices, in that it a standalone device with the capability to transfer data onto a host system as required. The data logger has the ability to record information at selected intervals for long periods of time.

3.4.6 Thermal Imaging Camera (TIC)

The Argus Mi-Tic E2v-Mi-320-3 is a lightweight, durable, infrared imaging device which provides vision enhancement in fire-fighting and other emergency response activities.

Figure 3.4.6 The Argus Mi-Tic E2v-Mi-320-3 thermal imaging camera

The target markings in the centre of the screen provide instant temperature readings of individual risks. The cameras constantly record the screen footage and this can be viewed for training and debrief purposes. The cameras have a thumb operated green on/off button operation, with a start-up time of 5 seconds. It's important that regular reviews of the thermal reference points are undertaken during incidents.

Figure 3.4.6 (a) Thermo graphic image taken with thermal imaging camera

A regular re-view of these thermograhic reference points, combined with naked eye observations will allow an IC to assess the effectiveness of the tactics that have been implemented and operations being carried out to resolve the incident safely (Greater Manchester Fire and Rescue Service, 2014)[30].

3.5 Experimental Procedure

3.5.1 Thermocouple Positioning

The temperatures within the panel and at the surfaces were determined with Type 'K' thermocouples. The thermocouples were fitted and secured consistently throughout all of the samples to allow comparisons to be made. Thirty thermocouples were fitted throughout the samples to determine temperatures within the insulated core, around the joint and at the exposed and cold face of the panels. The positions of the thermocouples are shown in figure 3.5.1 below.

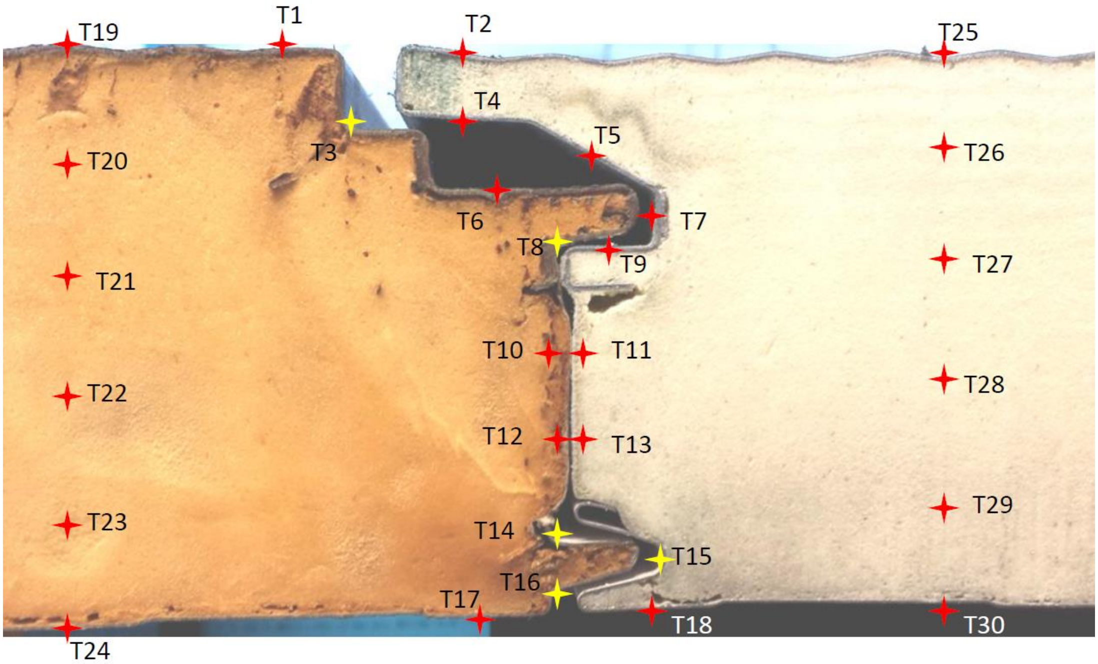


Figure 3.5.1 Thermocouple positions within the panel

The thermocouples measuring temperature within the insulated core were fixed in position and secured to the surface by ‘u’ staples and epoxy adhesive. This was to ensure that they did not become displaced under fire conditions and gave accurate readings throughout the duration the tests.

Summary

This chapter describes the various experimental options available that were considered when conducting this research. The test facility and the test arrangements are described in detail along with all of the equipment used to carry out the tests. Detailed drawing and photographs are provided to fully describe the small scale test methodology.

CHAPTER 4: RESULTS OF THE FIRE TEST DATA

4.1 Introduction

This chapter presents the fire test data.

In order to describe this to the reader the chapter is broken down into the following parts:

1. Measurement and collection of temperature profiles within the fire compartment measured by plate thermocouples.

2. Measurement and collection of temperature profiles within the body of the sample panels, measured by type ‘K’ thermocouples.

3. Measurement and collection of temperature profiles within the joint of the panels measured by type ‘K’ thermocouples.

4. Measurement and collection of temperatures profiles taken on the unexposed face of the panel from outside of the compartment. These measurements were taken on the external face of the panel and at the external joint profile by the use of thermal imaging technology.

5. Measurement and collection of detailed temperature profiles taken on the unexposed face of the panel from outside the compartment, by using thermal imaging camera.

6. Measurement and collection of the displacement of the panel joint measured by the displacement transducers on the external face of the sample panels.

7. Measurement and collection of temperature profiles at the panel and joint at a slice near to the unexposed surface.

4.2 Temperature profiles within fire compartment

Four plate thermocouples were located at the front of the container at varying heights and adjacent to the panels under test. The thermocouples were secured to a 15mm steel circular tube which was attached to a square steel bar. The square bar was held in place with a series of brackets which were integral to the container. The whole mechanism was designed and secured to ensure that the thermocouples remained in place for the duration of the test and were not subject to any interference by the collapsing pallet stack or any swirling effect caused by the fire.

The positions of the thermocouples were consistent for each of the tests. The wires from the thermocouples were fed up inside the steel tube and to a data recorder outside of the containers where the results were collected. Where any wires were exposed to the furnace they were protected by mineral wool insulation. The data recorder was calibrated to measure and record temperatures at 10s intervals for the duration of the test period.

4.2.1 Results of temperature within fire compartment

Four identical fire cribs were used and given the designation A,B,C and D. Table 4.2.1 provides a summary of the test samples, panel thickness and joint orientation for each of the specific tests.

Crib Designation	Tests	Panel Thickness (mm)	Joint Orientation
A	1 and 2	95mm	Vertical
B	3 and 4	95mm	Horizontal
C	5 and 6	120mm	Vertical
D	7 and 8	120mm	Horizontal

Table 4.2.1 Summary of test samples and crib designation

For each of the crib fires, an average value of the tempertures measured by the four plate thermocouples was recorded and results presented in Figure 4.2.1 below.

All four crib fires show similar characteristices with three showing peak temperures between 700 and 800°C with Crib A showing peak tempertures in excess of 800°C . All of the temperture profiles showed similar characteristic with three exhibiting a double peak and one a single peak.

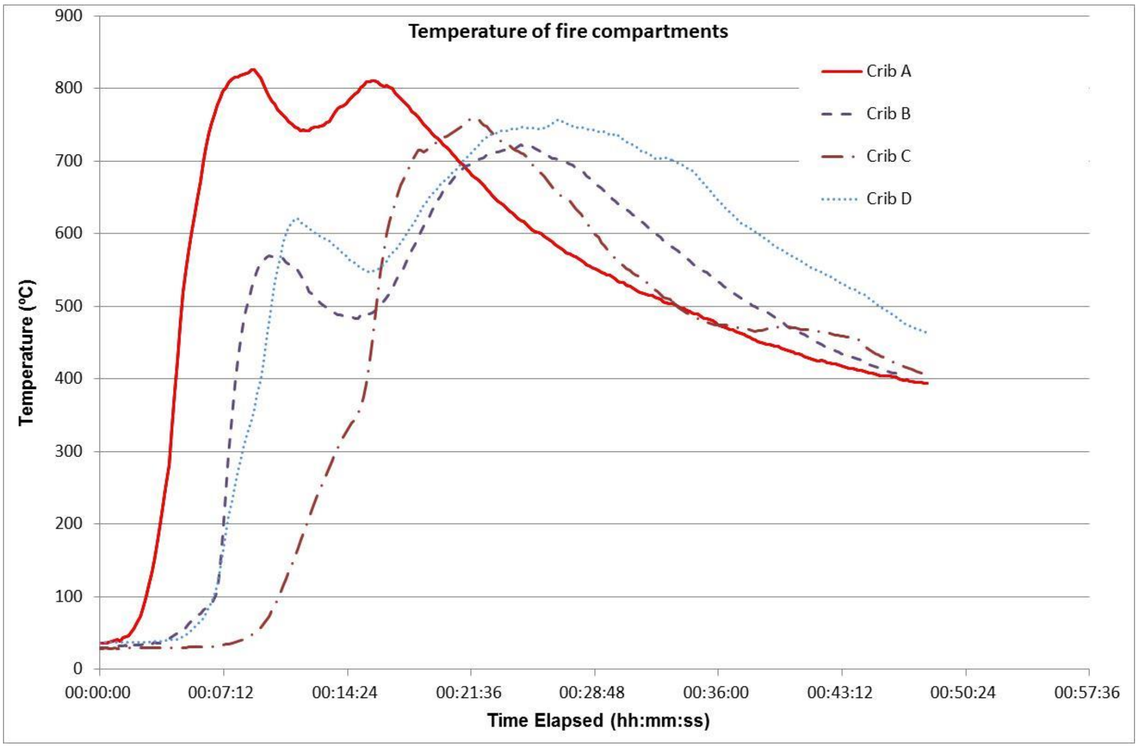


Figure 4.2.1 Temperature profiles of the four crib fires

4.3 Temperature profiles at different slices through the sandwich panel core

This section seeks to present the temperature profiles within the core of the sandwich panel samples. Figure 4.3 below describes the positions and designation of the thermocouples within the test samples. The positions of the thermocouples and their designations are consistent for all of the test samples, so that accurate comparisons can be made. All of the thermocouple designations prefixed with the letter T indicate the precise positions of the type K thermocouples. Table 4.3 describes the designation of the slices through the panel core and identifies which thermocouple results were used to provide the average temperature profiles.

It can be difficult for the Fire and Rescue Service to gain entry into buildings and compartments to fully to assess fire conditions within. This is further exacerbated when seeking to gain entry into buildings of sandwich panelled construction such as cold storage and chilled storage environments. This is due to increased integrity at the joints and external building envelope designed to maintain conditions within the facility. An alternative to gaining full entry to the building to assess internal conditions within would be to reveal the core material by utilising an electric drill or saw to reveal the core material from the outside of the compartment and then utilise the thermal imaging camera to determine the temperature of the exposed core material.

The purpose of recording and analysing the temperature profiles through the core material in in this way is to determine how effective this fire fighting measure would in evaluating fire conditions within a compartment as an alternative to attempting to gain full entry into the building and committing fire-fighters into the risk area.

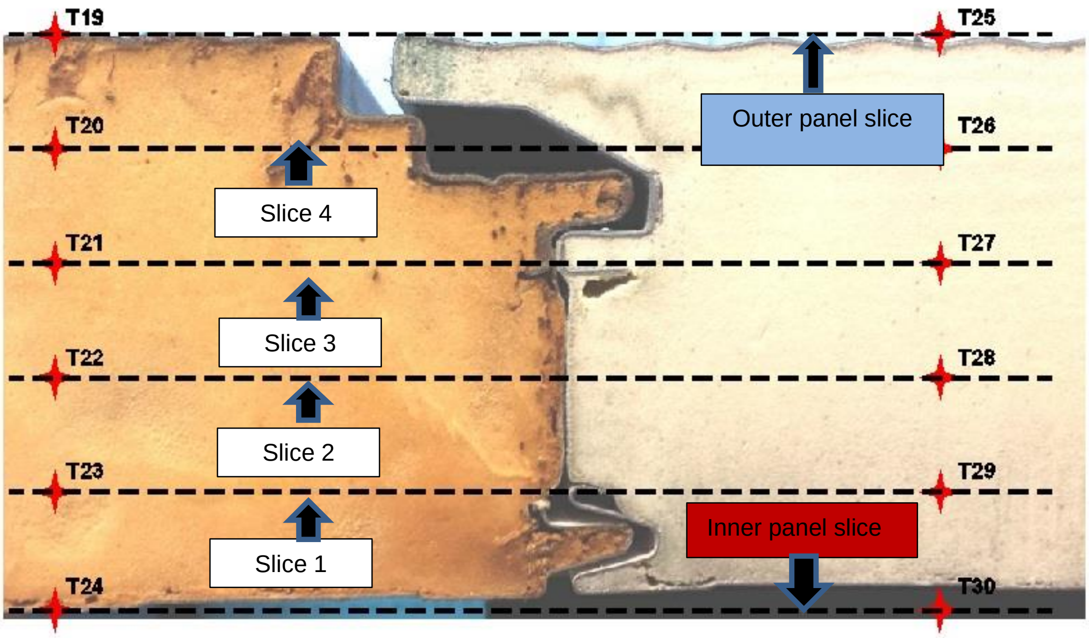


Figure 4.3 Slice profiles through body of sandwich panel

Average temperatures Thermocouples	Designation
T19/T25	Outer panel slice
T20/T26	Slice 4
T21/T27	Slice 3
T22/T28	Slice 2
T23/T29	Slice 1
T24/T30	Inner panel slice

Table 4.3 Summary of slice designation through the panel

4.3.1 Results of temperature profiles through the sandwich panel core

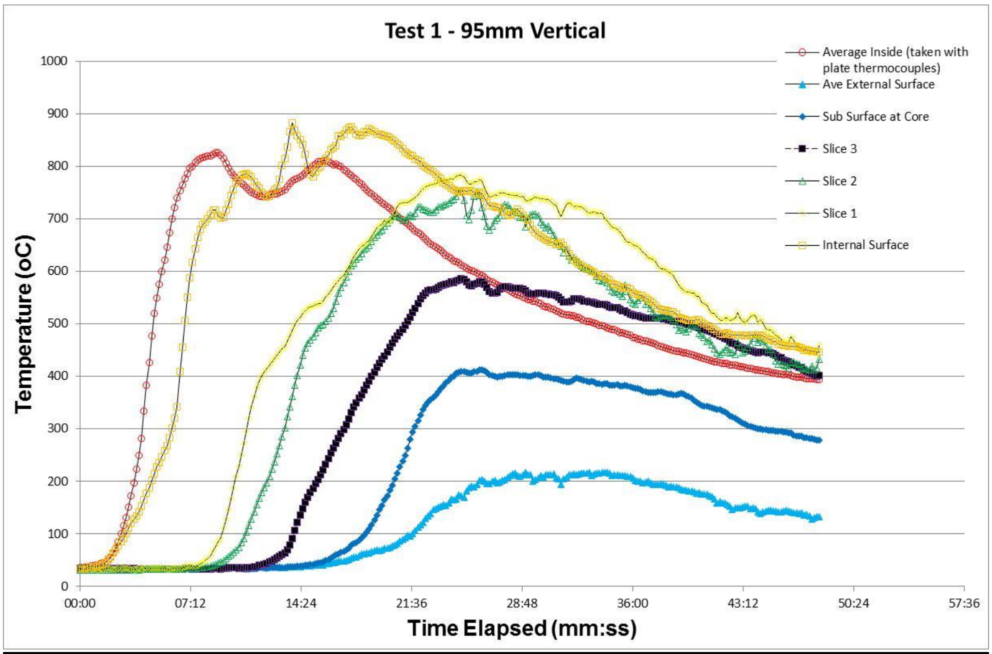


Figure 4.3.1.1 Test 1 - 95mm with vertical joint orientation

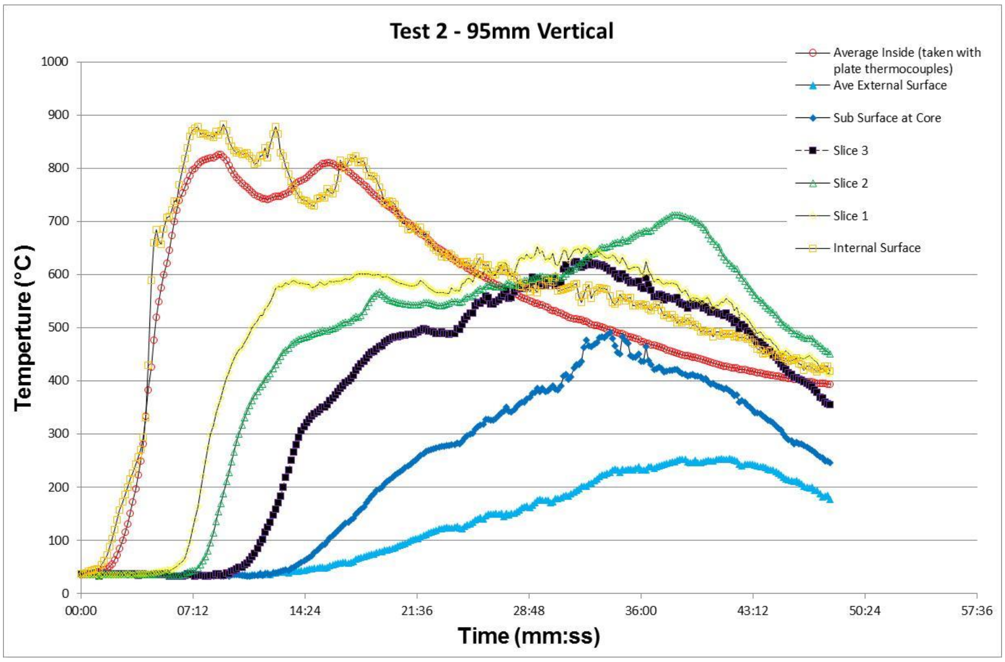


Figure 4.3.1.2 Test 2 - 95mm with vertical joint orientation

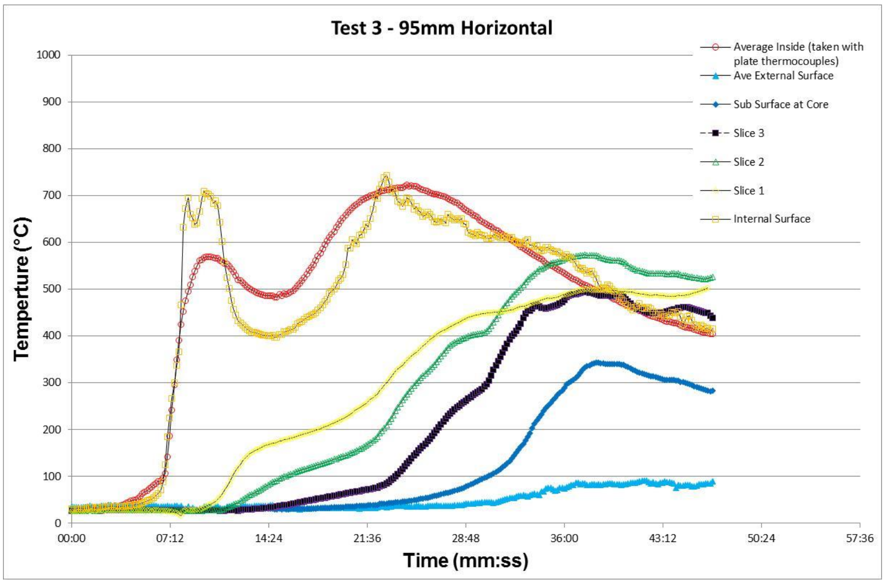


Figure 4.3.1.3 Test 3 - 95mm with horizontal joint orientation

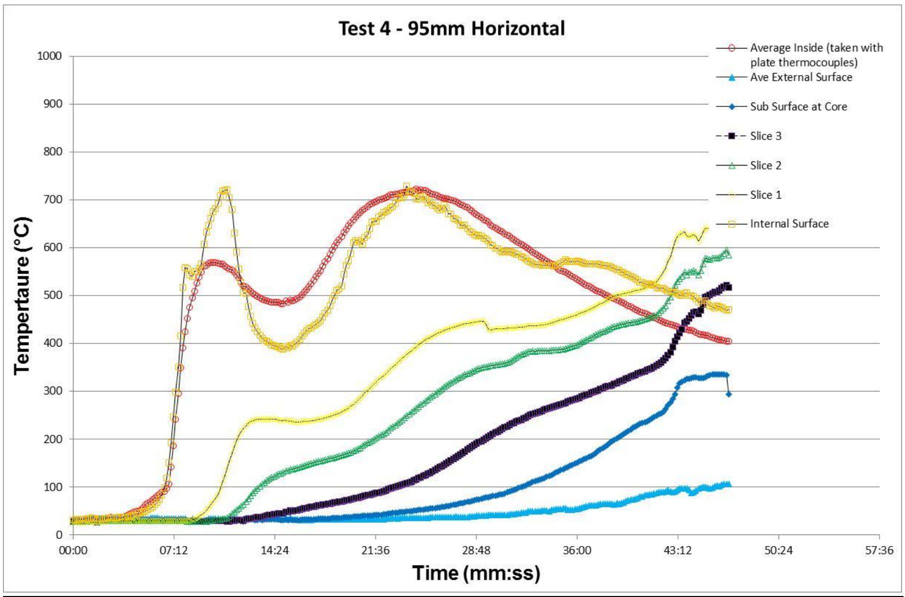


Figure 4.3.1.4 Test 4 - 95mm thickness with horizontal joint orientation

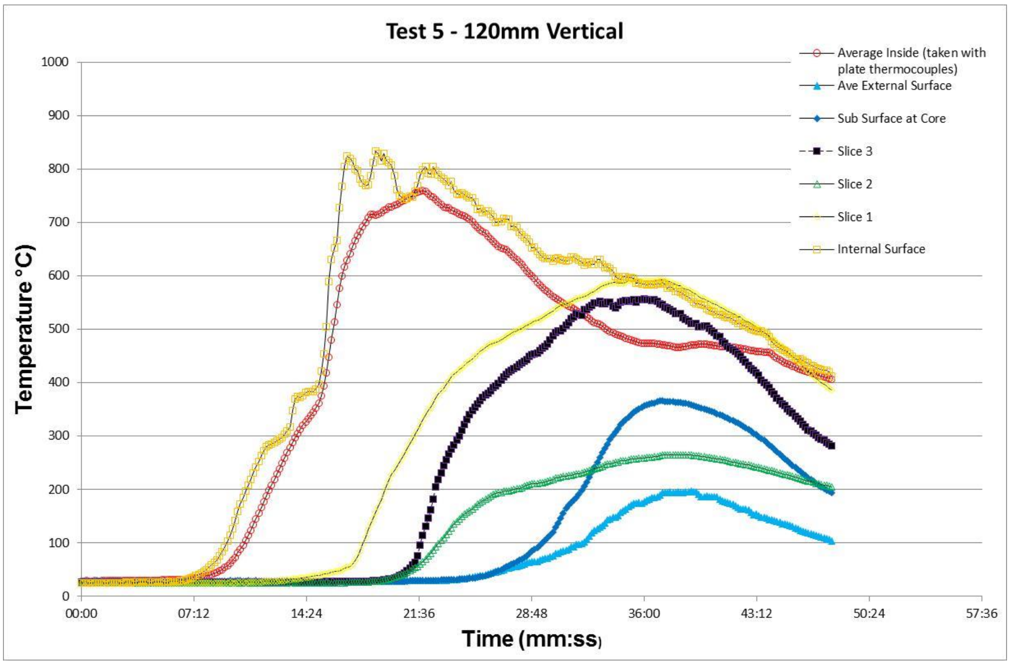


Figure 4.3.1.5 Test 5 120mm thickness with vertical joint orientation

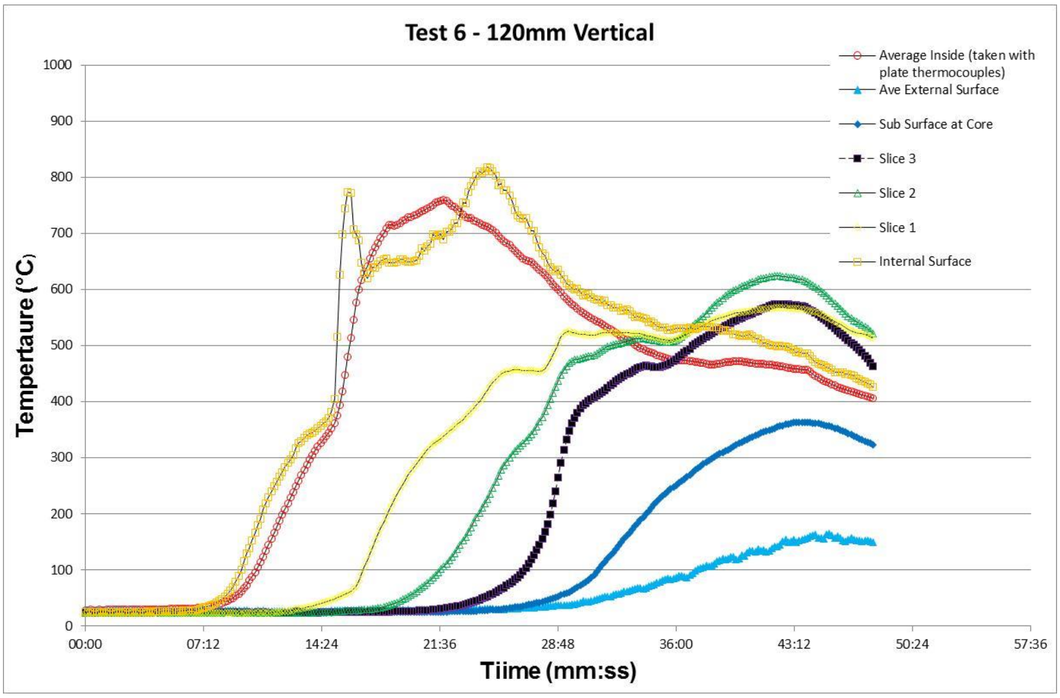


Figure 4.3.1.6 Test 6 120mm thickness with vertical joint orientation

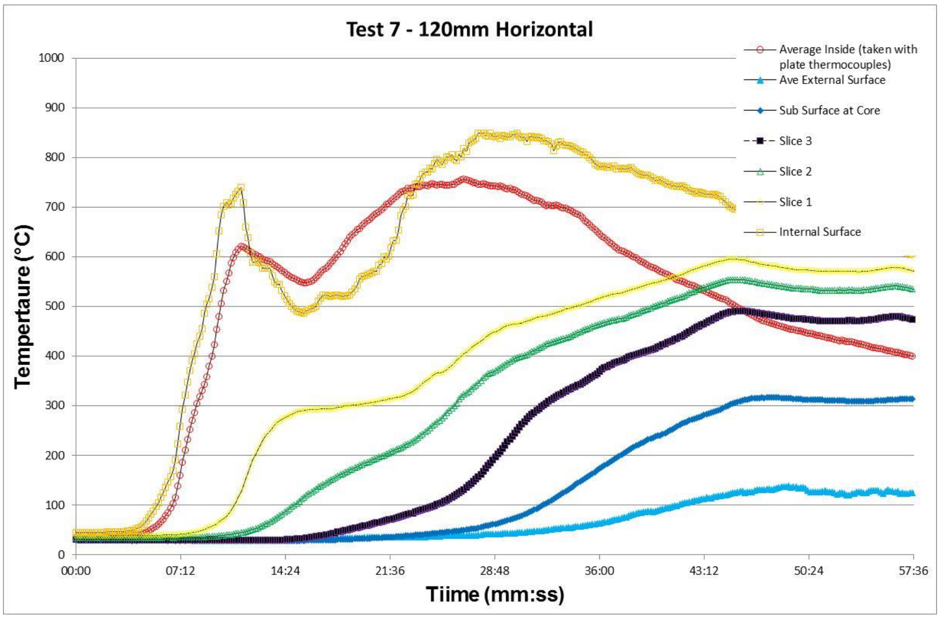


Figure 4.3.1.7 Test 7 120mm thickness with horizontal joint orientation

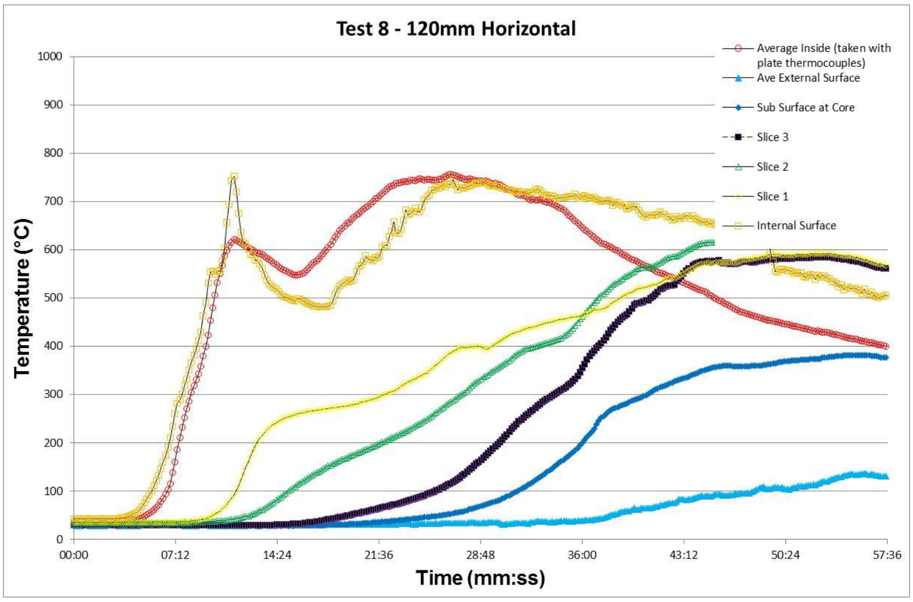


Figure 4.3.1.8 Test 8 120mm thickness with horizontal joint orientation

4.4 Temperature profiles at different slices through the joint

This section seeks to present temperature profiles within certain areas of the sandwich panel joint. The thermocouples within the panel joint are identified in the diagram below. The temperatures measured by the thermocouples at similar depths within the joint have been grouped together and an average temperature calculated. These groupings have been designated as slices and their designation described below.

This section considers the temperature profiles within the joint and seeks to determine whether it would be of benefit for the Fire and Rescue Service to open the joint of the sandwich panel from the unexposed face. By exposing the joint, temperature readings could be taken with thermal imaging equipment and this section considers the value of this approach in trying to determine the fire conditions within the compartment.

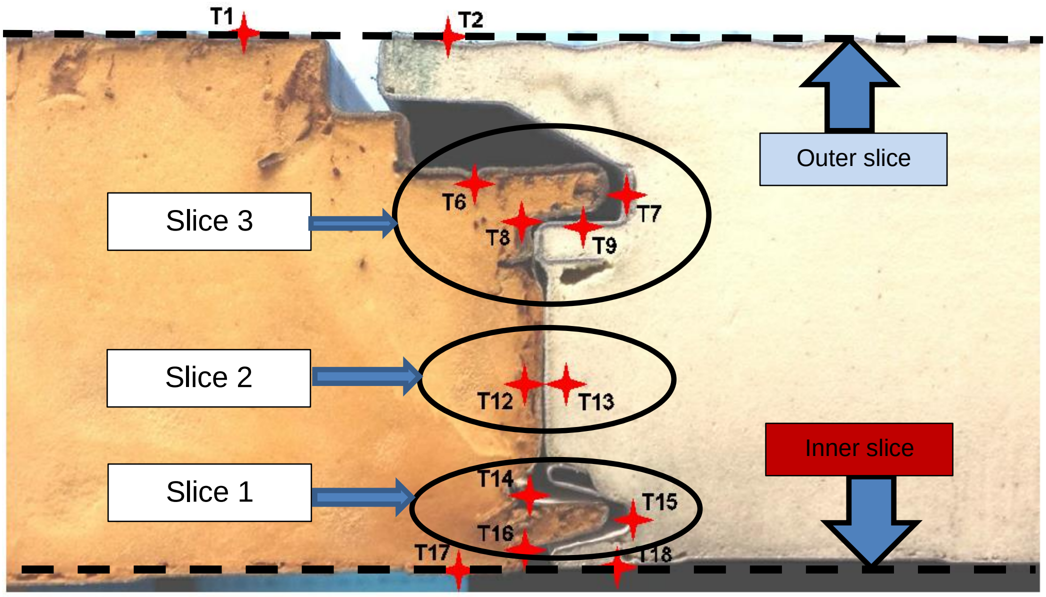


Figure 4.4 Slice profile and thermocouple positions within joint profile

Thermocouples	Designation
T17/T18	Inner Slice
T14/ T15/ T16	Slice 1
T12/ T13	Slice 2
T6/ T7/ T8/ T9	Slice 3
T1/ T2	Outer Slice

Table 4.4 Summary of slice designation through the joint profile

4.4.1 Results of temperature profiles through sandwich panel joint

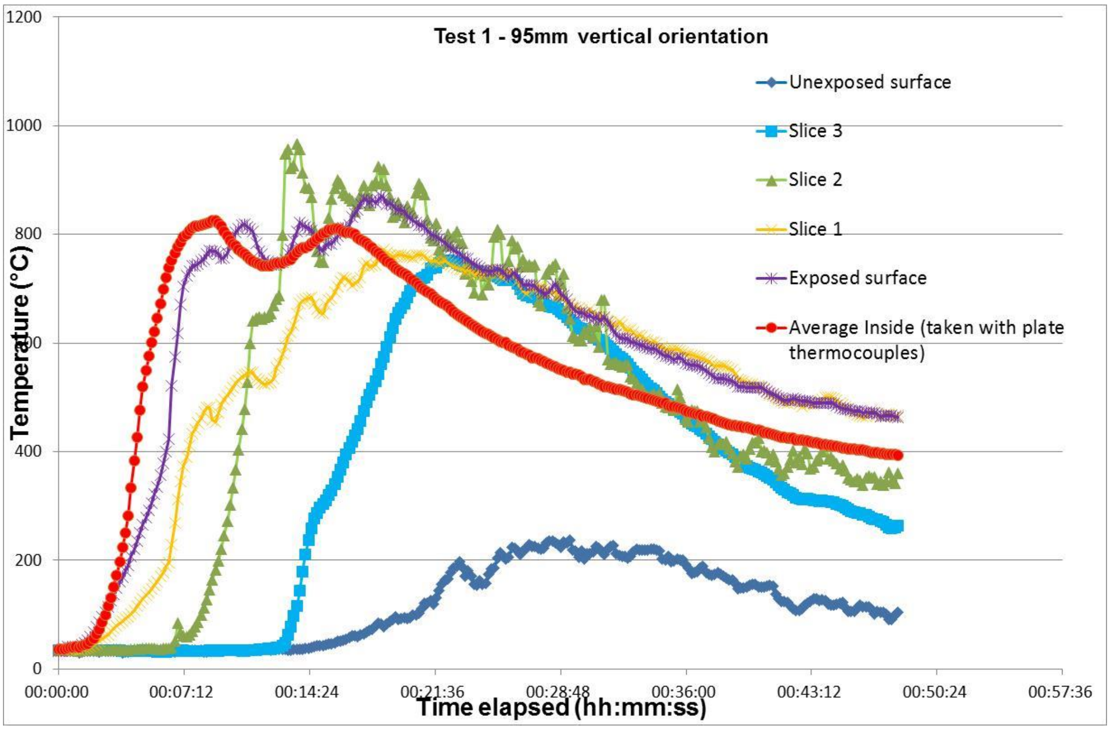


Figure 4.4.1(a) Test 1 – 95mm thickness with vertical joint orientation

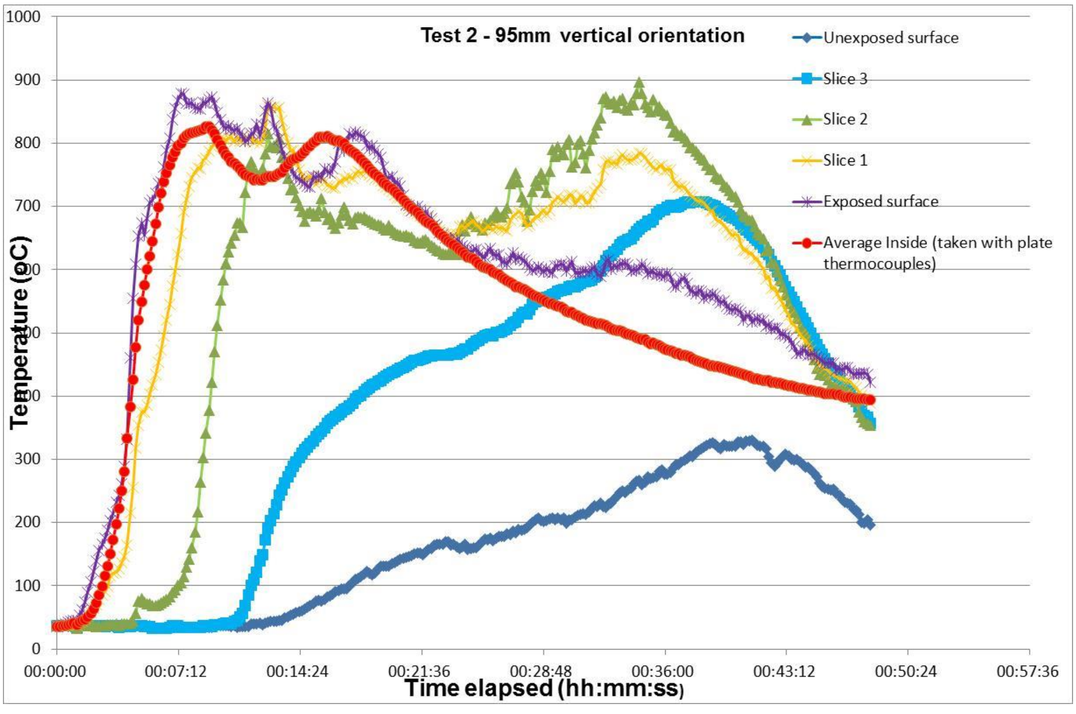


Figure 4.4.1(b) Test 2 – 95mm thickness with vertical joint orientation

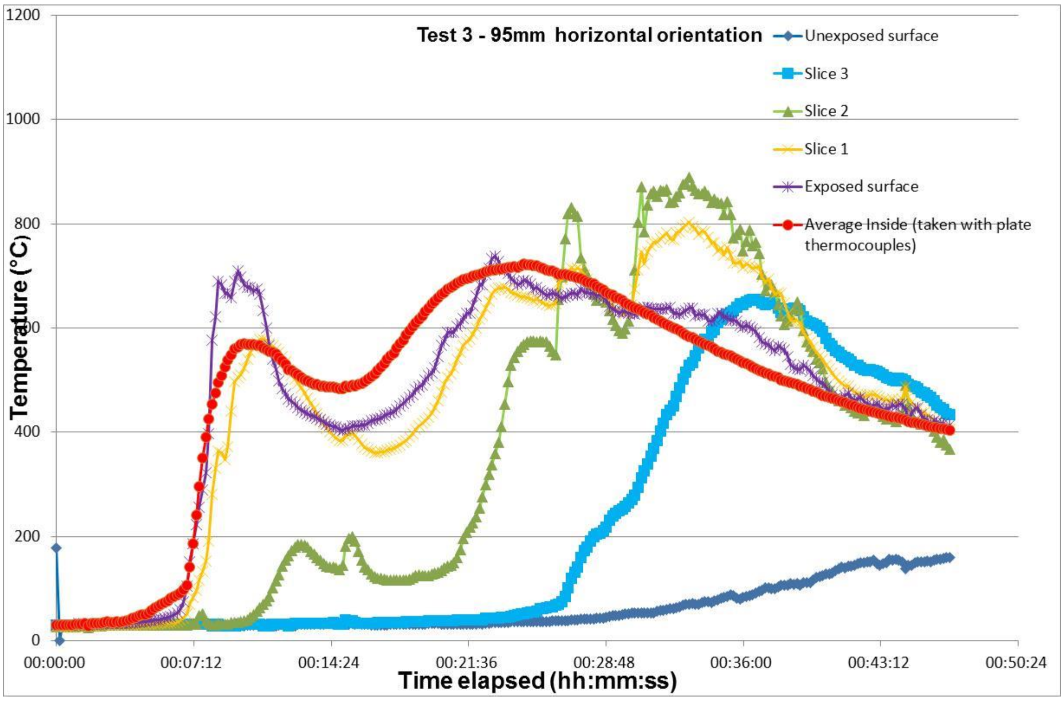


Figure 4.4.1(c) Test 3 – 95mm thickness with horizontal joint orientation

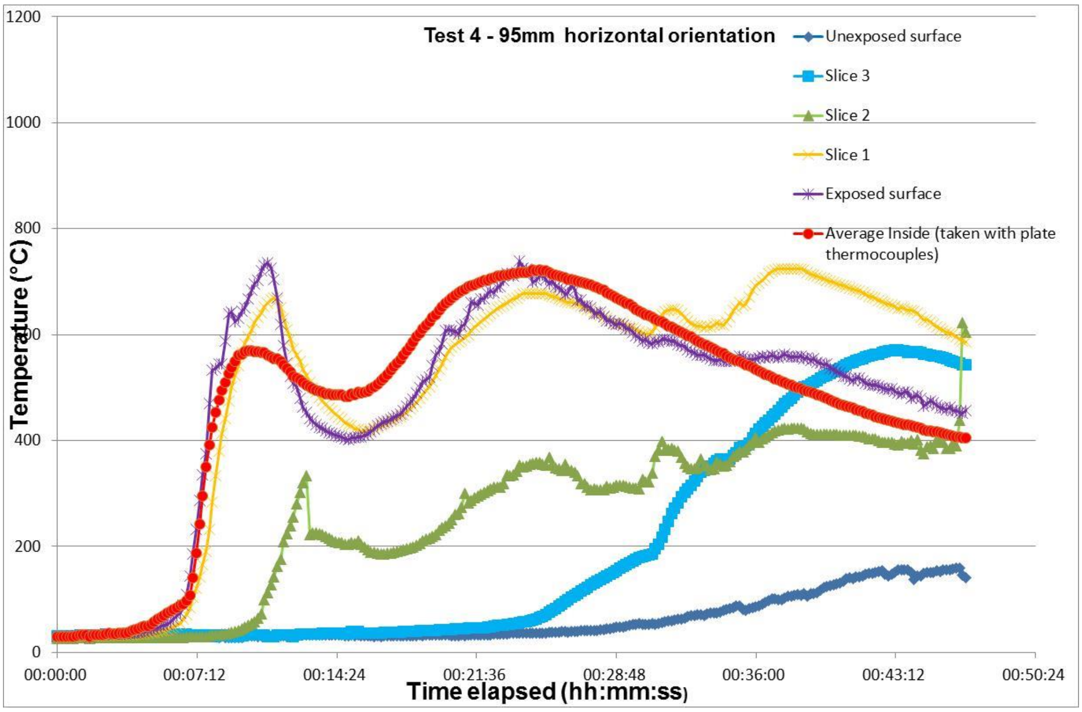


Figure 4.4.1(d) Test 4 – 95mm thickness with horizontal joint orientation

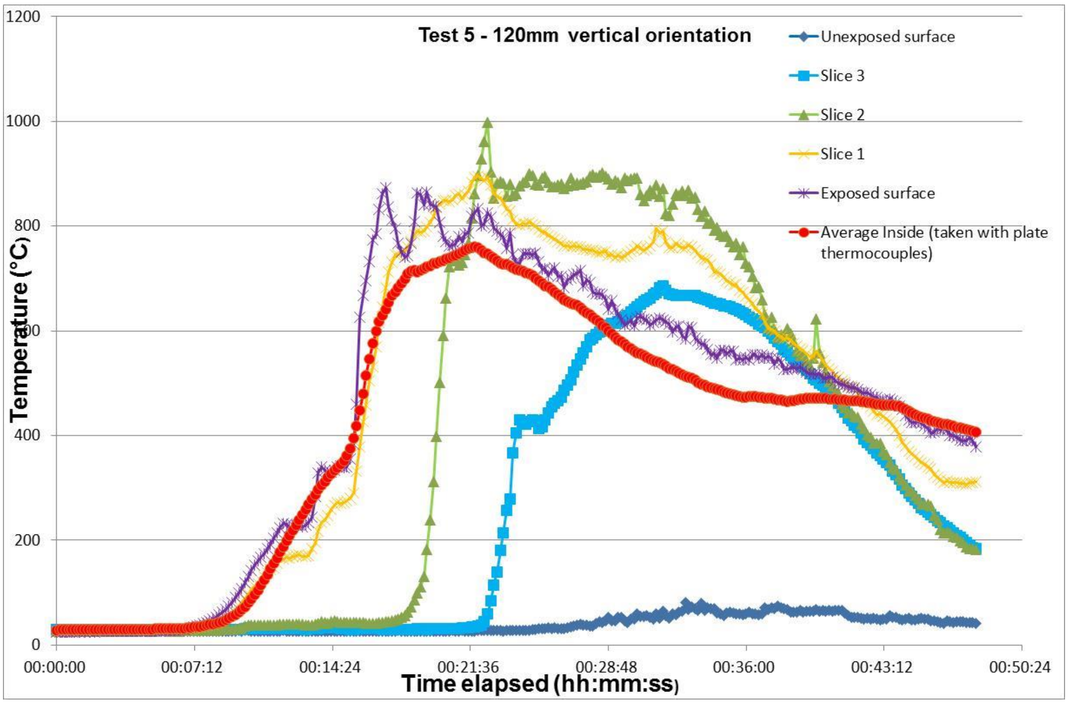


Figure 4.4.1(e) Test 5 – 120mm thickness with vertical joint orientation

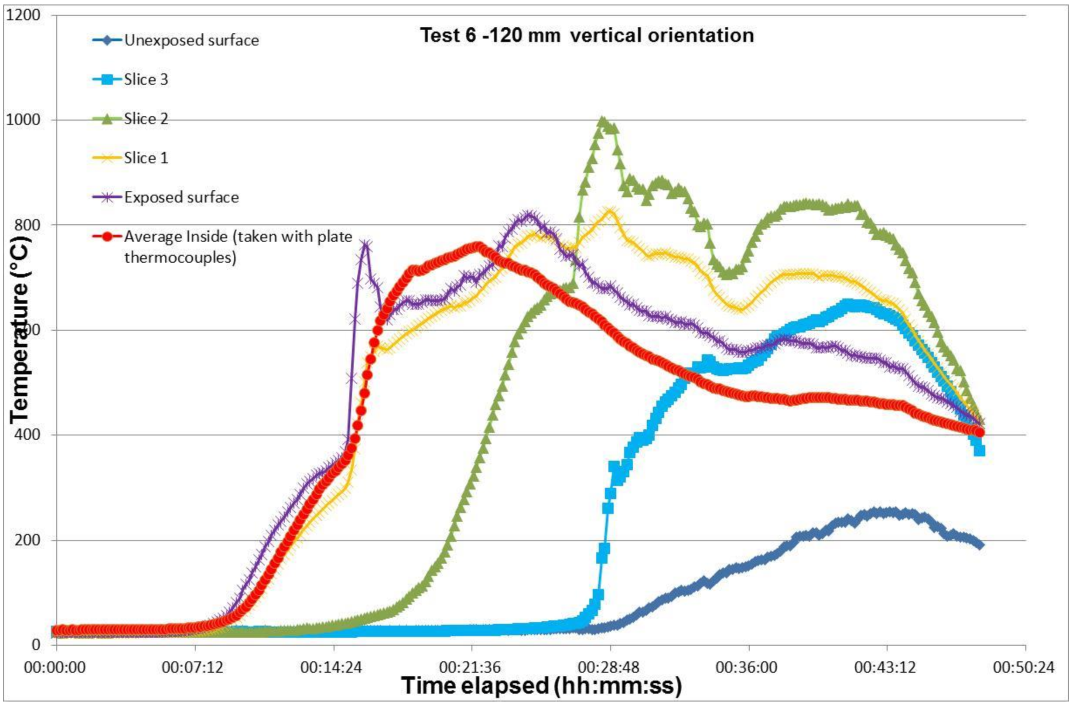


Figure 4.4.1(f) Test 6 – 120mm with vertical joint orientation

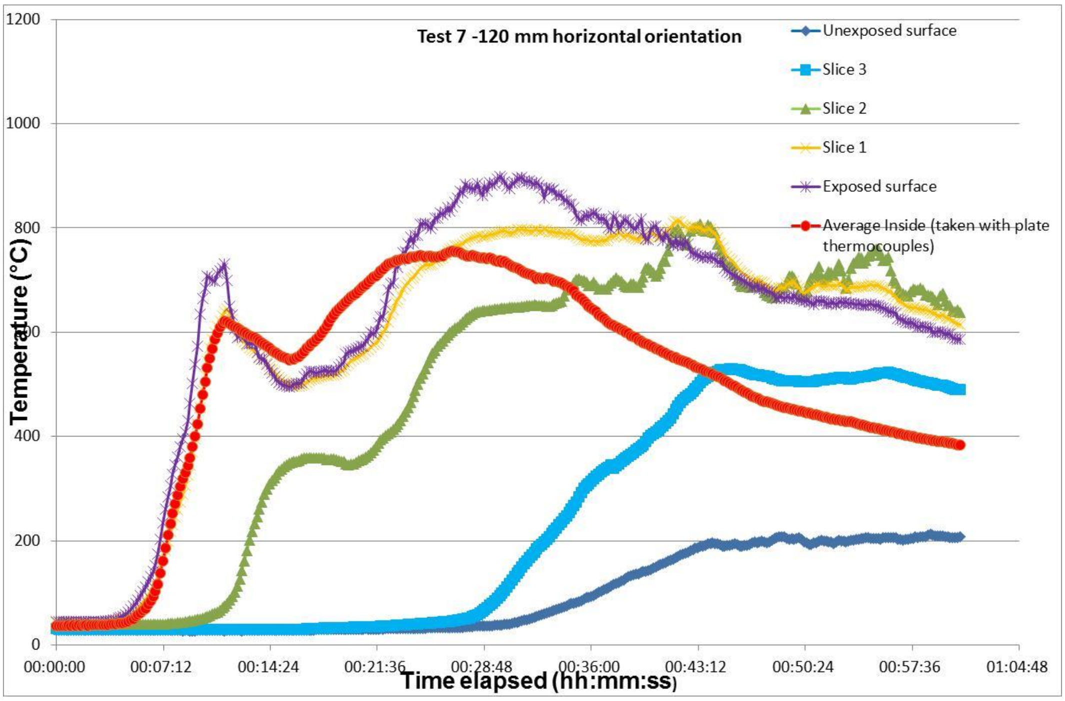


Figure 4.4.1(g) Test 7 – 120mm thickness with horizontal joint orientation

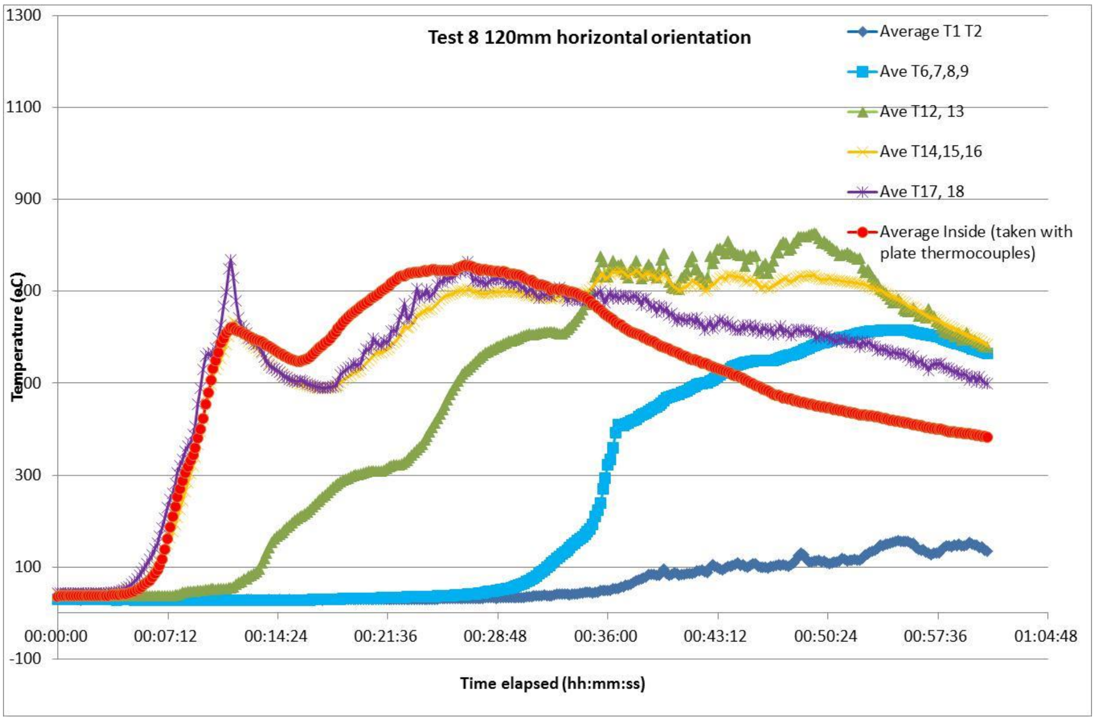


Figure 4.4.1(h) Test 8 – 120mm thickness with horizontal joint orientation

4.5 Temperature measurements taken on the unexposed face from outside of the fire compartment.

Where full entry into a compartment to assess fire conditions within is not achievable, either due to the security measures or some other circumstances, the Fire and Rescue Service will need to make that assessment from outside of the compartment. The most common method chosen by many Fire and Rescue Service is by using a thermal imaging camera (TIC) to gather temperature profile information on the external envelope of a building or compartment. As discussed in the literature review, this method is used to identify potential for fire within a compartment and extent of fire spread by comparing temperatures to ambient temperature.

These tests are designed to replicate conditions that could be met by the Fire and Rescue Service where they are confronted with fire conditions behind a sandwich panel and the only assessment that could be made is at the external envelope with a thermal imaging camera. As discussed in previous chapters the guidance on using thermal imaging cameras in this circumstance is limited and the guidance relies on determining temperature differences on the external envelope and this being associated with the extent of fire spread within the building or within the panel itself. The purpose of these tests is to consider temperature profiles on the unexposed face, at the panel, the joint and also at a metallic part of on the outside of the container to determine the temperature profiles of each and their relationship to the fire compartment temperatures.

The temperatures were taken manually from outside the container with a thermal imaging camera. The results were taken and recorded at regular intervals or when a significant event occurred, such as the emergence of a hot spot of flaming from in or around the panel. Each of the samples panels under test were split into four nominal segments 1, 2, 3 and 4 as indicated below in Figure 4.5 below.

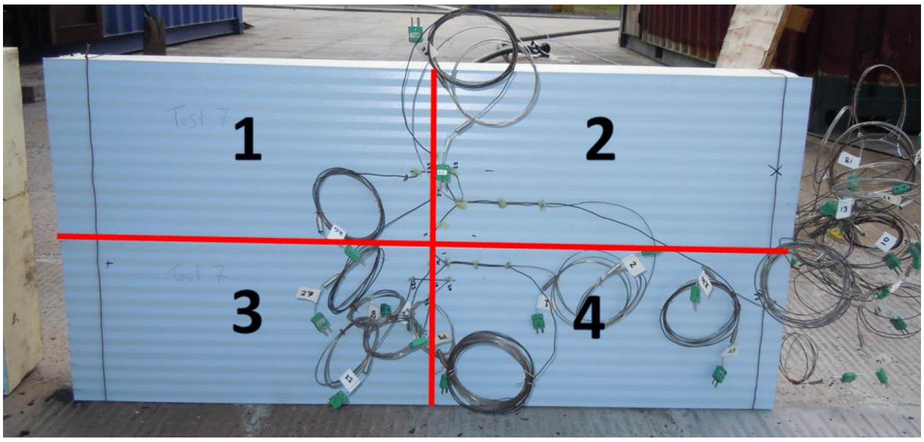


Figure 4.5 Segment designation of the sandwich panel sample.

At the appropriate time interval the four segment temperatures were taken alongside the temperature of the joint. The joint temperature was taken at the intersection of the two red lines shown in the above diagram. Measurements were taken at the same position on the joint, panel and container each time to ensure consistency in data collection.

In addition to the joint and sandwich panel temperatures, the external container temperature was also taken. This was done by taking the temperature at the metal façade at top of the external metal face of the container and allows a comparison to be drawn between the various elements of the sandwich panel samples and a metal component of the container.

The internal fire compartments temperatures were taken as the average of that recorded by the four plate thermocouples positioned at the front of the container directly above the two sandwich panel samples. The temperatures were recorded at 10 second intervals throughout the duration of the test.

4.5.1 Results of comparison between the internal and external temperatures

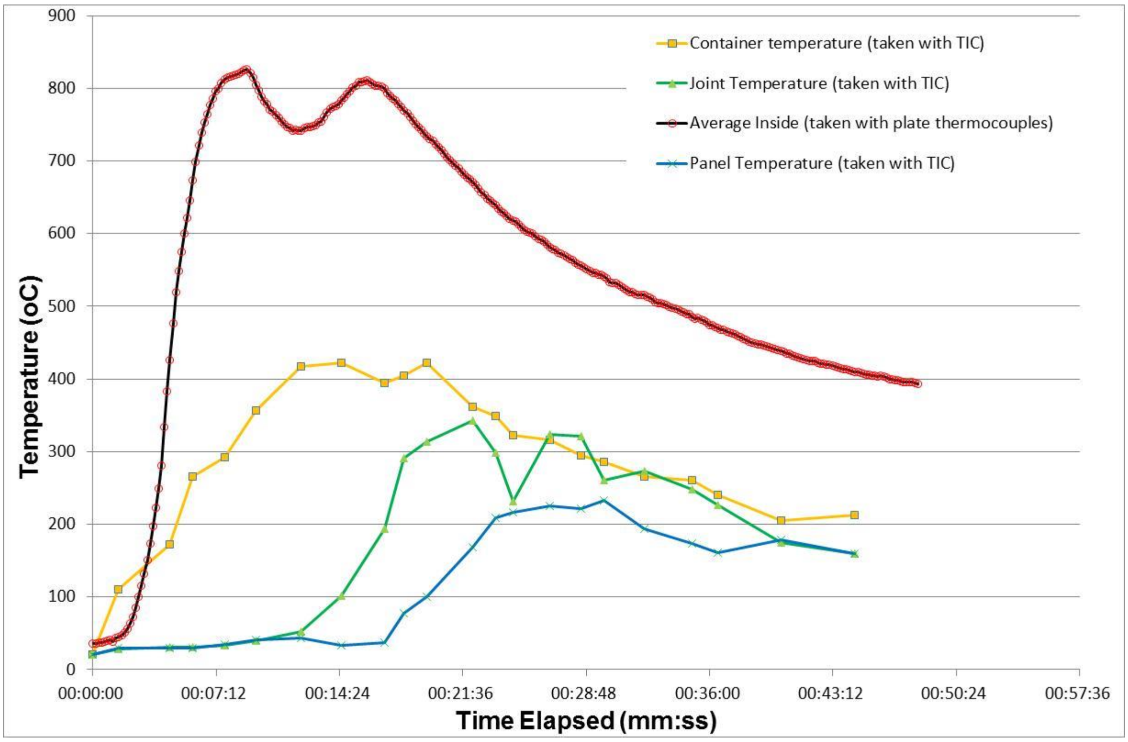


Figure 4.5.1(a) Test – 95mm thickness with vertical orientated joint

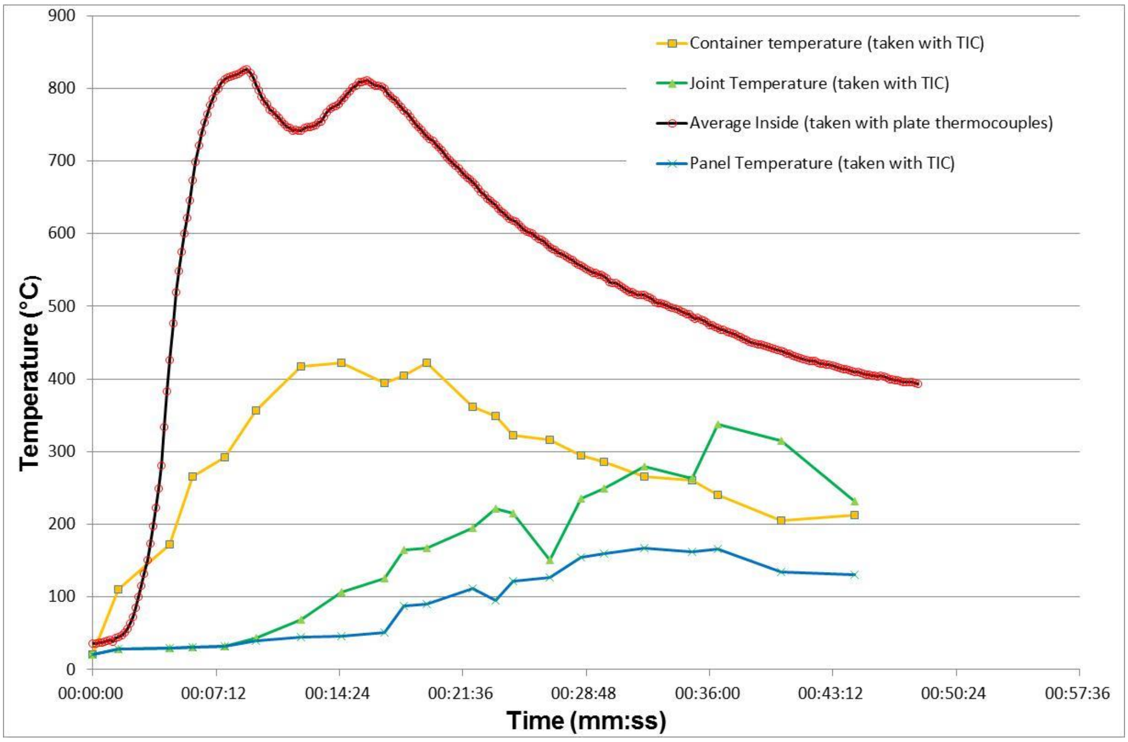


Figure 4.5.1 (b) Test 2- 95mm thickness with vertical orientated joint

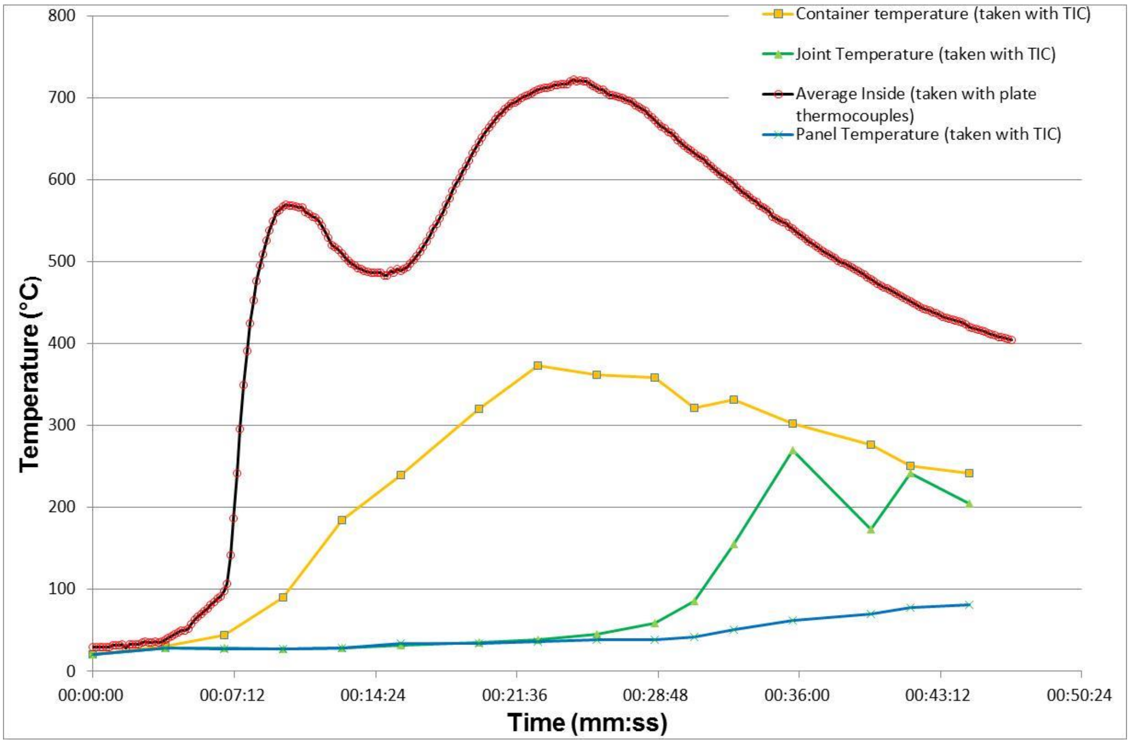


Figure 4.5.1.(c) Test 3 - 95mm thickness with horizontal orientated joint.

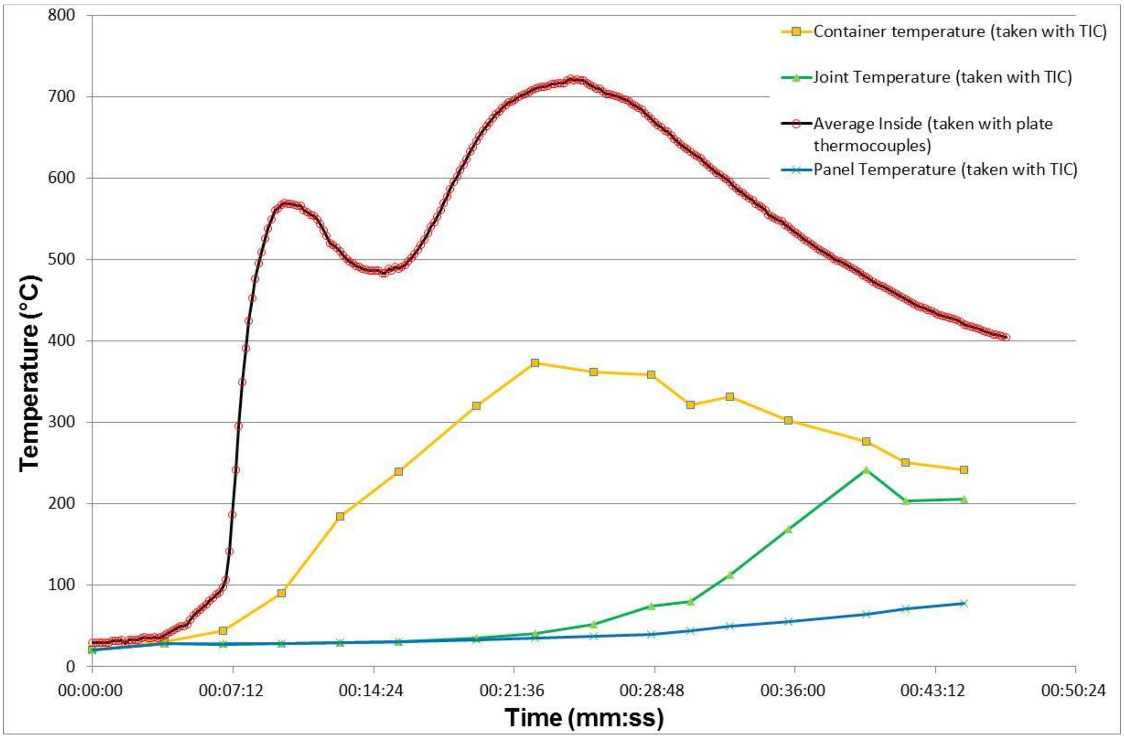


Figure 4.5.1.(d) Test 4 - 95mm thickness with horizontal orientated joint.

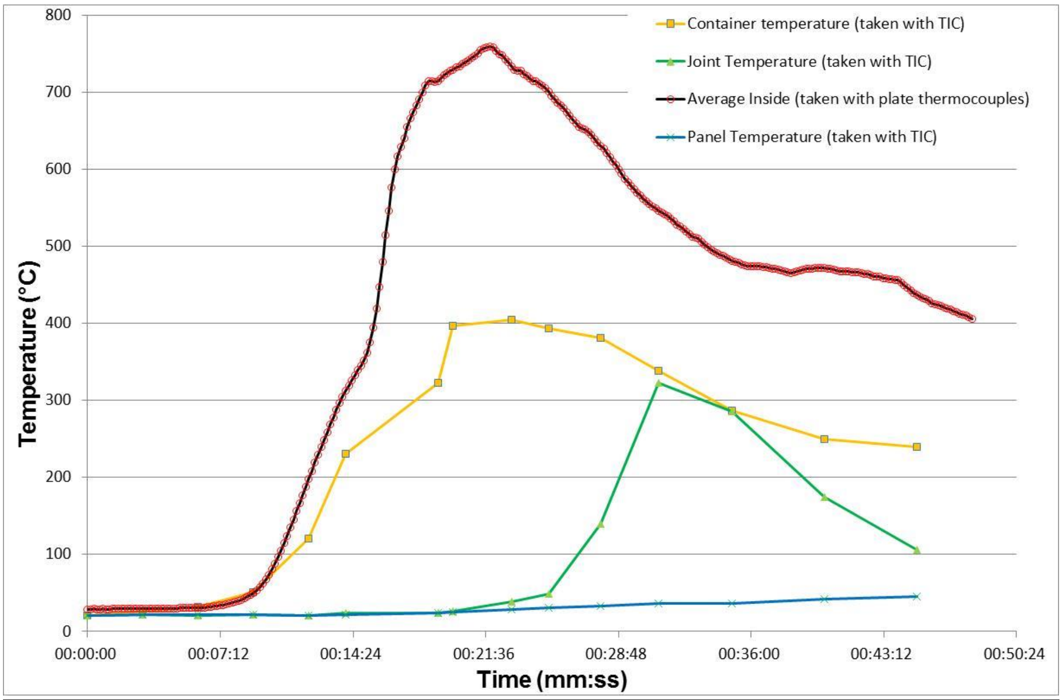


Figure 4.5.1.(e) Test 5 - 120 mm thickness with vertical orientated joint.

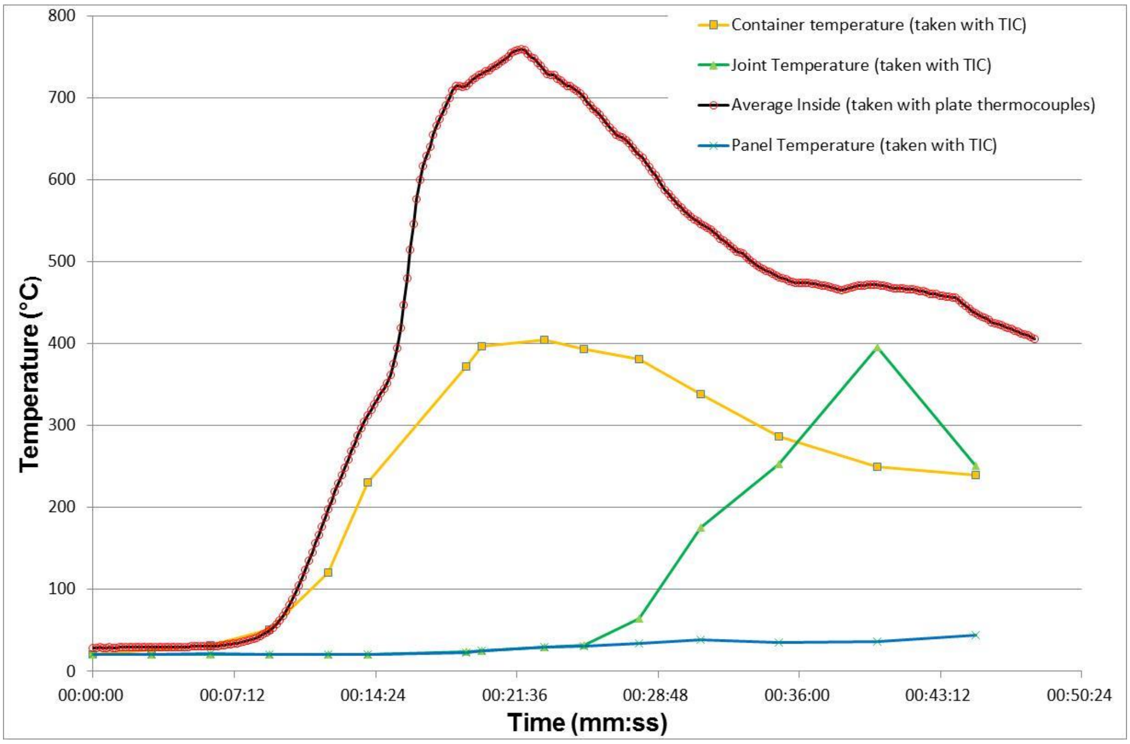


Figure 4.5.1.(f) Test 6- 120mm thickness with vertical orientated joint

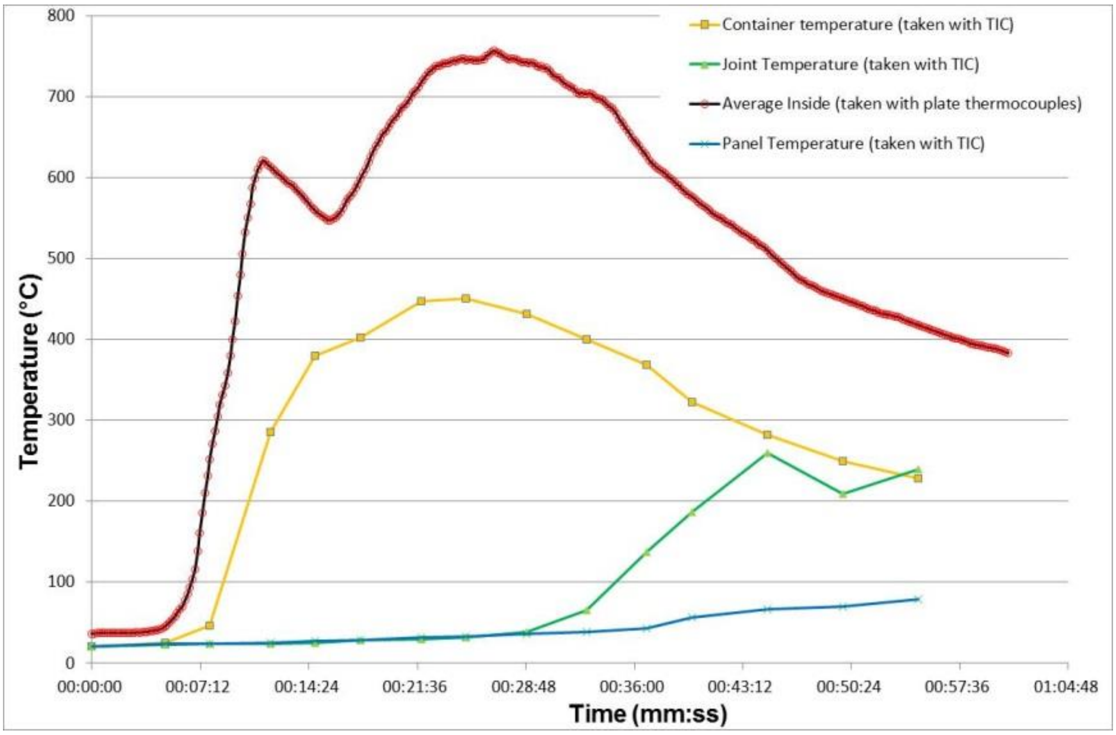


Figure 4.5.1.(g) Test 7- 120 mm thickness with horizontal orientated joint.

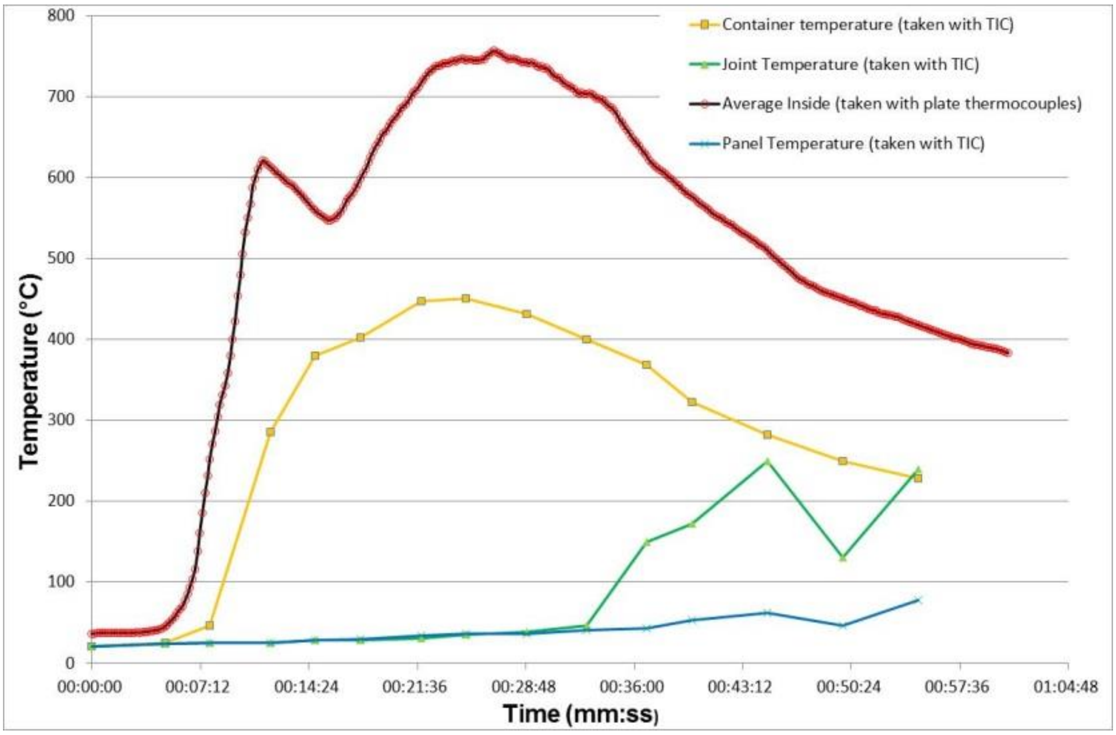


Figure 4.5.1(h) Test 8- 120 mm thickness with horizontal orientated joint.

4.6 Comparison between panel and joint temperature taken by thermal imaging camera from outside compartment in early stages of the fire.

This section examines in detail the results taken externally with the thermal imaging camera. It can been seen in the previous section that the panel and joint temperatures in all cases appear to show very little differences in temperature until the tests have progressed significantly. This section takes a more detailed examination of the temperature profiles on both the joint and panel to determine the actual temperature profiles in the early stages of the tests.

The thermal imaging camera was used to take temperatures on the external face of the panel and at the joint at regular intervals or when any significant event occurred. An analysis is made of the panel thicknesses and the joint configuration and conclusions made of the differences and whether this could be used to assist in fire fighting.

This tests and analysis is designed to replicate the conditions that may exist when the Fire and Rescue Service attend a fire at sandwich panelled building where full access is not possible. Where temperature profiles are being gathered from the outside the building in the early stages and it appears that the external panels and joint temperatures increase slowly and are little above ambient temperature, then this could give a false impression of the fire conditions within the compartment at this stage.

The purpose of collecting and analysing the temperature profiles of the joint and the panel at the early stages of the test is to provide some comparisons between the external temperatures in the early stages and consider how this information could be used to guide fire fighting decision making.

4.6.1 Results of comparison between panel and joint temperature taken by thermal imaging camera from outside compartment in early stages of the fire.

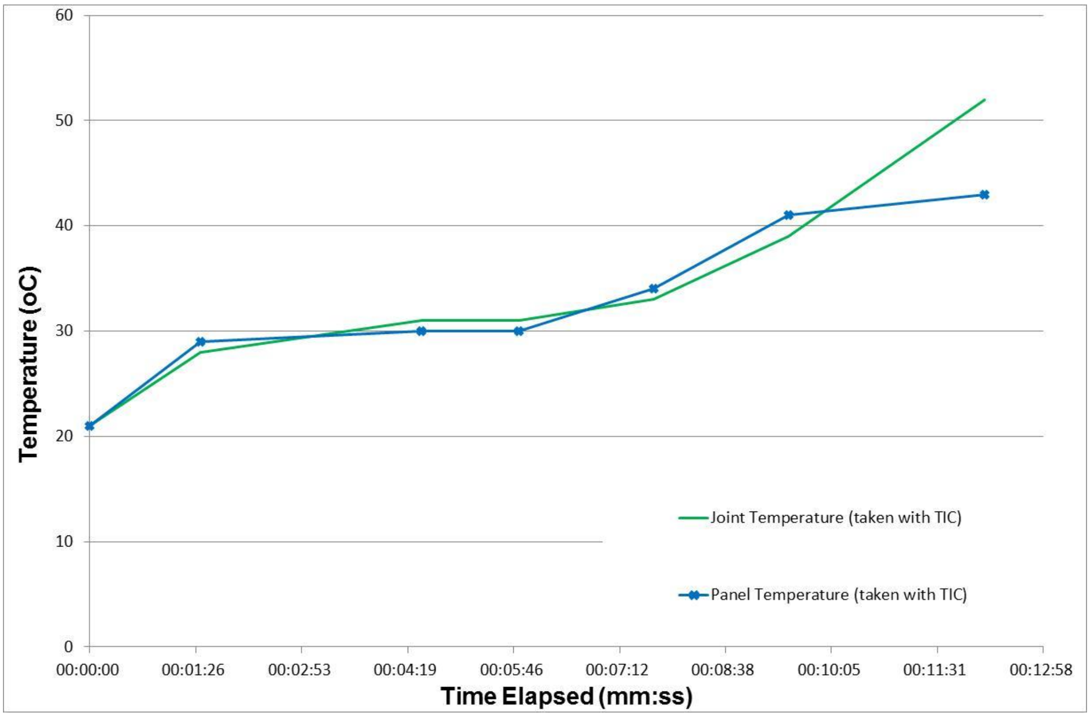


Figure 4.6.1(a) Test 1- 95mm thickness with vertical orientated joint

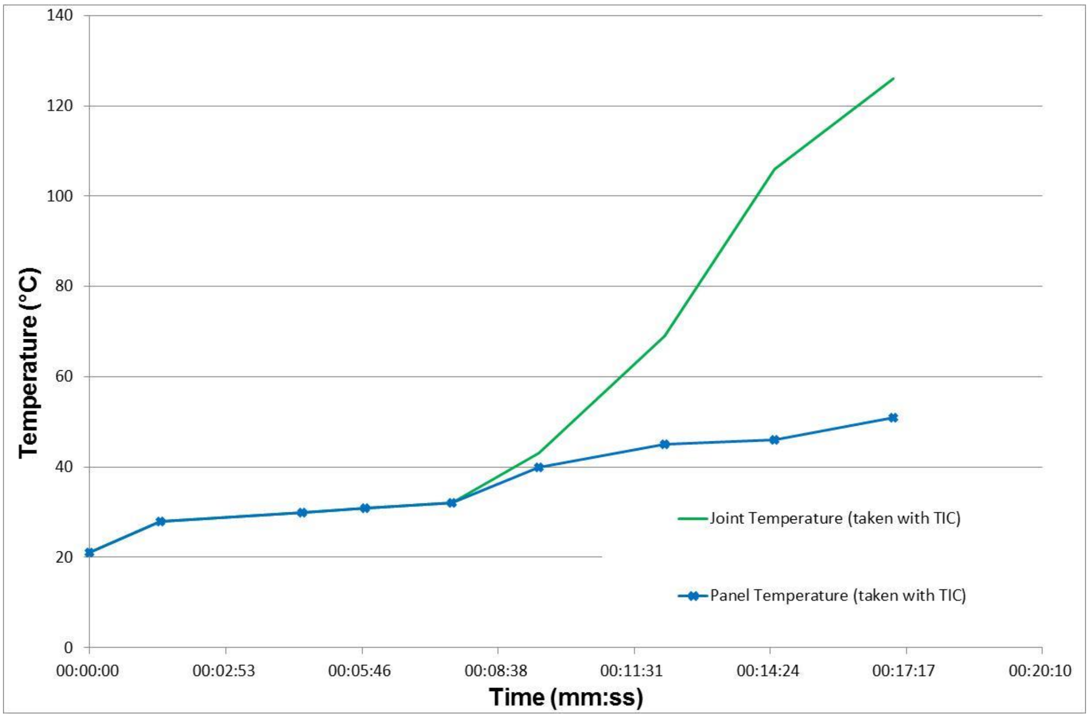


Figure 4.6.1(b) Test 2 - 95mm thickness with vertical orientated join

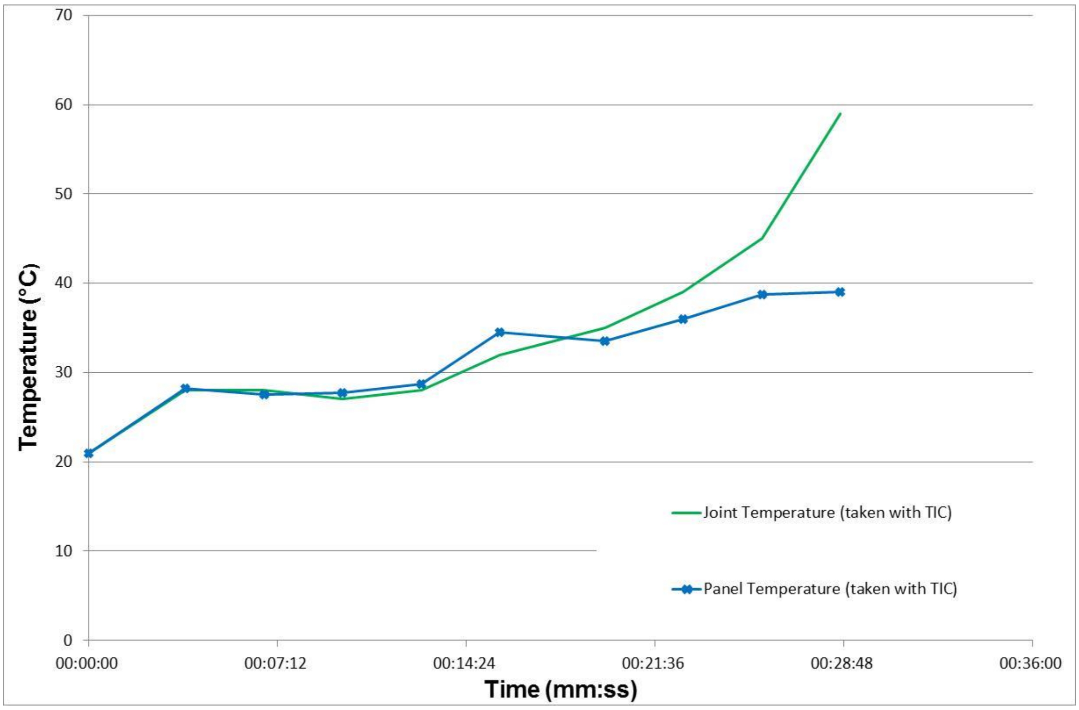


Figure 4.6.1(c) Test 3 - 95mm thickness with horizontally orientated joint

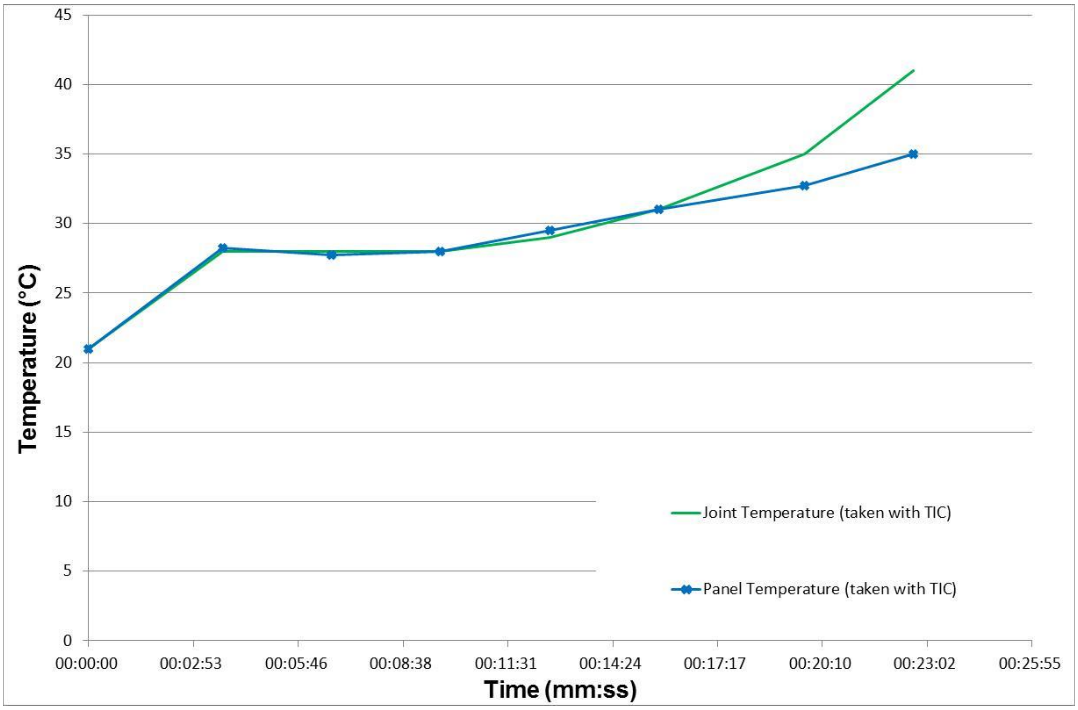


Figure 4.6.1(d) Test 4 - 95mm thickness with horizontally orientated joint

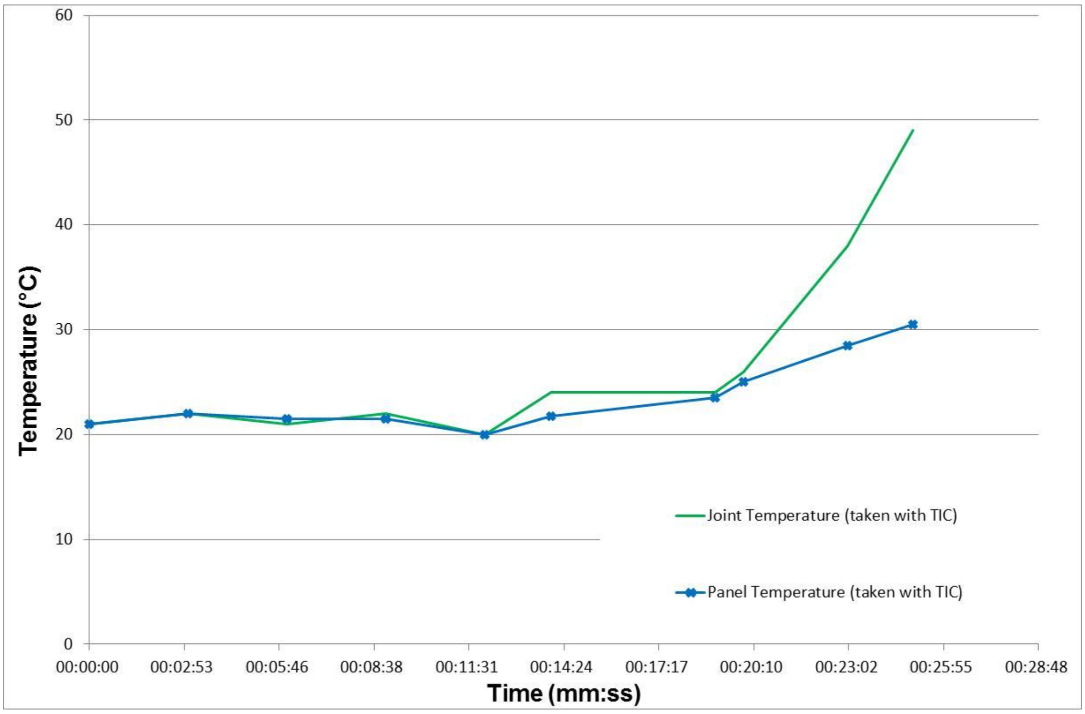


Figure 4.6.1(e) Test 5 - 120mm thickness with vertically orientated joint

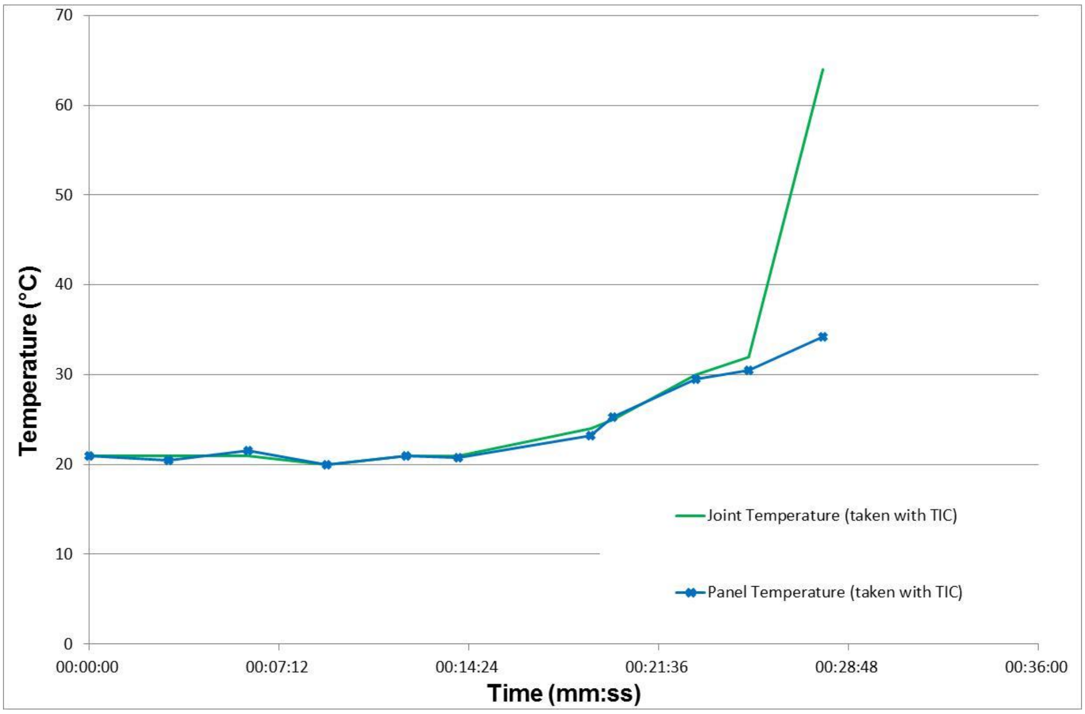


Figure 4.6.1(f) Test 6 120mm thickness with vertically orientated joint

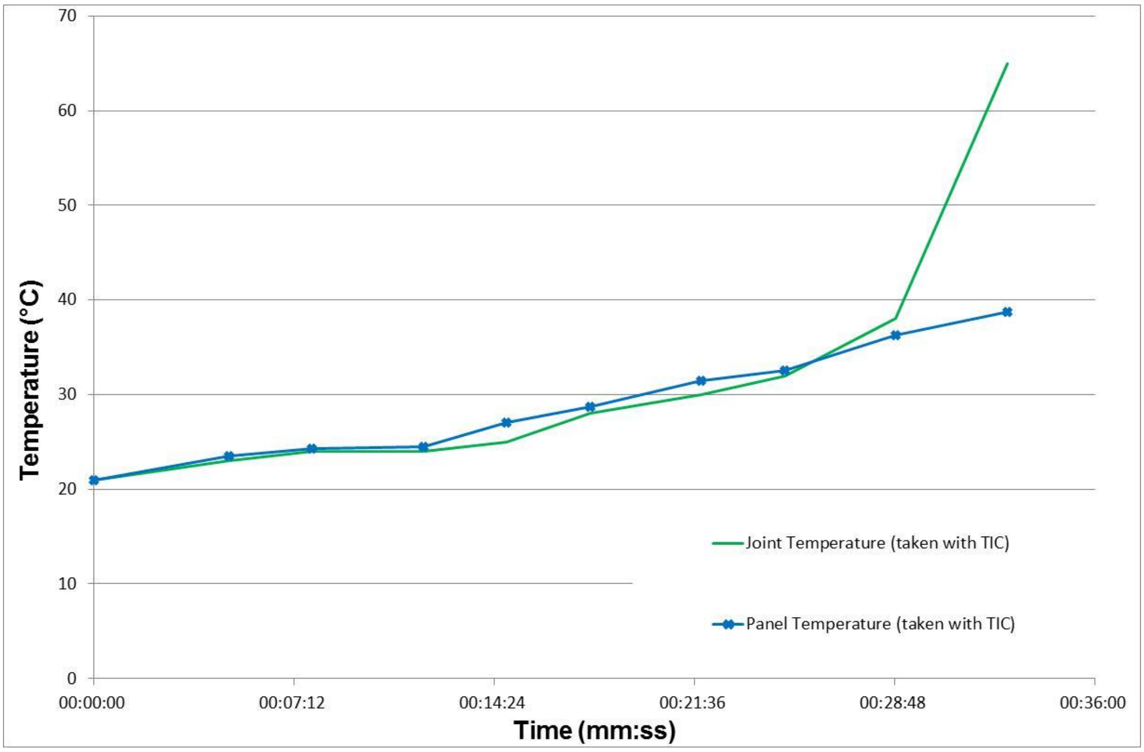


Figure 4.6.1(g) Test 7 120mm thickness horizontal joint orientation

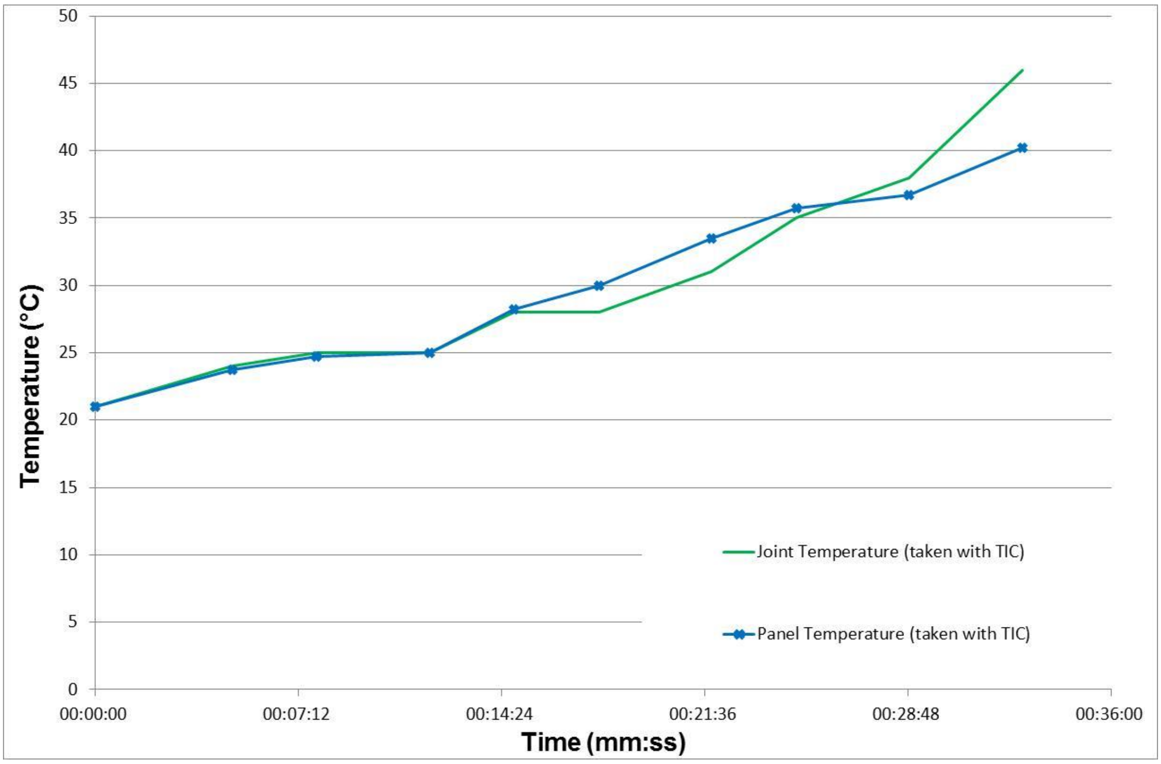


Figure 4.6.1(h) Test 8 - 120mm thickness horizontal joint orientation

4.7 Displacement profiles taken from outside of the container.

The purpose of taking these measurements was primarily to assist the work of Andrew Foster, a PhD student at Manchester University who is assessing temperature profiles within sandwich panel construction by using mathematical modelling methods. The measurements taken in these series of tests are to be used to inform and validate the mathematical model that he is developing.

In the literature review there was no guidance or information identified detailing deflection in sandwich panel construction when subjected to fire conditions. This was an opportunity to examine the defection profiles in each of the fire tests and consider whether any correlation between the deflection on the outer face and the fire compartment conditions exists.

Although some guidance exists for UK Fire and Rescue Services in relation to the risks associated with expansion of the inner face of walls potentially creating instability, no further consideration was given to what the fire temperatures within the compartment. This was therefore considered an opportunity to collect and analysis the results of the defection profiles on the external face of sandwich panels exposed to real fire conditions and comment on whether this information can be used to influence fire fighting decision making.

Displacement profiles were taken from outside of the container using linear displacement transducers and the results recorded by a data logger every 10 seconds throughout the test duration, using four separate channels designated 129, 130, 131, and 132. Two linear displacement transducer were positioned either side of each panel joint being tested. They were positioned at the centreline of each sample being tested, 10mm either side of the joint detail as show in figure 4.7 below. This arrangement was consistent for all of the tests.

Figure 4.7 Linear displacement transducers in situ during tests

This method is designed to measure displacement at the joint over the duration of the test period. This will allow the results to be analysed to determine whether a relationship can be established between the temperature of the compartment and the displacement measured.

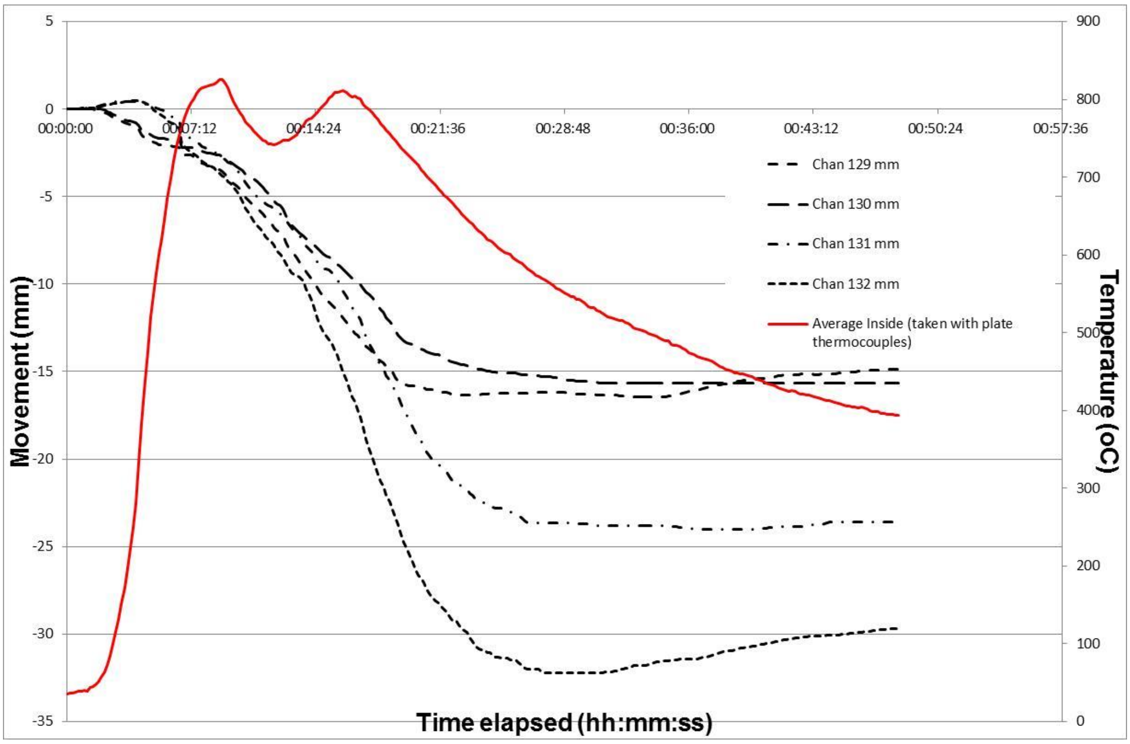


Figure 4.7.1(a) Movement deviations for Test 1 and Test 2

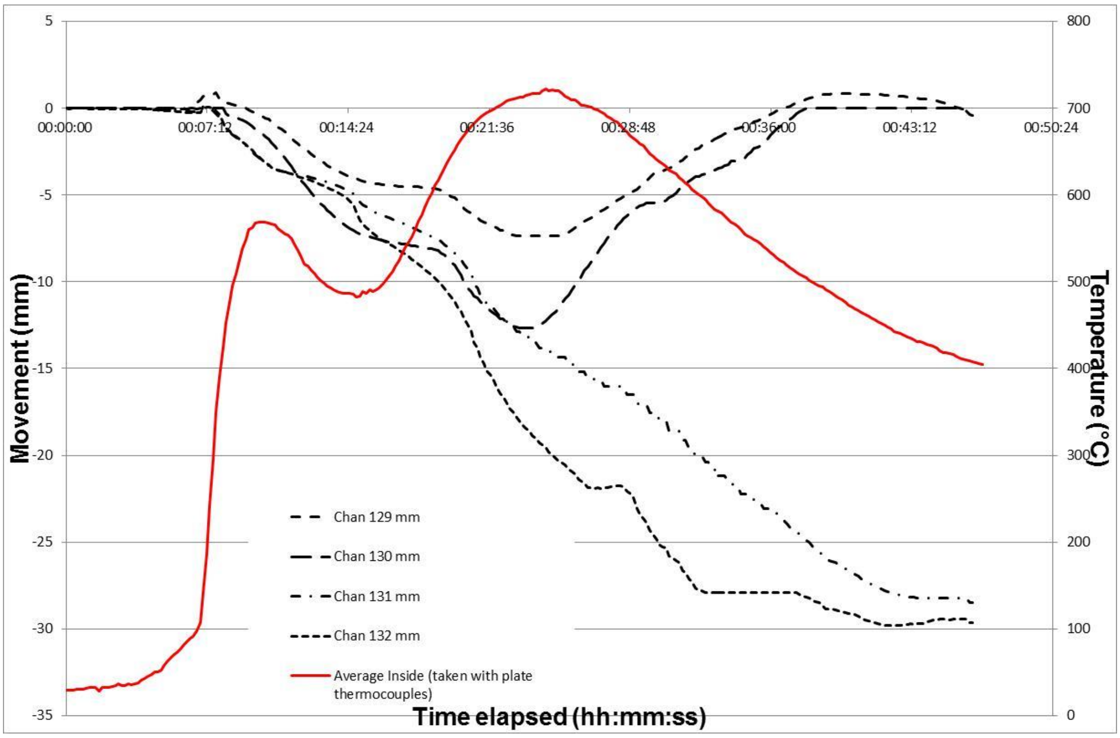


Figure 4.7.1(b) Movement deviations for Test 3 and Test 4

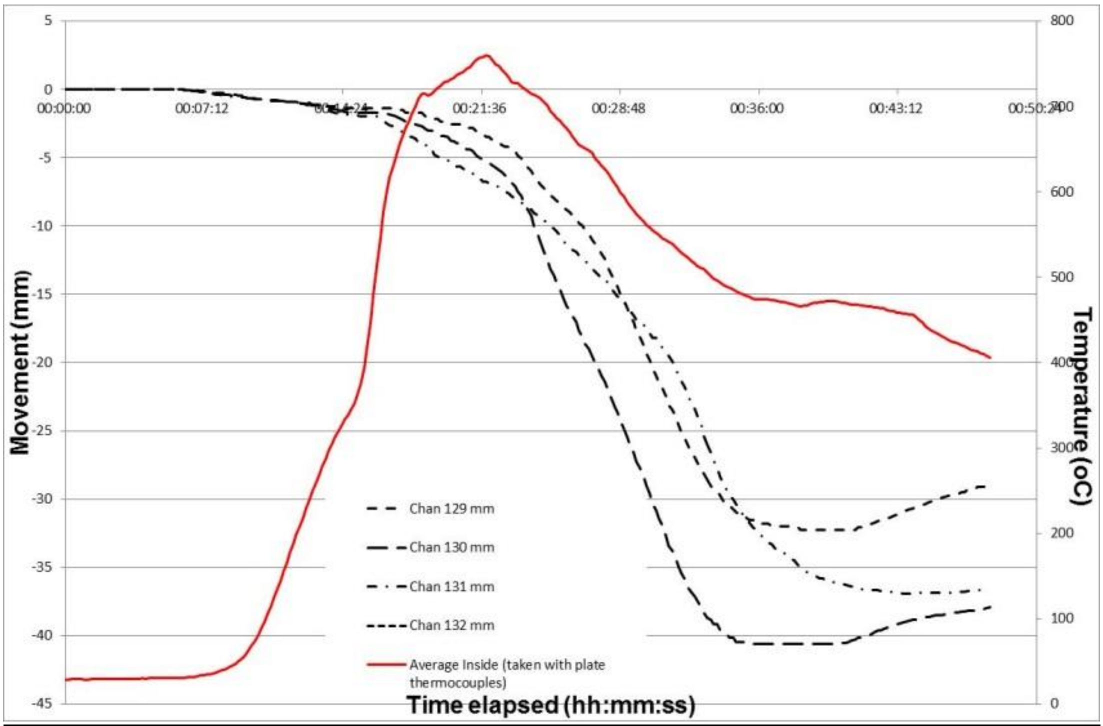


Figure 4.7.1(c) Movement deviations for Test 5 and Test 6

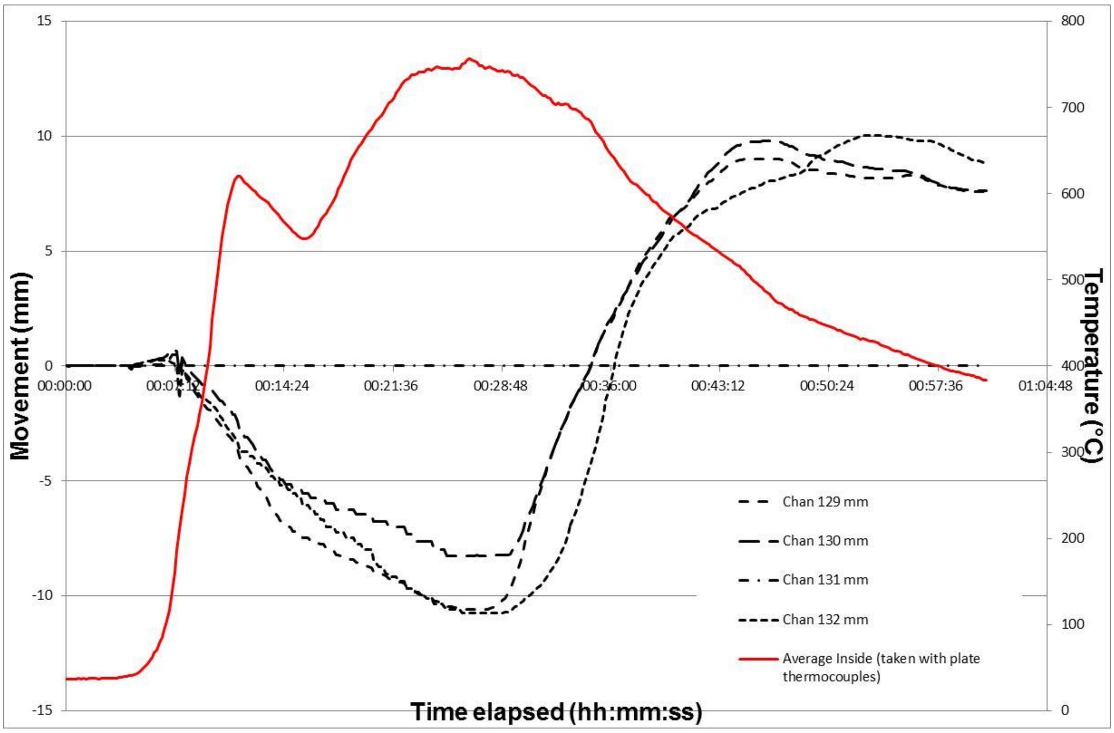


Figure 4.7.1(d) Movement deviations for Test 7 and Test 8

4.8 Temperatures taken 10mm below exposed surface and at equivalent depth at joint

Much of the guidance documents available to Fire and Rescue Services suggest that where sandwich panels are involved in fire then the outer facing can be peeled back to reveal and identify the core type. The purpose of this action is primarily to determine whether the core is combustible or not which would then inform fire fighting decision making. It is acknowledged that the action of revealing the core and joint at a 10mm depth from the unexposed face represents a simple practical action that could be carried out by Fire and Rescue Services utilising simple hand tools and relatively quickly.

However where the external facing has been peeled back this could provide an opportunity to examine the temperature profile just below the surface of the exposed face and compare those temperatures at the joint at a similar depth for the external unexposed face of the sandwich panel. This section seeks to determine whether taking temperature readings at the joint and sandwich panel core 10mm below the surface of the unexposed face would provide information relating to the fire conditions within the compartment.

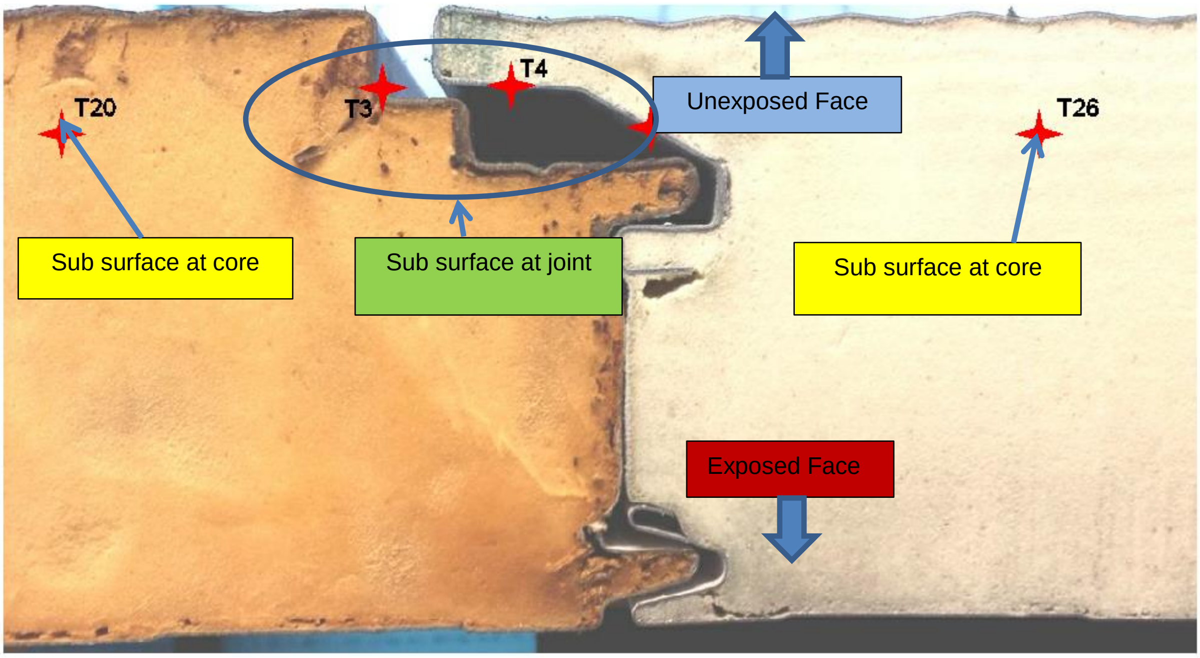


Figure 4.8 Slice profile at joint and core 10mm below surface of unexposed face

By measuring and comparing the temperatures at the same depth from the unexposed surface at both the joint and at the core of the sandwich panel allows a comparison to be drawn between the joint core temperature profiles. This information can then be analysed to determine whether the temperatures at these points bear any relationship to the temperatures within the fire compartment.

It would be expected that the temperatures at 10mm below the surface would reach a higher temperature sooner than at the unexposed surface. However the results will be analysed to determine whether there is a practical value in revealing the core and joint to determine the temperatures within.

Position of thermocouples	Average readings of thermocouples
10mm below surface of core	T20,T26
10mm below surface of joint	T3, T4, T5

Table 4.8 Description of thermocouples positions used to provide average readings

4.8.1 Temperature profiles taken at joint and core 10mm below surface

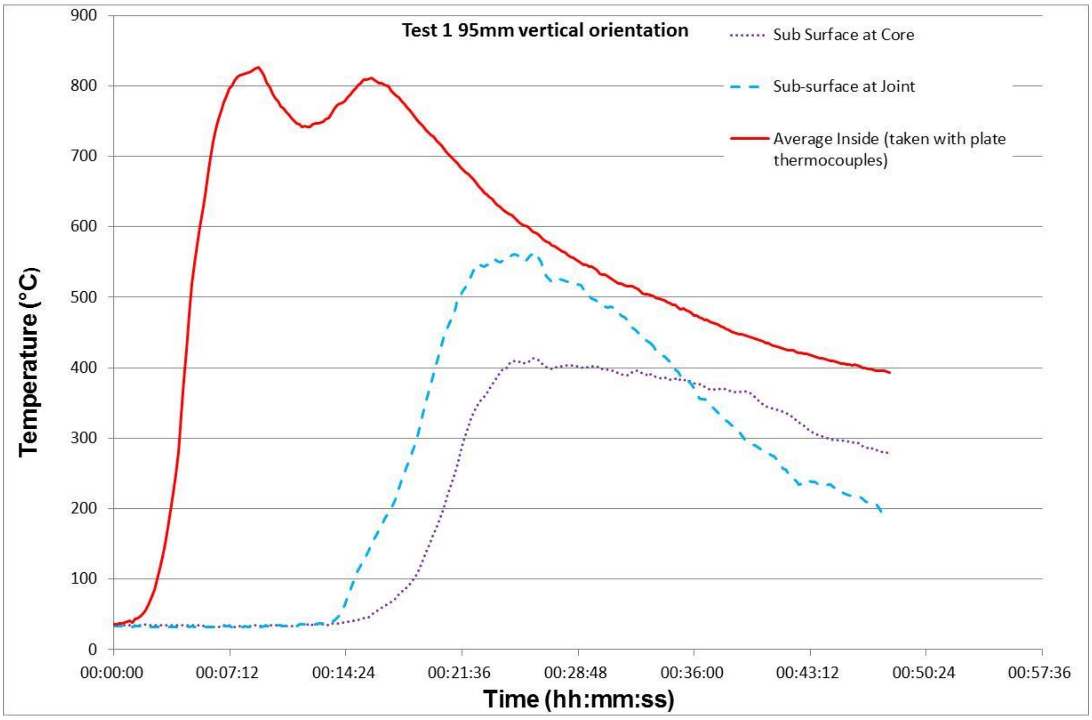


Figure 4.8.1(a) Test 1 95mm thickness with vertically orientated joint profile

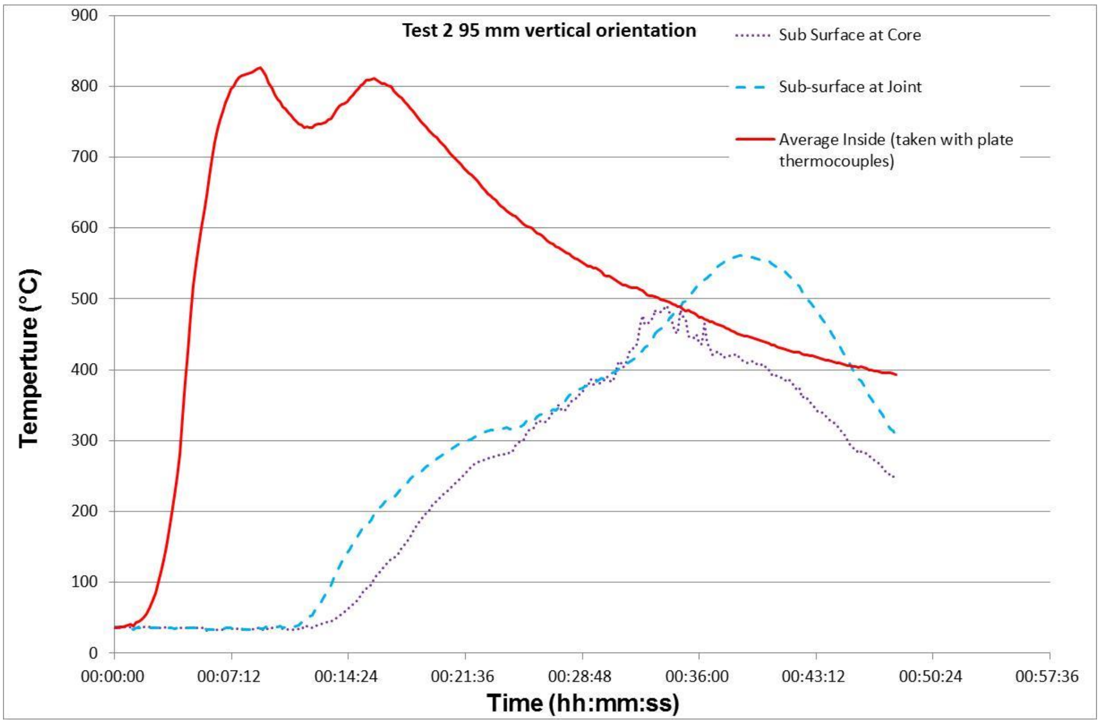


Figure 4.8.1.(b) Test 2 95mm thickness with vertically orientated joint profile

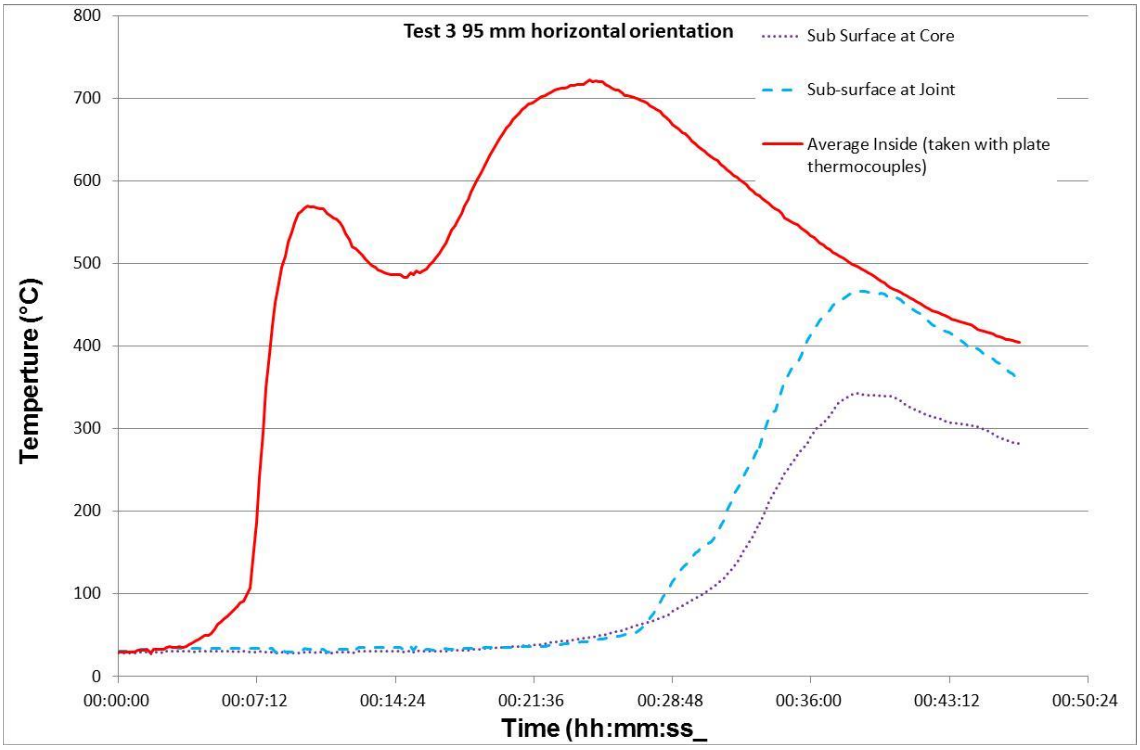


Figure 4.8.1.(c) Test 3 - 95mm thickness with horizontally orientated joint profile

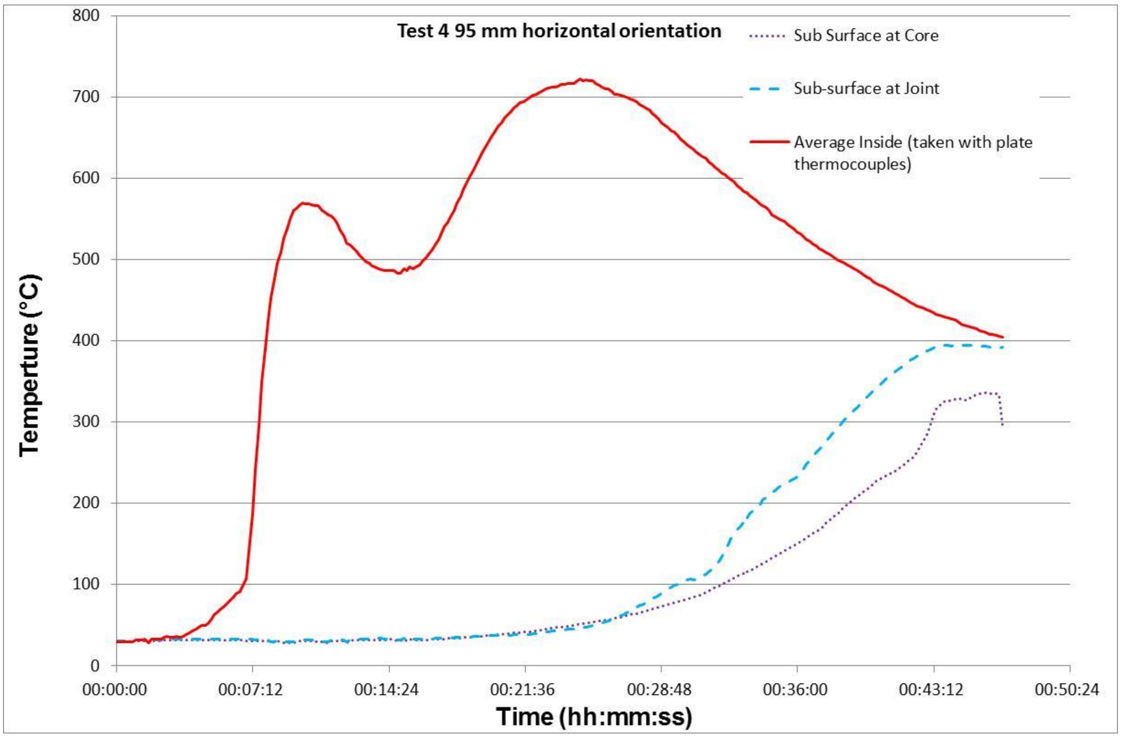


Figure 4.8.1.(d) Test 4- 95mm thickness with horizontally orientated joint profile

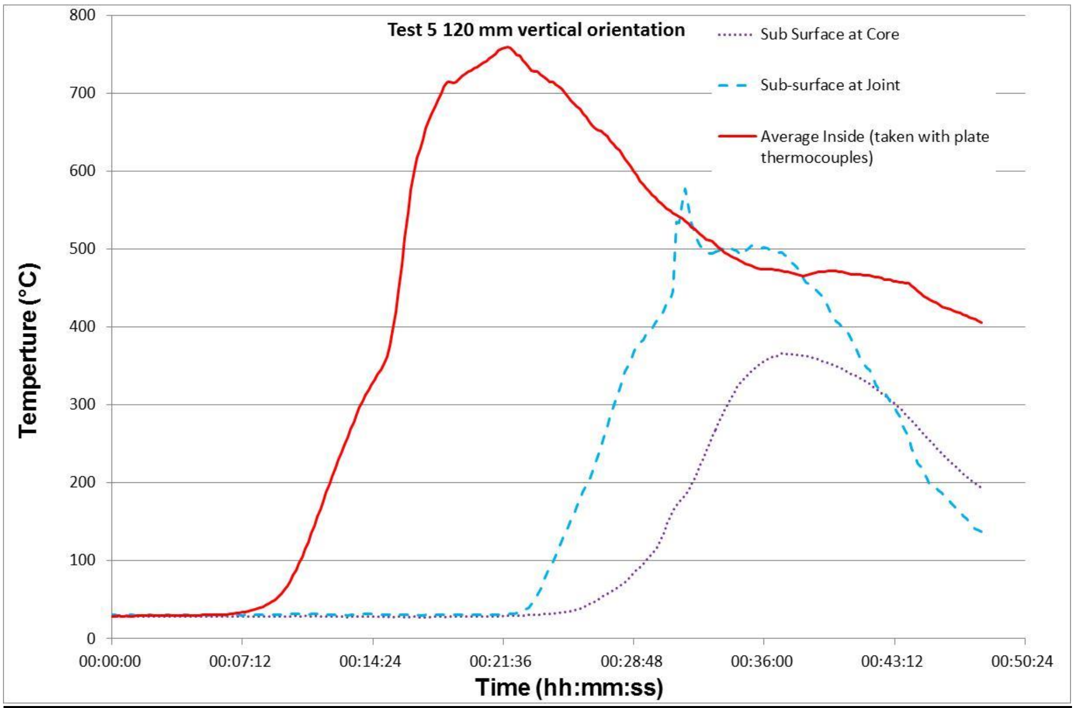


Figure 4.8.1.(e) Test 5 - 120mm thickness with vertically orientated joint profile

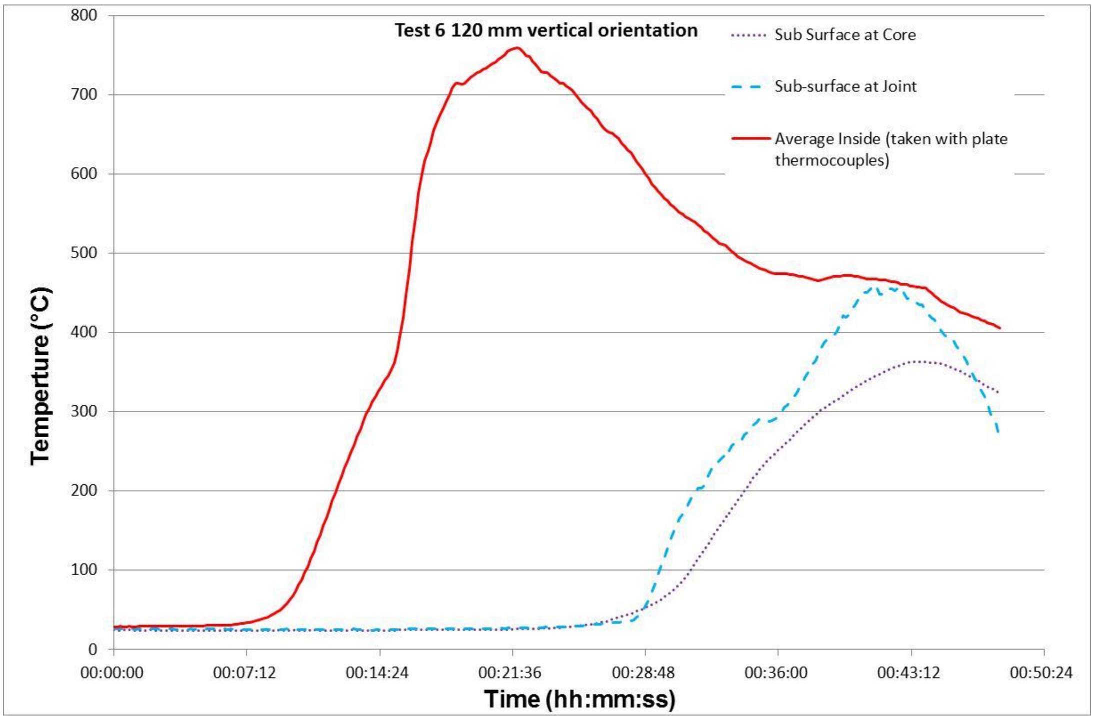


Figure 4.8.1(f) Test 6 - 120mm thickness with vertically orientated joint profile

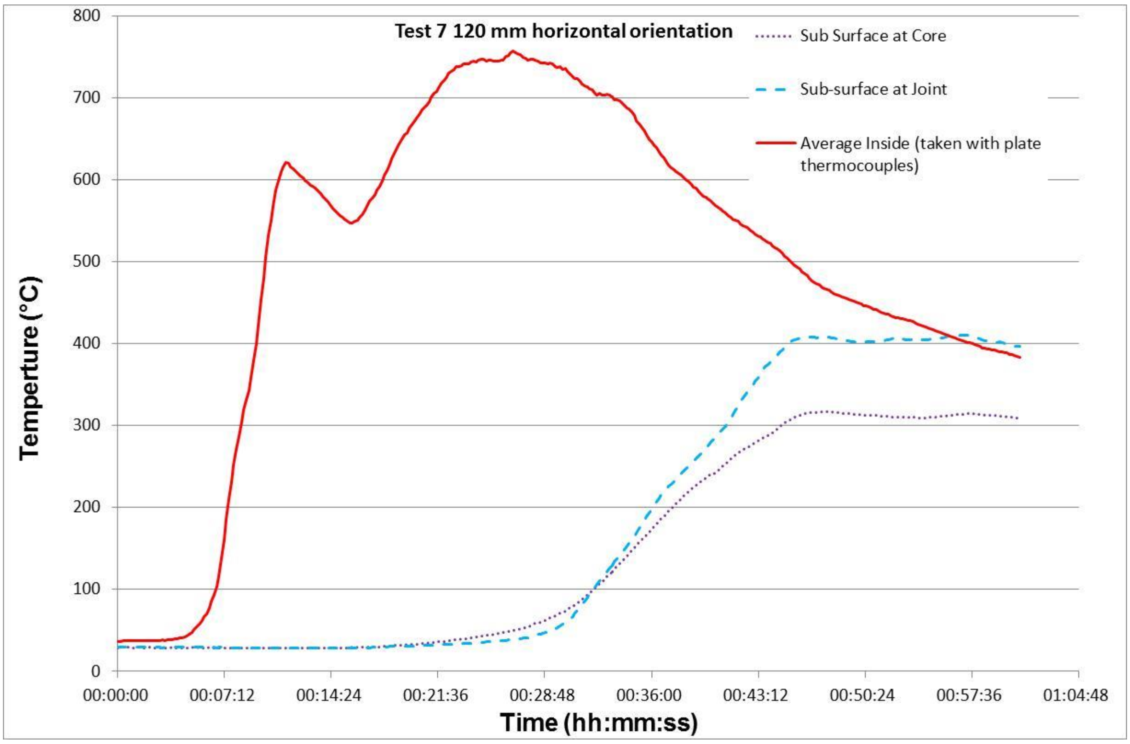


Figure 4.8.1(g) Test 7 - 120mm thickness with horizontally orientated joint profile

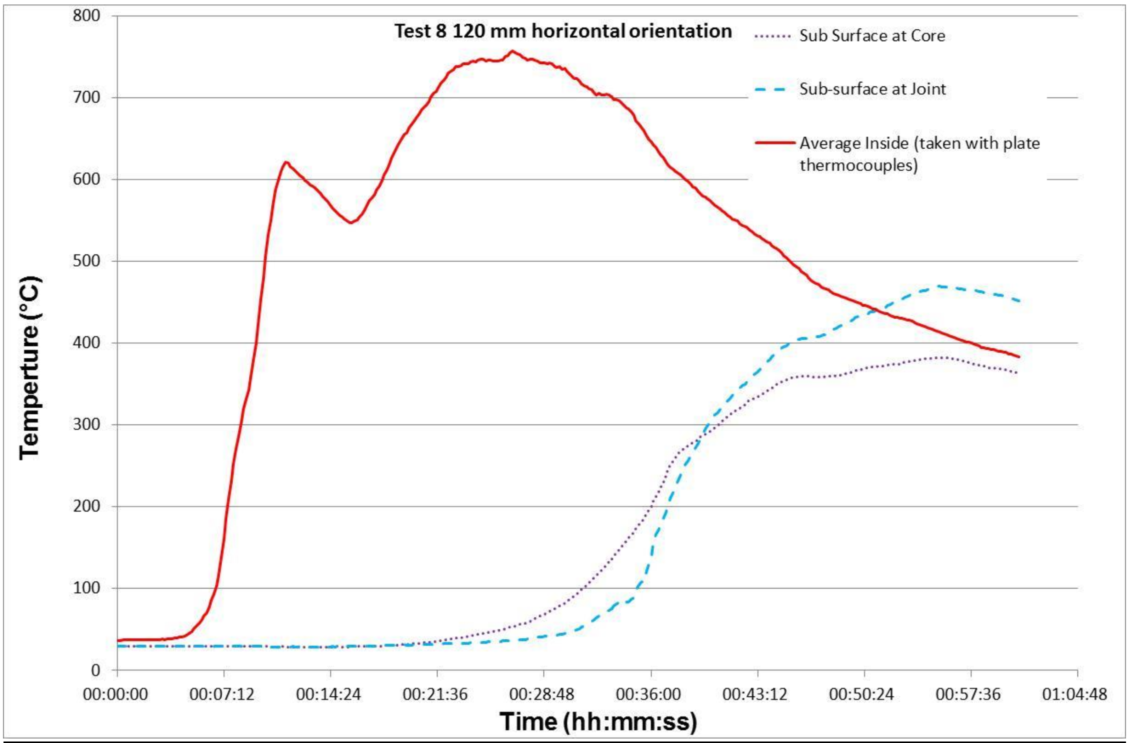


Figure 4.8.1(h) Test 8 - 120mm thickness with horizontally orientated joint profile

4.9 Rate of change of temperature at the joint and panel.

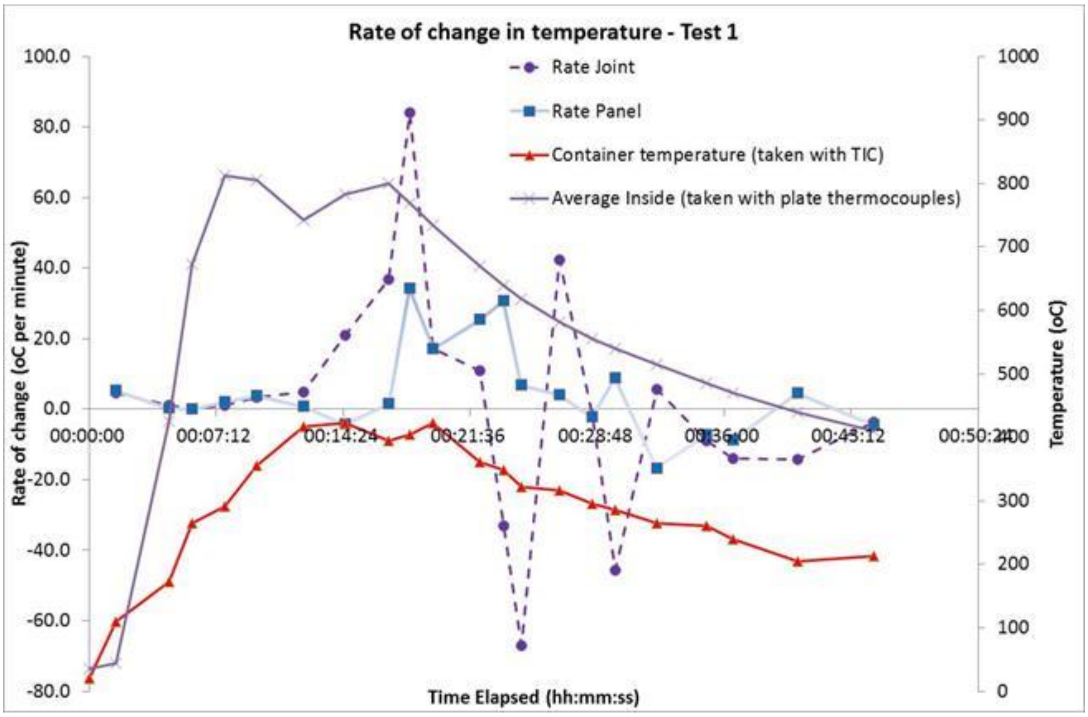


Figure 4.9(a) Test 1 - Rate of change of temperature at the joint and panel

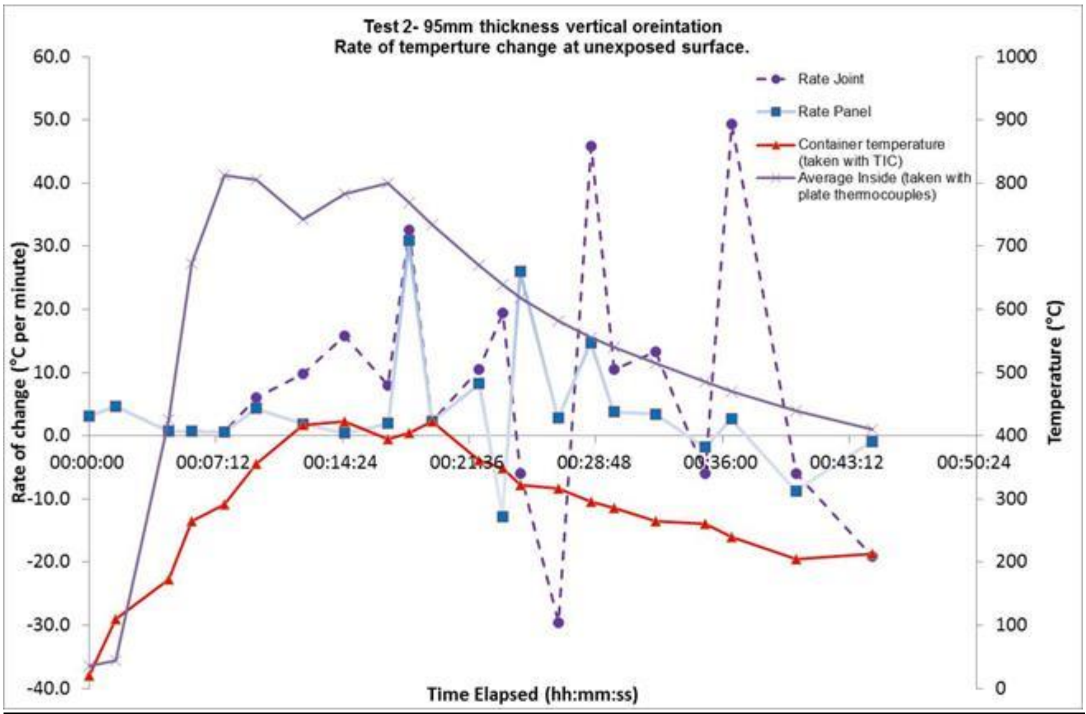


Figure 4.9(b) Test 2 - Rate of change of temperature at the joint and panel

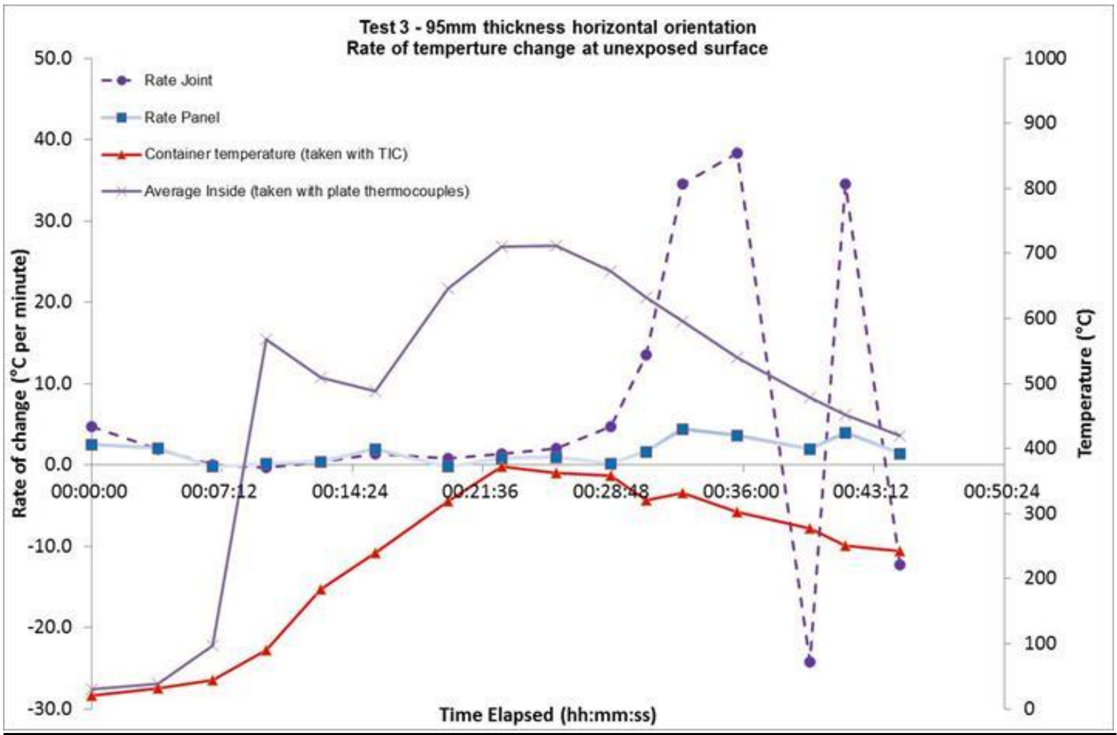


Figure 4.9(c) Test 3 - Rate of change of temperature at the joint and panel

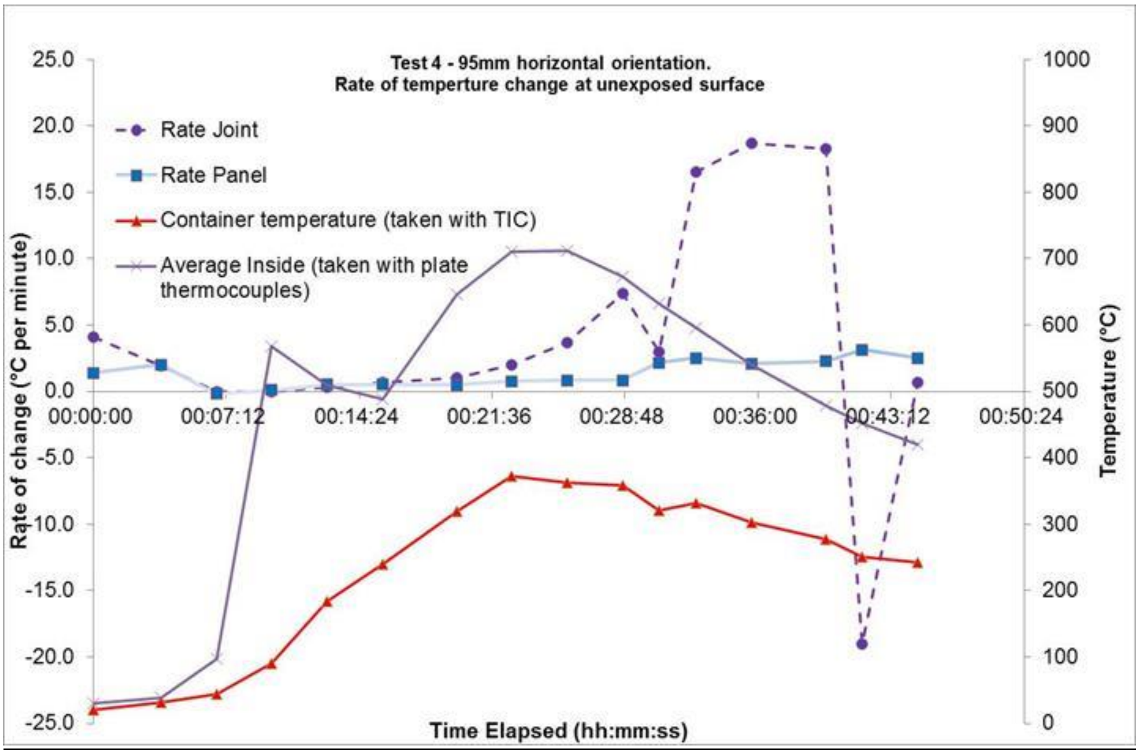


Figure 4.9(d) Test 4 - Rate of change of temperature at the joint and panel

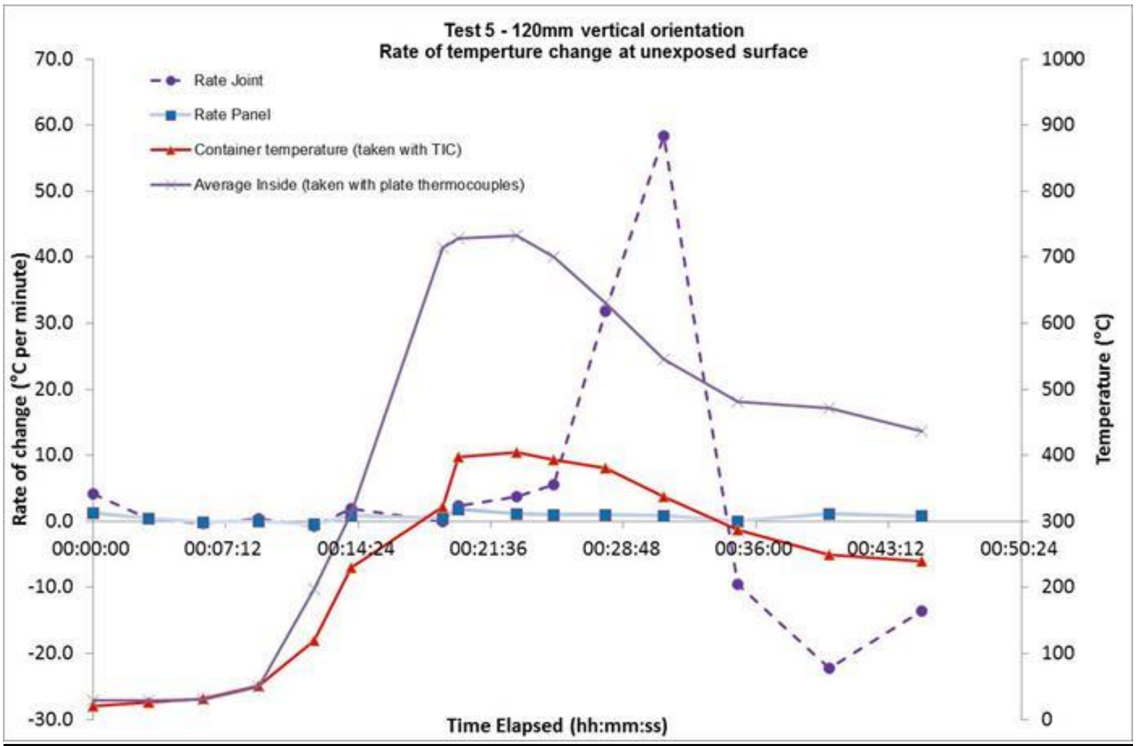


Figure 4.9(e) Test 5 - Rate of change of temperature at the joint and panel

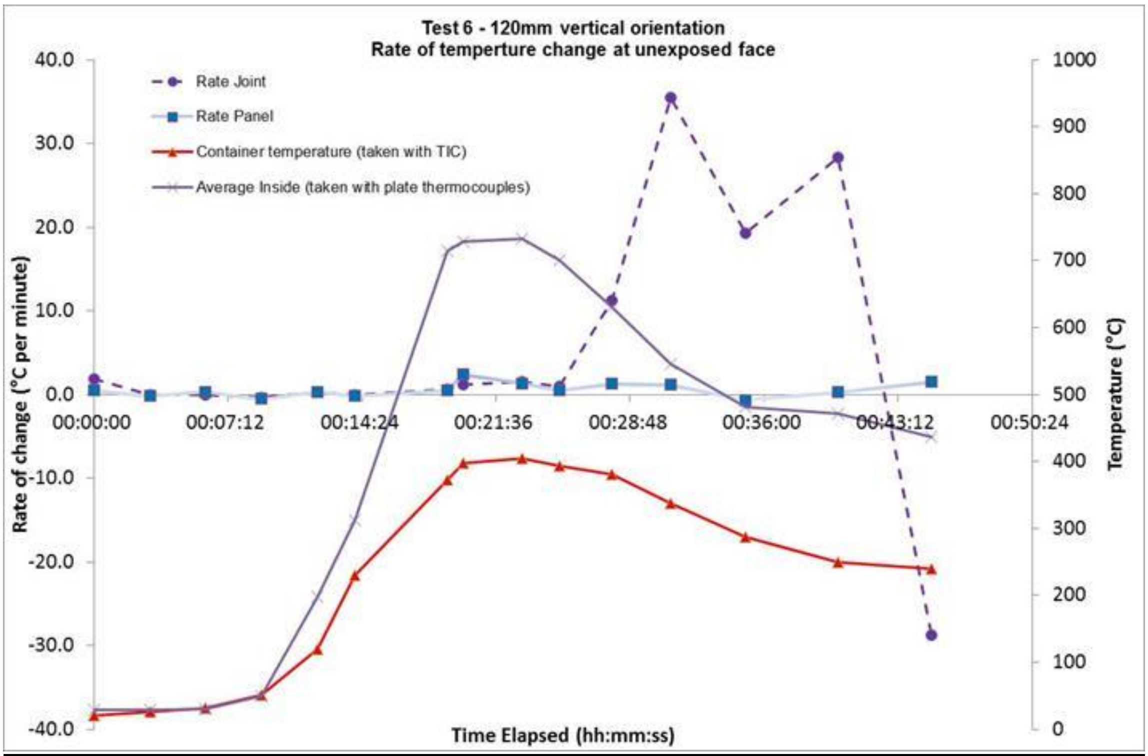


Figure 4.9(f) Test 6 - Rate of change of temperature at the joint and panel

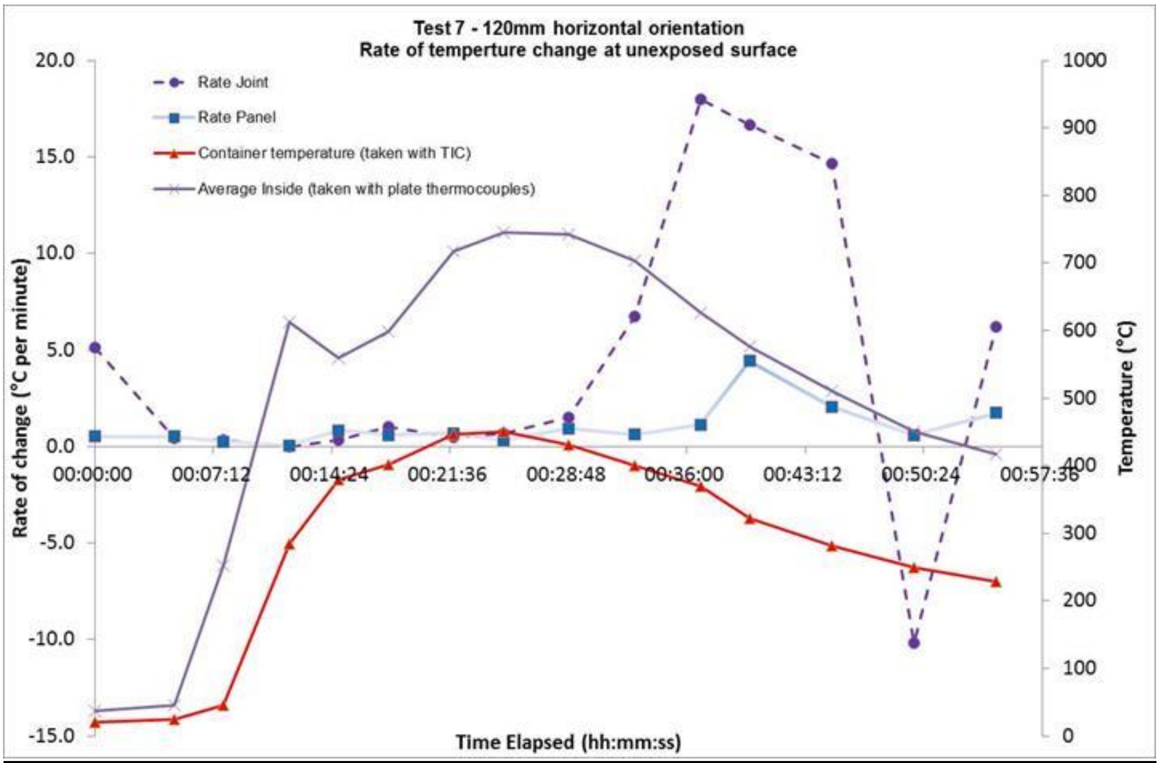


Figure 4.9(g) Test 7 - Rate of change of temperature at the joint and panel

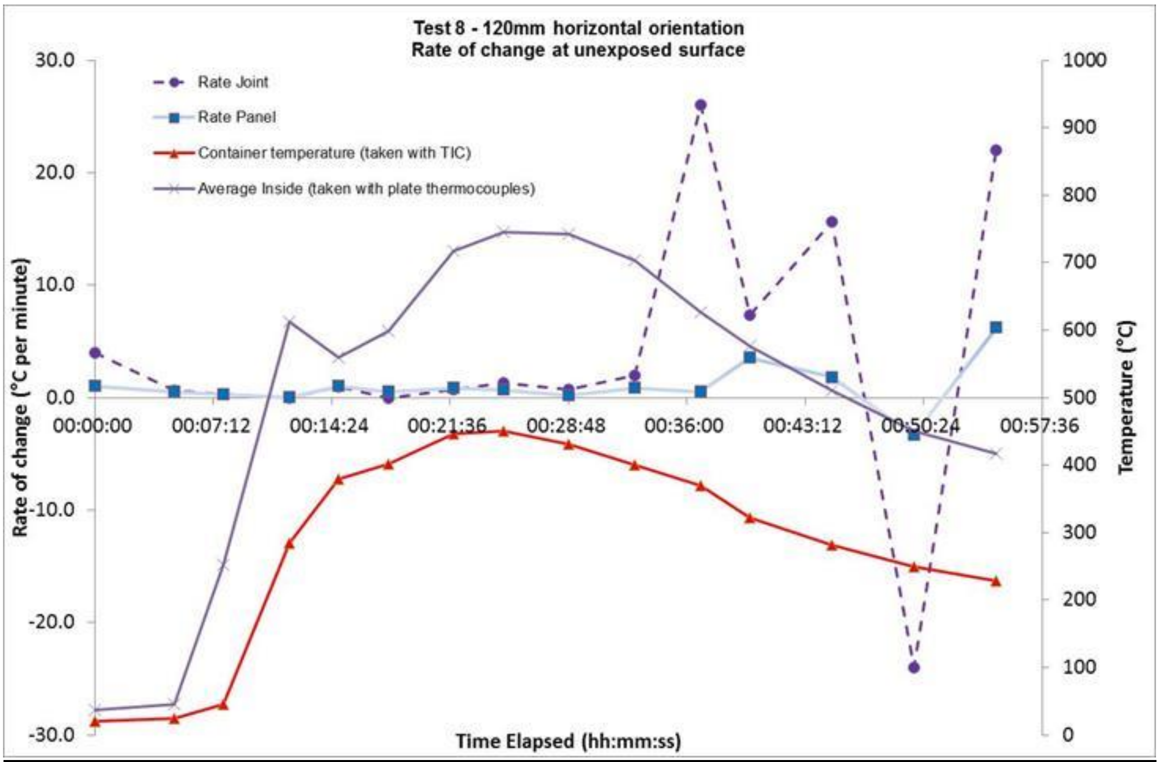


Figure 4.9(h) Test 8 - Rate of change of temperature at the joint and panel

4.10 Rate of change of temperature taken at the core and joint 10mm below the surface of the unexposed face.

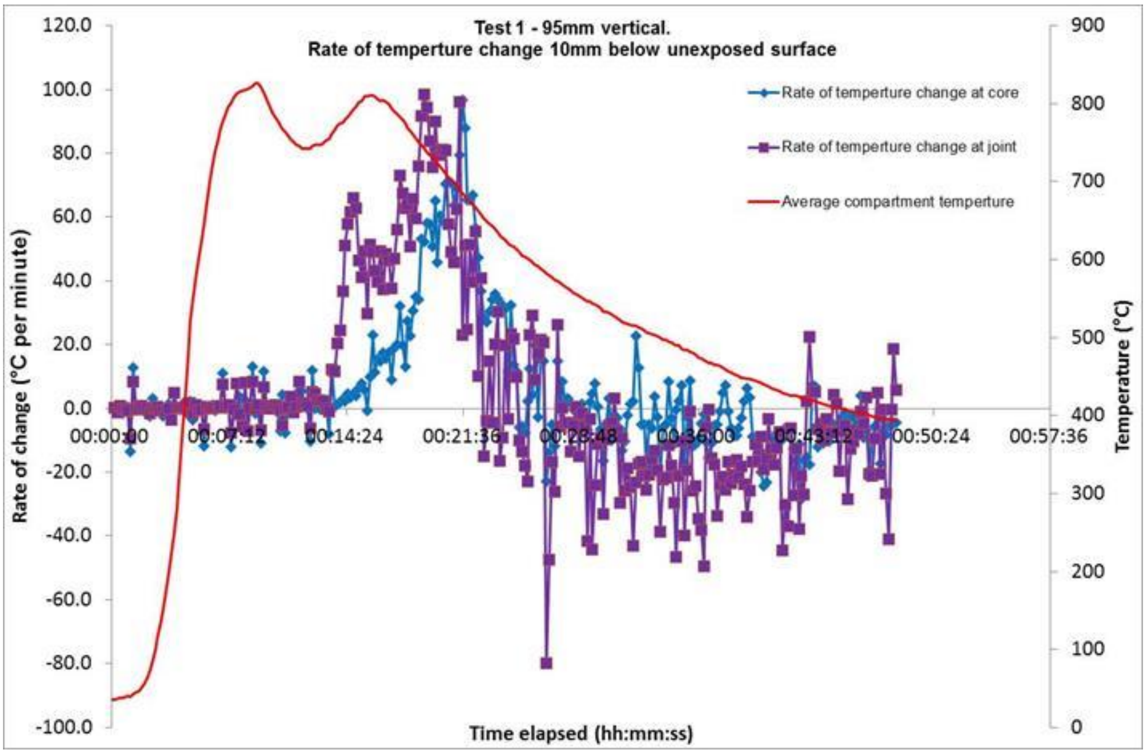


Figure 4.10(a) Test 1 - Rate of change of temperature at core and joint 10mm below

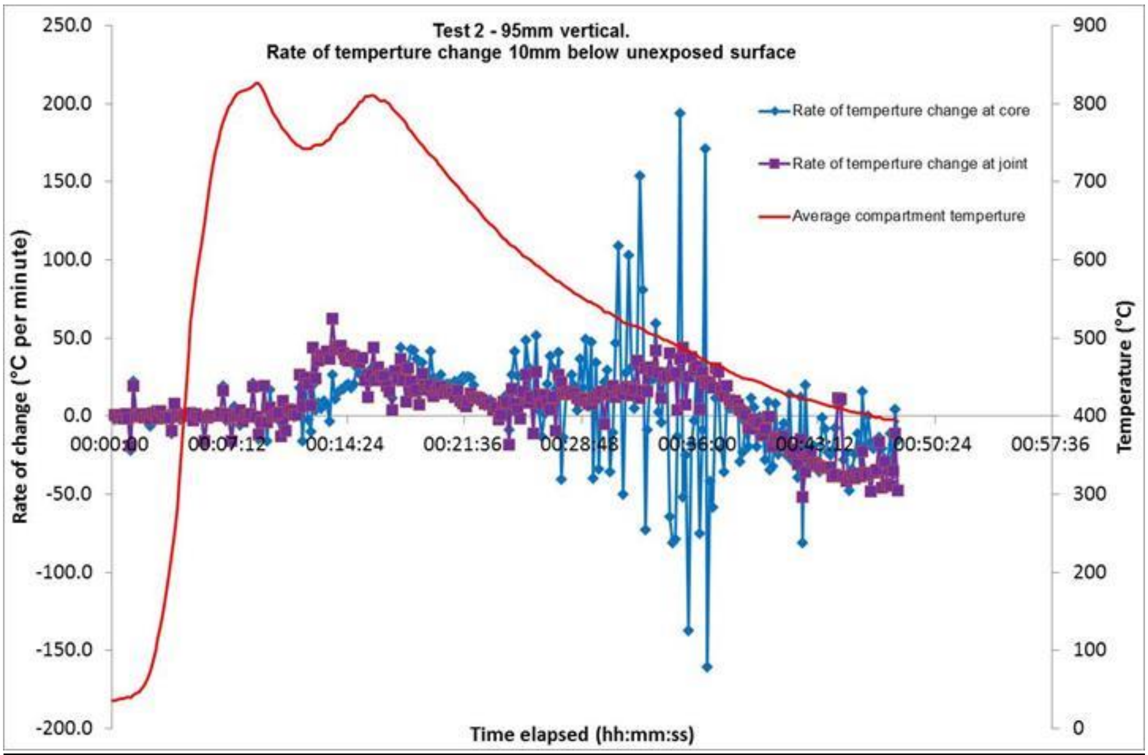


Figure 4.10(b) Test 2 - Rate of change of temperature core and joint 10mm below

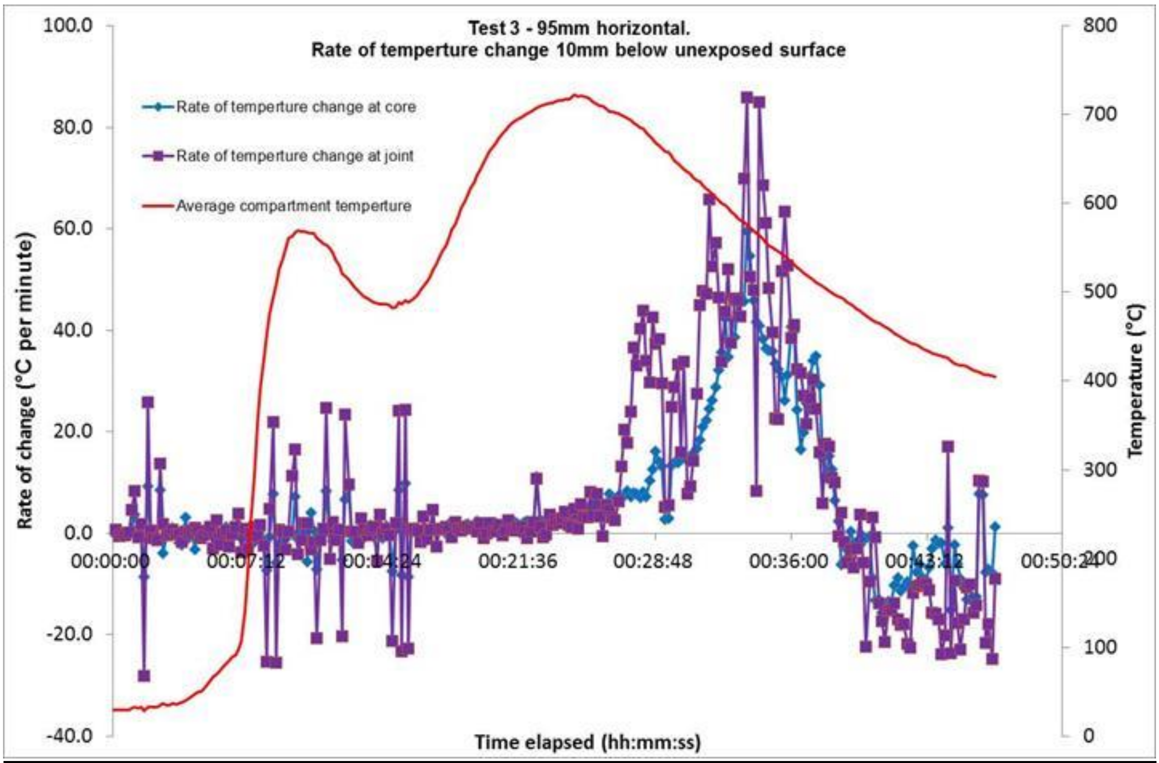


Figure 4.10(c) Test 3 - Rate of change of temperature at core and joint 10mm below

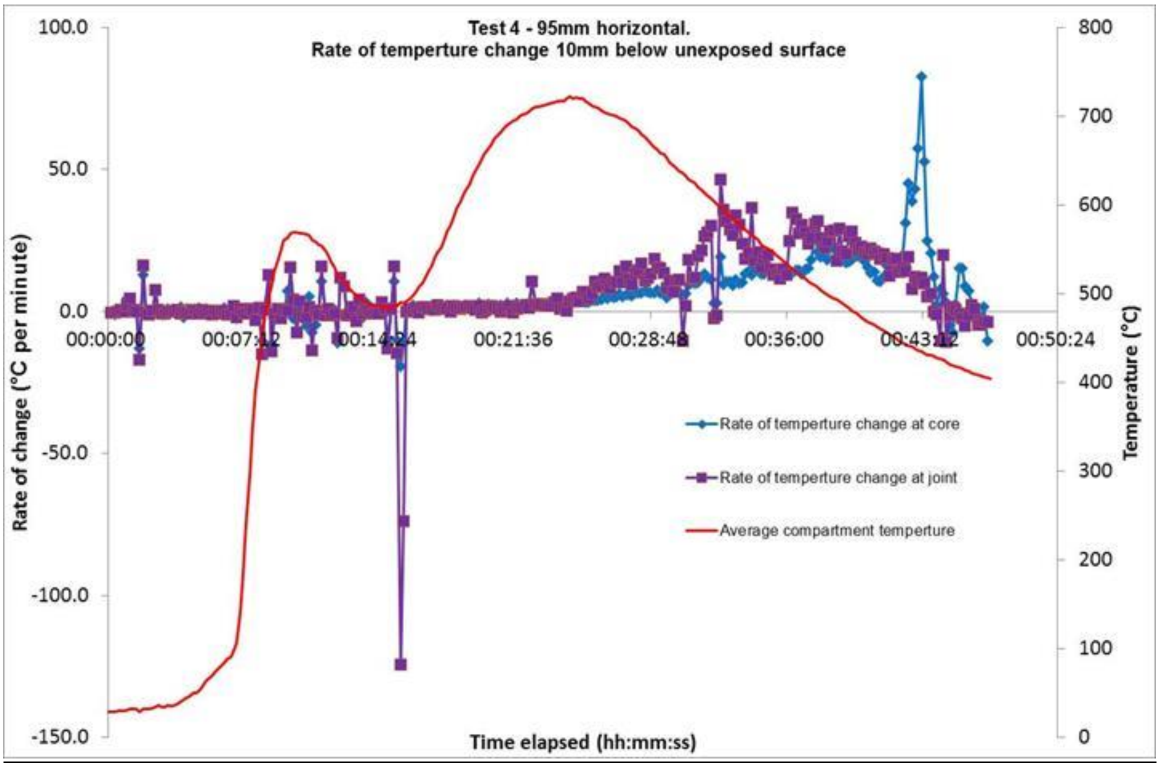


Figure 4.10(d) Test 4 - Rate of change of temperature at core and joint 10mm below

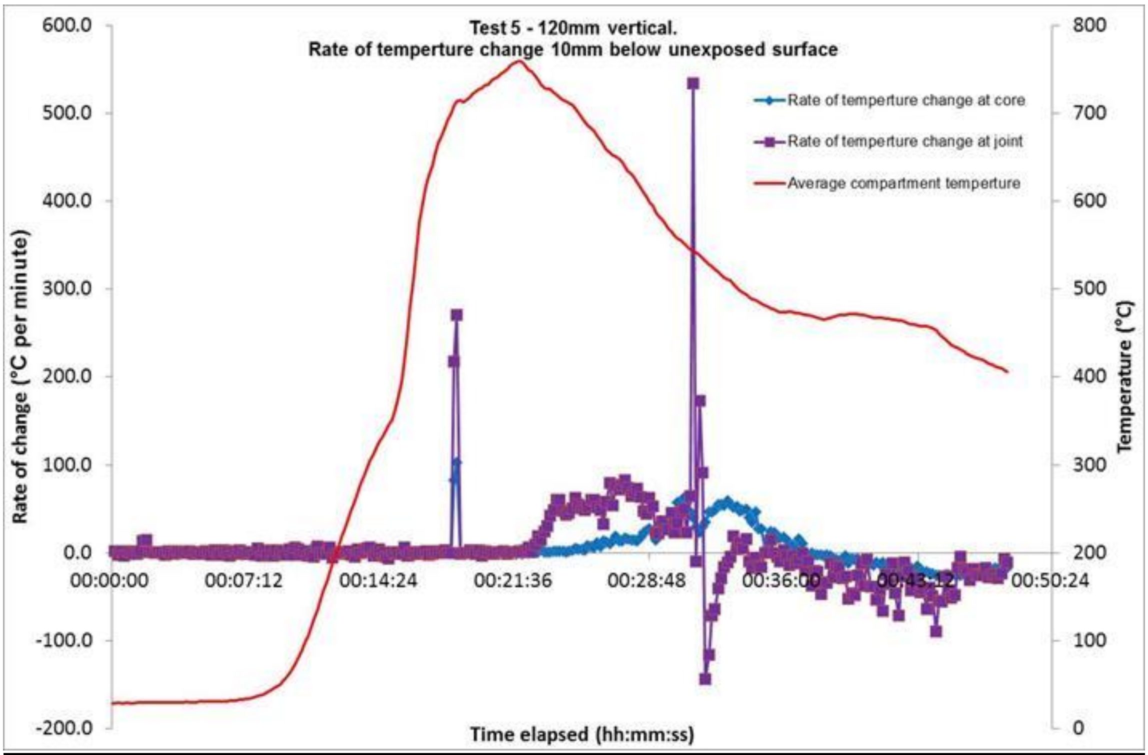


Figure 4.10(e) Test 5 - Rate of change of temperature at core and joint 10mm below

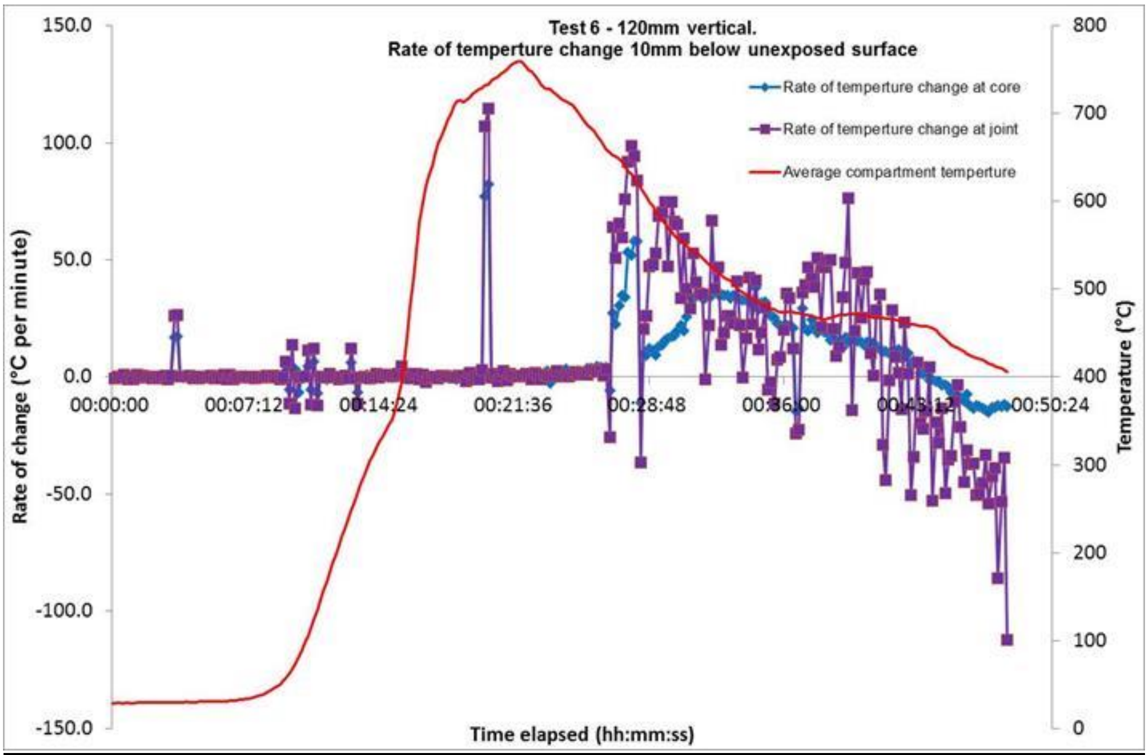


Figure 4.10(f) Test 6 - Rate of change of temperature at core and joint 10mm below

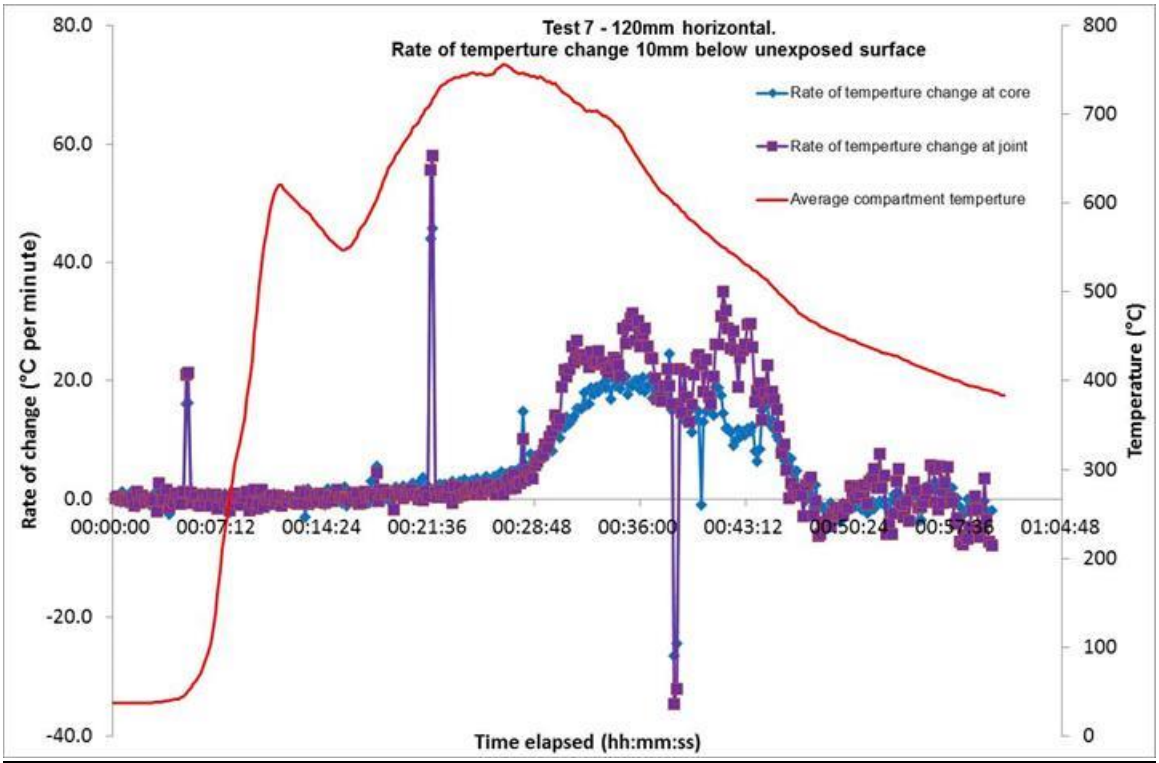


Figure 4.10(g) Test 7 - Rate of change of temperature at core and joint 10mm below

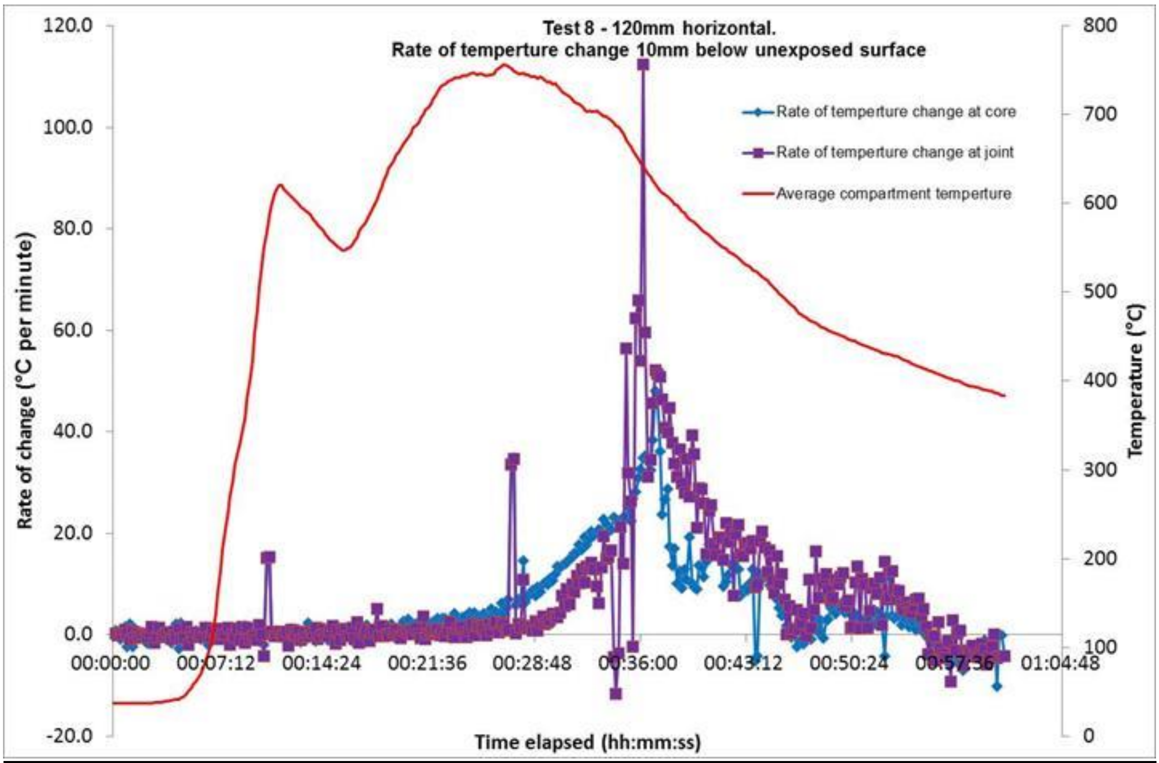


Figure 4.10(h) Test 8 - Rate of change of temperature at core and joint 10mm below

4.11 Summary

This chapter describes the fire testing methodology and the rational for collecting the results and how this is linked to firefighting procedures. The measurement and collection of data is broken down into the 7 areas below results presented in graphical form for all of the tests.

- Measurement and collection of temperature profiles within the fire compartment measured by plate thermocouples.
- Measurement and collection of temperature profiles within the body of the sample panels, measured by type ‘K’ thermocouples.
- Measurement and collection of temperature profiles within the joint of the panels measured by type ‘K’ thermocouples.
- Measurement and collection of temperatures profiles taken on the unexposed face of the panel from outside of the compartment. These measurements were taken on the external face of the panel and at the external joint profile by the use of thermal imaging technology.
- Measurement and collection of detailed temperature profiles taken on the unexposed face of the panel from outside the compartment, by using thermal imaging camera.
- Measurement and collection of the displacement of the panel joint measured by the displacement transducers on the external face of the sample panels.
- Measurement and collection of temperature profiles at the panel and joint at a slice near to the unexposed surface.
- Rate of change of temperature at the joint and panel taken at the exposed surface with the thermal imaging camera.
- Rate of change of temperature at the joint and panel 10mm below the exposed surface.

CHAPTER 5: ANALYSIS OF THE FIRE TEST RESULTS AND IMPLICATIONS ON FIREFIGHTING

5.1 Introduction

This chapter provides an analysis of the results derived from the small scale experiments and presented in the previous chapter. This analysis considers a number of areas and offers suggestions whether this information could be used for informing fire fighting decision making.

1. Analysis of temperature profiles within the compartment.
2. Analysis of temperature profiles throughout the panel core.
3. Analysis of temperature profiles within the panel joints.
4. Analysis of the temperature profiles at the unexposed panel face taken with the thermal imaging camera.
5. Detailed analysis of the temperature profile on the unexposed panel face taken with the thermal imaging camera.
6. Analysis of the panel displacement taken at the unexposed face with linear displacement transducers.
7. Analysis of the temperature profile of the panel core and joint taken 10mm below the surface of the unexposed face.
8. Analysis of the time taken for the temperatures at the joint and panel core to diverge, taken with the thermal imaging camera.
9. Analysis of the rate of temperature change at the joint taken at the unexposed face with the thermal imaging camera.
10. Analysis of the rate of temperature change at the panel taken at the unexposed face with the thermal imaging camera.
11. Analysis of the rate of change of temperature at the panel core and joint at 10mm below the surface of the unexposed face, taken with the thermal imaging camera.
12. Analysis of temperature profiles taken on external face of test container.

In considering the results of the analysis and comment on how this information may be used to inform firefighting decision making, it is important to take into account the Fire and Rescue Service risk philosophy and what firefighting options may be available.

UK Fire and Rescue Service Risk Philosophy

The risk philosophy adopted by the UK Fire and Rescue Service and supported within a national framework provides a generic approach to risk follows:

- The Fire and Rescue Service may risk our lives a lot, in a highly calculated manner, to protect saveable lives.
- The Fire and Rescue Service may risk our lives a little, in a highly calculated manner, to protect saveable property.
- The Fire and Rescue Service will not risk our lives at all for lives or property that are already lost.

Fire fighting Options

Within the context of the risk philosophy stated above it is important to consider what fire fighting options are available when having made an assessment of the fire conditions within a compartment. In broad terms the following tactics are available when considering compartment fire fighting:

- If the conditions within the compartment are too severe then it may be accepted that any persons or property within the compartment have already been lost. Where the severity has the potential to affect the structure and the stability of the compartment defensive fire fighting (i.e. fire fighting from an external position) would be the chosen fire fighting tactic.

- If conditions within the compartment are too severe it may be accepted that person or properties within the compartment have already been lost. However, if the integrity and stability of the compartment is unaffected, then it may be acceptable to operate within an adjacent compartment. This may be to prevent fire spread into other adjacent compartments or to perform some other function.

- If conditions within the compartment are favourable and an effective attack on the fire could be performed to protect saveable life or property. Offensive fire fighting (i.e. fire fighting from an internal position) would be an acceptable tactic; however the position would need to be constantly reassessed to ensure that the internal conditions remain tenable.

5.2 Analysis of results of temperature profiles within fire Compartment

Figure 4.2.1 confirms that the four compartment fires show similar temperture profile charaterstics and all of the test samples are exposed to fires of similar heat output and peak tempertures. Table 4.9.1 provides a summary of the peak compartment tempertures and the time for these tempertures to be attained. It can be seen that three of the crib fires reach their peak tempertures between 21minutes and 26 minutes and just one reaches the peak temperture in just 8 minutes. The high peak temperatures indicate that all fires experienced a post-flashover phase.

Crib Designation	Test Designation	Peak compartment temperture (°C)	Time to peak compartment temperture (minutes)
A	1 and 2	825	8
B	3 and 4	720	24
C	5 and 6	760	21
D	7 and 8	755	26

Table 5.2 - Comparison between peak compartment temperatures

5.3 Analysis of results of temperature profiles throughout the panel core

5.3.1 Introduction

This analysis considers the temperature profile through the core material. As discussed earlier in the chapter, where the Fire and Rescue Service are unable to gain access into a compartment alternative methods are considered.

A compartment fire is a very dynamic event and the Fire and Rescue Service have to consider a number of risks, hazards and priorities before developing a tactical plan to resolve the incident. The purpose of analysing the temperature profiles through the core material is to consider whether there is any benefit in revealing the core material to determine the temperature profile within. Clearly revealing the core material by drilling or some other method would take time and resources. However if this did not give any value to determining fire compartment conditions then alternative tactics would be better employed.
The sub-sections below describe the temperature profiles at various slices throughout the panels. However it would be expected that the temperature of the panel slice closest to the

fire compartment (slice1) would better reflect the temperature profile of the fire compartment. The thermocouple labelling is fully described in figure 4.3 and table 4.3. Therefore this analysis considers all the panel slices but focuses on the temperature profile of slice 1.

The first part of the analysis considers the time for slice 1 to exhibit a temperature increase of 2°C above ambient. This is considered the lowest practical temperature increase that would register on a thermal imaging camera and indicate a developing fire.

The second part of the analysis considers the time taken for the Fire and Rescue Service to attend incidents and take some form of activity. The time to attend will vary depending upon a number of factors including, geography, and locally agreed response standards. However, reviewing attendance standards across the UK, a reasonable assumption is 10 minutes from the call to the Fire and Rescue Service arriving in site and a further 5 minutes to allow gathering of information and planning an operational response (total of 15 minutes from the time of call). This analysis also examines the temperatures of slice 1 after 15 minutes has elapsed which would give a more realistic assessment of the conditions and temperatures faced by the Fire and Rescue Service at the beginning of the operational phase.

5.3.2 Test 1 – 95mm thickness with vertically orientated joint

The compartment reached a peak temperature of 823°C at 8 minutes. At this time slice 1 reached a temperature of 354°C.
Slice 1 showed a 2°C rise above the ambient temperature at 5 minutes, when the compartment temperature had reached 645°C.
At 15 minutes duration, slice 1 reached a temperature of 532°C whereas the compartment temperature was 784°C.

5.3.3 Test 2 – 95mm thickness with vertically orientated joint

The compartment reached a peak temperature of 823°C at 8 minutes. At this time slice 1 reached a temperature of 45°C, 12°C above the starting temperature.

Slice 1 showed a 2°C rise above the ambient temperature at 5 minutes, when the compartment temperature had reached 519°C.

At 15 minutes duration, slice 1 reached a temperature of 576°C whereas the compartment temperature was 784°C.

5.3.4 Test 3 – 95mm thickness with horizontally orientated joint

The compartment reached a peak temperature of 721°C at 24 minutes. At this time slice 1 reached a temperature of 347°C.

Slice 1 showed a 2°C rise above the ambient temperature at 1 minute, when the compartment temperature had reached 396°C.

At 15 minutes duration, slice 1 reached a temperature of 175°C whereas the compartment temperature was 488°C.

5.3.5 Test 4 – 95mm thickness with horizontally orientated joint

The compartment reached a peak temperature of 721°C at 24 minutes. At this time slice 1 reached a temperature of 45°C, 12°C above the starting temperature.

Slice 1 showed a 2°C rise above the ambient temperature at 5 minutes, when the compartment temperature had reached 519°C.

At 15 minutes duration, slice 1 reached a temperature of 239°C whereas the compartment temperature was 488°C.

5.3.6 Test 5 – 120mm thickness with vertically orientated joint

The compartment reached a peak temperature of 759°C at 22 minutes. At this time slice 1 reached a temperature of 361°C.

Slice 1 showed a 2°C rise above the ambient temperature at 4 minutes, when the compartment temperature had reached 35°C.

At 15 minutes duration, slice 1 reached a temperature of 39°C whereas the compartment temperature was 352°C.

5.3.7 Test 6 – 120mm thickness with vertically orientated joint

The compartment reached a peak temperature of 759°C at 22 minutes. At this time slice 1 reached a temperature of 334°C.

Slice 1 showed a 2°C rise above the ambient temperature to 25°C at 5 minutes, when the compartment temperature had reached 519°C.

At 15 minutes duration, slice 1 reached a temperature of 48°C whereas the compartment temperature was 352°C.

5.3.8 Test 7 – 120mm thickness with horizontally orientated joint

The compartment reached a peak temperature of 754°C at 26 minutes. At this time slice 1 reached a temperature of 400°C.

Slice 1 showed a 2°C rise above the ambient temperature at 3 minutes, when the compartment temperature had reached 50°C.

At 15 minutes duration, slice 1 reached a temperature of 285°C whereas the compartment temperature was 556°C.

5.3.9 Test 8 – 120mm thickness with horizontally orientated joint

The compartment reached a peak temperature of 754°C at 26 minutes. At this time slice 1 reached a temperature of 389°C.

Slice 1 showed a 2°C rise above the ambient temperature at 4 minutes, when the compartment temperature had reached 50°C.

At 15 minutes duration, slice 1 reached a temperature of 251°C whereas the compartment temperature was 556°C.

5.3.10 Summary

Table 5.3.10 and 5.3.10 (a) below summarises the data provide in the previous section. In all of the tests the time taken for slice 1 to reach a temperature of 2°C above ambient ranges between 1 minute and 5 minutes. In general when slice 1 reaches 2°C above ambient the compartment temperatures at this time are between 357°C and 645°C. The exception to this is test 7 and 8 where the compartment temperature is 50°C attributed to initial difficulty in igniting the crib.

It is clear that a minimal rise above ambient at slice 1 is not a true reflection on the actual compartment temperatures. Therefore exposing the core material to take temperature readings would not provide adequate information on the compartment temperture.

Where the temperatures were taken at 15 minutes provides a far better correlation between the temperatures at slice 1 and the compartment temperatures. In all cases the compartment temperatures are between 200°C and 320°C higher than that recorded at slice 1.

Test	Time for slice 1 to attain temperature 2°C > ambient (minutes).	Compartment temperature (°C).
1	5	645
2	5	519
3	1	396
4	5	519
5	4	357
6	5	519
7	3	50
8	4	50

Table 5.3.10 – Time for temperature at slice 1 to reach 2°C above ambient.

Test	Temperature at slice 1 (°C)	Compartment Temperature (°C)
1	532	784
2	576	784
3	175	488
4	239	488
5	39	352
6	48	352
7	285	566
8	251	556

Table 5.3.10 (a) – Comparison between temperature at slice 1 and the compartment taken after 15 minutes duration.

From the summary above it is clear that it would be impossible during fire fighting to obtain temperatures of slice 1. Direct observation could only be made by removing or drilling through the panel. This has significant implications to Fire and Rescue Services as a temperature recorded at slice 1 being slightly above ambient and yet the compartment temperature is between 300ºC and 500ºC, approaching flashover conditions.

At 15 minutes from the start of the tests the temperatures at slice 1 ranges from 39°C to 576°C when the compartment temperatures range from 352°C to 784°C. Although there are significant differences in the core temperatures and compartment

temperatures there is a greater degree of confidence that high temperature exist in the compartment using temperatures taken at a minimum of 15 minutes into the test.

5.4 Analysis of results of temperature profile within joints

5.4.1 Introduction

This section provides an analysis of temperature profiles within designated areas of the sandwich panel joint. The designated areas are representative of average temperatures at certain distances from the exposed face of the sandwich panel and shown in Figure 5.4.1 below.

As described in the previous section it can be difficult to determine the fire conditions with compartments where access is limited. This section considers the temperature profiles within the joint and seeks to determine whether it would be of benefit for the Fire and Rescue Service to expose the joint of the sandwich panel from the unexposed face. By exposing the joint, temperature readings could be taken with thermal imaging equipment and this section considers the value of this approach in trying to determine the fire conditions within the compartment. Clearly if the joint can be fully opened then access to the fire compartment if afforded and the actual compartment temperature determined. However it is unlikely that a joint will be fully opened due to the integrity of the jointing designs in use today. It will be assumed that the access to the joint will be limited and the Fire and Rescue Service will expose the joint with basic hand tools, which is a realistic scenario.

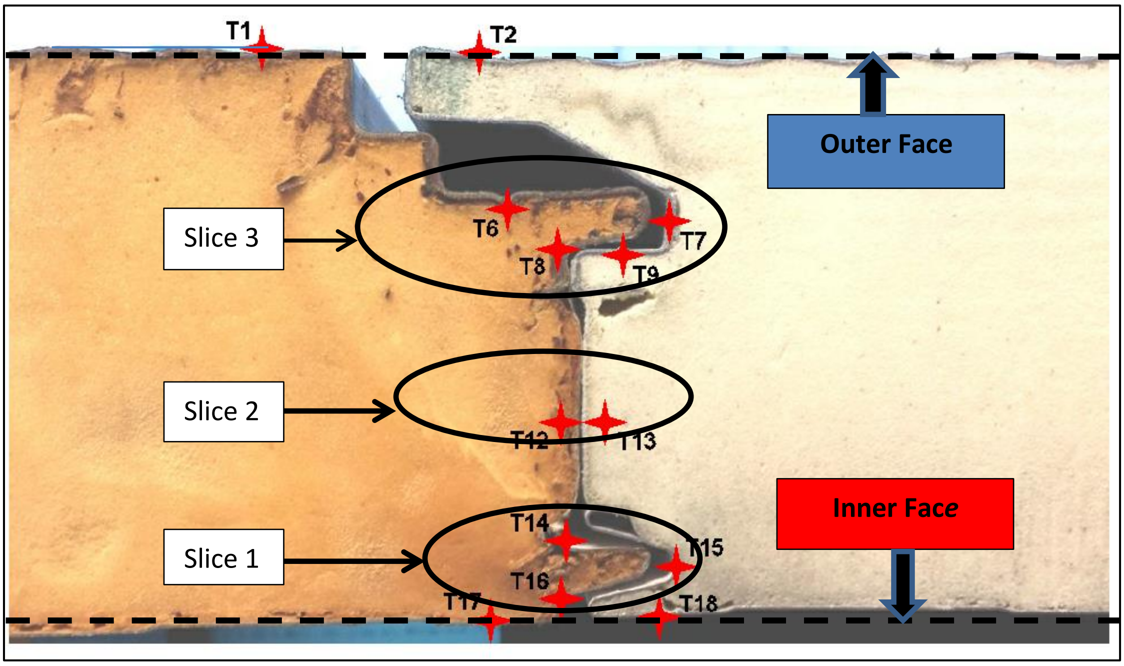


Figure 5.4.1 Designation of the slice profiles throughout the joint

As described in the previous section, the second part of the analysis considers the time taken for the Fire and Rescue Service to attend incidents and take some form of activity. An attendance time of 10 minutes is assumed and a further 5 minutes investigation and planning time before an operation response is made. This analysis also examines the temperatures of slice 1 after 15 minutes has elapsed which would give a more realistic assessment of the conditions and temperatures faced by the Fire and Rescue Service at the beginning of the operational phase.

5.4.2 Test 1 – 95mm thickness with vertical joint orientation

The strongest correlation to the fire compartment temperatures and the measurement taken at the internal surface of the panel is shown by the cluster of thermocouples designated as slice 1. At 2 minutes into the test slice 1 begin to show a temperature increase above ambient. Slice 2 and slice 3 show little sign of increase above ambient temperature until 7 minutes and 14 minutes into the test respectively.

Throughout the duration of this test the temperature of the unexposed side of the panel reached a maximum of 232ºC after 28 minutes.

After 15 minutes both slice 3 and the joint at the unexposed surface showed temperatures of 303°C with temperatures in the compartment recorded as 795°C

5.4.3 Test 2 – 95mm thickness with vertical joint orientation

As in test 1, slice 1 shows the strongest correlation to the temperature profile of the fire compartment. Again slice 2 reaches a higher peak temperature than that reached by the fire compartment. Slice 3 shows no increase in ambient temperature until 10 minutes into the test at which time the peak compartment temperatures have already been reached. Slice 3 reached its peak temperature of 700ºC at 40 minutes into the test some 28 minutes after the fire compartment had reached its maximum temperatures.

Throughout the duration of this test the temperature of the unexposed side of the panel reached a maximum of 321ºC after 40 minutes.

After 15 minutes both slice 3 and the joint at the unexposed surface showed temperatures of 325°C with temperatures in the compartment recorded as 795°C.

5.4.4 Test 3 – 95mm thickness with horizontal joint orientation

Slice 1 showed the strongest correlation with the fire compartment temperatures. The increase above ambient temperature started 5 minutes after the beginning of the test, whereas in test 1 and test 2 the increase was significantly sooner. The peak temperature in slice 2 did not occur until 28 minutes into the test, some 7 minutes after the maximum temperature reached by the fire compartment. Slice 3 showed little increase above ambient temperature until 25 minutes into the test, which is significantly greater than that shown in test 1 and test 2.

Throughout the duration of this test the temperature of the unexposed side of the panel reached a maximum of 155ºC after 43 minutes.

After 15 minutes both slice 3 and the joint at the unexposed surface showed temperatures of 41°C with temperatures in the compartment recorded as 483°C.

5.4.5 Test 4 – 95mm thickness with horizontal joint orientation

Slice 1 shows a strong correlation with the fire compartment temperature profile; albeit the temperatures are lower than those of the fire compartment for most of the test. Slice 1 begins to show an increase above ambient temperature after 5 minutes into the test and slice 2 after 7 minutes. Slice 1 shows a peak temperature of 750ºC at 36 minutes the same maximum temperature reached by the fire compartment. However at 36 minutes the fire compartment temperature had reduced to 450ºC.

The temperature profile of slice 2 was broadly similar to that of the fire compartment but with much lower temperatures being recorded throughout the duration of the test. Slice 3 showed an increase above ambient temperature after 14 minutes into the test, at this time the fire compartment temperatures had reached the first peak and had reduced to 450ºC. The temperature of slice 3 continued to rise to a maximum of 480ºC at 43 minutes at which time the compartment temperature had reduced to 400ºC. The temperature of the unexposed side reached a maximum of 180ºC after 43 minutes into the test, 23 minutes after the maximum fire compartment temperature.

Throughout the duration of this test the temperature of the unexposed side of the panel reached a maximum of 150ºC after 43 minutes.

After 15 minutes both slice 3 and the joint at the unexposed surface showed temperatures of 34°C with temperatures in the compartment recorded as 483°C.

5.4.6 Test 5 – 120mm thickness with vertical joint orientation

Slice1 showed a temperature increase above ambient at 6 minutes, slice 2 at 9 minutes and slice 3 after 21 minutes.

Slice 2 showed a rapid temperature rise at 17 minutes to its maximum temperature of 1000ºC at 19 minutes. At this time the temperature of the fire compartment was just past its peak temperature of 780ºC. From that point the temperature of slice 2 remained higher than the fire compartment temperature until 40 minutes elapsed.

Throughout the duration of this test the temperature of the unexposed side of the panel reached a maximum of 65ºC after 33 minutes.

After 15 minutes both slice 3 and the joint at the unexposed surface showed temperatures of 43°C with temperatures in the compartment recorded as 352°C.

5.4.7 Test 6 – 120mm thickness with vertical joint orientation

Slice 1 showed an increase above ambient temperature at 7 minutes. The fire compartment reached its maximum temperature of 780ºC at 21 minutes whereas slice 1 reached its maximum temperature of 810ºC at 28 minutes.

Slice 2 showed an increase above ambient temperature at 10 minutes into the test, at this time the fire compartment temperature showed 200ºC. Slice 2 reached a maximum temperature of 1000ºC at 28 minutes. At this time the fire was into its decay stage with recorded a temperature of 600ºC.

Slice 3 showed an increase above ambient temperature after 25 minutes into the test, at this time the fire compartment temperature had reduced from its maximum to 450ºC. The temperature of the unexposed face reached its maximum temperature of 230ºC after 43 minutes, at which time the compartment temperature had reduced to 430ºC.

Throughout the duration of this test the temperature of the unexposed side of the panel reached a maximum of 251ºC after 42 minutes.

After 15 minutes both slice 3 and the joint at the unexposed surface showed temperatures of 43°C with temperatures in the compartment recorded as 352°C.

5.4.8 Test 7 – 120mm thickness with horizontal joint orientation

Slice 1 showed an increase above ambient temperature at 4 minutes into the test. The temperature profile of this slice matched that of the fire compartment up until the first temperature peak was reached. Slice 2 showed an increase above ambient after 7 minutes into the test.

Slice 1 and 2 both reached maximum temperatures of 800ºC at 43 minutes into the test at a time when the fire compartment temperature had reduced to 450ºC.

Slice 3 showed an increase above ambient temperature after 24 minutes which corresponds to the time that the peak temperature was reached within the fire compartment.

Throughout the duration of this test the temperature of the unexposed side of the panel reached a maximum of 202ºC after 48 minutes.

After 15 minutes both slice 3 and the joint at the unexposed surface showed temperatures of 30°C with temperatures in the compartment recorded as 556°C.

5.4.9 Test 8 – 120mm thickness with horizontal joint orientation

Slice 1 showed an increase above ambient temperature at 4 minutes and mirrored the temperature profile of the fire compartment up until the first peak temperature. After that time the profiles are similar with slice 1 showing a lower temperature than the fire compartment until the beginning of the decay phase. After that time slice 1 continued to show higher temperatures than that of the compartment.

Slice 2 showed an increase above ambient temperature after 7 minutes reaching a peak temperature of 870ºC at 50 minutes into the test. At this time the fire was 25 minutes into its decay phase with fire compartment temperatures recorded as 370ºC.

Slice 3 showed an increase above ambient temperature at 26 minutes which corresponds to the maximum compartment temperature recorded. Slice 3 reached its maximum temperature of 600ºC at 55 minutes into the test, the corresponding fire compartment temperature at this time was 400ºC.

Throughout the duration of this test the temperature of the unexposed side of the panel reached a maximum of 152ºC after 54 minutes. After 15 minutes both slice 3 and the joint at the unexposed surface showed temperatures of 28°C with temperatures in the compartment recorded as 556°C.

5.4.10 Summary

Test No	Compartment temperature (°C)	Slice1 temperature (°C)	Slice2 temperature (°C)	Slice3 temperature (°C)	Temperature at unexposed surface (°C)
1	795	662	770	303	303
2	795	730	692	325	325
3	483	403	182	41	41
4	483	429	204	34	34
5	352	272	43	43	43
6	352	300	43	43	43
7	556	504	333	30	30
8	556	512	186	28	28

Table 5.4.10 - Temperatures taken throughout the joint taken after 15 minutes duration.

As would be expected in all of the tests the slice nearest to the fire compartment (slice 1) is most representative of the actual fire temperatures. Although the 95mm samples follow a similar profile of the compartment temperatures, the temperatures recorded in slice 1 are normally significantly lower than the compartment temperatures and cannot therefore be relied on as an indicator of the temperatures within the compartment.

The temperature profiles in slice 1 of the 120mm samples follow the temperature profile of the fire compartment almost exactly up until at least 600ºC,after this time the temperatures of slice 1 are generally lower than the peak compartment temperatures and therefore not a good indication of the fire compartment temperatures. Once the peak compartment temperature has been reached and the fire is in decay the temperature profile of slice 1 remains higher than that of the fire compartment for the whole of the decay period. After the peak compartment temperature has been reached then the temperatures of slice 1 continue to be higher than that of the fire compartment.

At 15 minutes into the test the temperatures at the joint at the unexposed surface are in the range of 28°C to 325°C. At this time the compartment temperatures range from 352°C to

795°C. Therefore external temperature measurements would not provide reliable information on the compartment temperatures at this time.

At 15 minutes into the test, temperatures at slice 1 range from 272°C to 662°C whereas the compartment temperatures range from 352°C to 795°C. This would provide a good indicator of high temperatures within the compartment if access to the joint could be achieved. At this time the compartment fires are either approaching or have reached their peak temperatures.

However a more practical approach would be to observe joint temperatures at the unexposed surface. At 15 minutes these temperatures range from 28°C to 325°C whereas the compartment temperatures range between 352°C to 795°C.

It is difficult to measure the inner temperatures of the joint and as demonstrated the inner joint temperatures are not directly comparable to the fire temperatures. In order to determine the compartment temperature conditions it would be necessary to fully open the joint or drill through the panel to make a direct observation.

5.5 Analysis of results of temperature profile at unexposed face taken with thermal imaging camera.

5.5.1 Introduction

This section provides an analysis of the results taken externally with the thermal imaging camera. This is the most commonly used approach taken by the Fire and Rescue Service when confronted with a fire within a compartment where access is not readily available. The results of the temperature profiles at the joint, the panel and an external metal façade are analysed and guidance provided whether this information could be used to inform fire fighting decision making.

This section provides an analysis of temperatures at the joint and panel taken externally by the thermal imaging. This section provides a closer analysis of the temperatures of both the joint and panel up to the point at which full and irrevocable divergence takes place. This analysis examines the relationship between the external temperatures of the panel and joint taken externally and compares the results with the fire compartment temperatures. Divergence of temperature between the panel and joint is an indicator of integrity loss at the joint which could have implications for fire-fighters operating in adjacent compartments.

5.5.2 Test 1 - 95mm thickness with vertically orientated joint

During Test 1 a hot spot was evident in quadrant 2. As the position within this quadrant was the position where the panel temperature was taken it is acknowledged that the average readings across the panel will be higher. It is clear from Figure 4-5-1-1 below that the container temperature and the compartment temperature follow the same trend although the average internal compartment temperature reaches over 800°C whilst the external container temperature reaches over 400°C.

All of the trend lines in this test show an increase as would be expected. The temperature at the joint showed a consistent increase throughout the growth phase of the fire but a sudden decline was observed from 22 minutes to 24 minutes which saw a reduction in the joint temperature from 343°C to 232°C.

The compartment temperatures profile exhibited a double peak profile as explained in pervious chapter, the maximum peak recorded 826°C at 9 minutes. The maximum external panel temperatures measured 233°C at 29 minutes and the joint temperature 343°C at 22 minutes. These maximum temperatures were reached at 20 minutes and 12 minutes respectively after the peak compartment temperature was reached. The time lag between the peak joint temperature and the peak compartment temperature was 12 minutes.

Minimal temperature changes take place up until 5 minutes and then the rate of change of both is significant. At 10 minutes both the panel and the joint record temperatures of 41°C and total divergence occurs with the joint showing a higher temperature for the remainder of the duration of the test.

5.5.3 Test 2 -95mm thickness with vertically orientated joint

The maximum external panel temperature was reached at 24 minutes and the corresponding joint temperature reached at 36 minutes. These maximum temperatures were reached at 23 minutes and 27 minutes respectively after the maximum temperatures reached within the compartment. Flaming was observed at the top of test panel at 6 minutes due to the position of the vertical restraint which allowed the panel to pivot around this point forcing the top of the panel from the container recess. The data has not revealed that this had any significant effect on the test results and therefore the data is considered reliable. This was remedied in all subsequent tests by ensuring that the vertical restraints were long enough to support the whole of the vertical length of the test panels.

This decline is replicated in Test 2 which saw a similar decline at 23 minutes from 221°C to 151°C at 26 minutes after which an increasing trend was noted until the duration of the test. Both the panel and joint profiles take the same path from ambient temperature up until 32°C. From ambient temperature to 28°C the rate of rise is rapid over 01:30mins and then both profiles show moderate increases up until 32°C. The time lag between the peak joint temperature and the peak compartment temperature was 12 minutes.

At 32°C divergence takes place with the joint temperature increasing from 32°C to 126°C over the remainder of the test duration whereas the panel temperature increases from 32°C to 51°C for the same duration.

Both the panel and joint profiles take the same path from ambient temperature up until 32°C. From ambient temperature to 28°C the rate of rise is rapid over the next 2 minutes and then both profiles show moderate increases up until 32°C.

After 10 minutes total divergence takes place at 32°C divergence with the joint temperature increasing from 32°C to 126°C over the remainder of the test duration whereas the panel temperature increases from 32°C to 51°C for the same duration.

<u>5.5.4 Test 3 -95mm thickness with horizontally orientated joint</u>

The compartment temperatures profile exhibited a double peak profile as explained in pervious chapter. The maximum peak recorded 722°C at 24 minutes. In Test 3 and Test 4 the fire temperatures within the compartment showed the first peak 567°C and the temperatures taken outside in relation to the panel temperatures were both 28°C. Both the panel and joint temperatures showed little increase above ambient temperature until over just over 21 minutes had elapsed. The time lag between the peak joint temperature and the peak compartment temperature was 11 minutes.

In Test 3 the maximum external panel temperatures measured 81°C at 44 minutes and the corresponding joint temperature 270°C at 35 minutes. These maximum temperatures were reached at 20 minutes and 11minutes after the peak compartment temperature was reached.

Both panel and joint temperatures increase rapidly from ambient temperature to 28°C at 3 minutes. Both temperature profiles remain almost constant up until 7 minutes when divergence is first observed with the panel temperature showing higher temperatures.
This trend changes at 18 minutes with joint temperatures changing from 33°C to 59°C whereas the panel temperature only increases from 33°C to 39°C for the remaining period of

the test duration. Both panel and joint temperatures increase rapidly from ambient temperature to 28°C at 3 minutes. Divergence is observed at 22 minutes when the panel and joint temperature reached 36ºC.

5.5.5 Test 4 -95mm thickness with horizontally orientated joint

In Test 4 the maximum external panel temperature was reached at 44 minutes and the corresponding joint temperature reached at 36 minutes. These maximum temperatures were reached at 23 minutes and 27 minutes after that reached by the peak compartment temperatures. The time lag between the peak joint temperature and the peak compartment temperature was 15 minutes.

Both panel and joint temperatures increase rapidly from ambient temperature to 28°C over a period of 3 minutes. Both profiles increase steadily until 15 minutes where they both showed temperatures of 31°C at this time. Divergence occurs at 15 minutes with the joint temperature increasing from 31°C to 41°C at 22 minutes and the corresponding panel temperature increasing from 31°C to 35°C over the same time period.

Both panel and joint temperatures increase rapidly from ambient temperature to 28°C over a period of 3 minutes. Both profiles increase steadily until 15 minutes where they both show temperatures of 31°C at this time. Divergence occurs at 20 minutes with the joint temperature increasing from 31°C to 41°C at 22 minutes and the corresponding panel temperature increasing from 31°C to 35°C over the same time period.

5.5.6 Test 5 -120mm thickness with vertically orientated joint

The compartment temperatures profile exhibited a double peak profile as explained in pervious chapter. The maximum peak recorded 760°C at 21 minutes. In Test 5 the maximum external panel temperatures measured 45°C at 44 minutes and the corresponding maximum joint temperature 313°C at 30 minutes. These maximum temperatures were reached at 23 minutes and 19 minutes after the peak compartment temperature was reached. The time lag between the peak joint temperature and the peak compartment temperature was 9 minutes.

Both panel and joint temperatures show increases from ambient temperature to 22°C over an initial 3 minutes period. A dip in both panel and joint temperature profiles to 20°C is observed at 12 minutes. Complete divergence takes place at 20 minutes when the panel and joint reach 25ºC. After that time both panel and joint temperatures continue to increase to a maximum of 31°C and 49°C respectively until test completion at 25 minutes.

5.5.7 Test 6 -120mm thickness with vertically orientated joint

In Test 6 the maximum external panel temperature was reached at 44 minutes and the maximum joint temperature reached at minutes. These maximum temperatures were reached at 23 minutes and 18 minutes after that reached by the peak compartment temperatures. Both panel and joint temperatures increase from ambient to 22°C over the first 14 minutes of the test period and then progressively increase up to 30°C at 23 minutes. The time lag between the peak joint temperature and the peak compartment temperature was 18 minutes.

Divergence occurs at 23 minutes up to 27 minutes where temperatures of the panel and joint reach 34°C and 64°C respectively at this time.

Both panel and joint temperatures increase from ambient to 22°C over the first 14 minutes of the test period and then progressively increase up to 30°C at 23 minutes. Divergence begins at 20 minutes and then permanently at 25 minutes, where temperatures of the panel and joint reach 31°C and 64°C respectively at this time.

5.5.8 Test 7 -120mm thickness with horizontally orientated joint

In this test temperatures begin to show some convergence through the slices after 43 minutes but do not completely converge at any time within the test duration.

The maximum temperature of the inner face was recorded as 848°C at 27 minutes; this corresponds to 28°C recorded at the external face at that time. The maximum temperature recorded at the external face was 138°C at 49 minutes with corresponding temperatures recorded as 664°C and 452°C recorded at the inner face and within the compartment respectively; this corresponds to a time of 23 minutes into the decay phase of the fire. The time lag between the peak joint temperature and the peak compartment temperature was 18 minutes.

The compartment temperatures profile exhibited a double peak profile as explained in pervious chapter. The maximum peak recorded 756°C at 26 minutes. In Test 7 the maximum external panel temperatures measured 79°C at 54 minutes and the corresponding joint temperature 395°C at 39 minutes. These maximum temperatures were reached at 28 minutes and 18 minutes after the peak compartment temperature was reached.

Both panel and joint temperatures increase at similar rates from ambient temperature to 25°C at 11 minutes. Both then increase up to a temperature of 33°C recorded at 24 minutes with the panel temperature showing a higher than the joint temperature during this period.
Both panel and joint temperatures increase at similar rates from ambient temperature to 25°C at 11 minutes. Both then increase up to a temperature of 33°C recorded at 24 minutes with the panel temperature showing a higher than the joint temperature during this period. Total divergence occurs at 28 minutes when both panel and joint temperatures reach 28ºC.

5.5.9 Test 8 -120mm thickness with horizontally orientated joint

In Test 8 the maximum external panel temperature of 77°C was reached at 54 minutes and the corresponding joint temperature reached at 44 minutes. These maximum temperatures were reached at 23 minutes and 18 minutes after that reached by the peak compartment temperatures. Both panel and joint temperatures increase at similar rates from ambient to 25°C at 11 minutes, they then follow a similar rate increase to 28°C. Divergence occurs at this point with the panel temperature showing a higher temperature that that recorded at the joint. This trend continues up until 26 minutes when the joint and panel temperature profiles converge at 36°C. The time lag between the peak joint temperature and the peak compartment temperature was 18 minutes.

After this time divergence continues again up to 32 minutes where the maximum joint and panel temperatures are recorded at 46°C and 42°C respectively. During this period the joint temperature has maintained a higher temperature than the panel temperature.

Both panel and joint temperatures increase at similar rates from ambient temperature to 25°C at 11 minutes. Both then increase up to a temperature of 33°C recorded at 24 minutes with the panel temperature showing a higher than the joint temperature during this period.

Divergence begins at 28 minutes when the joint and panel temperatures reach 36ºC. This trend continues until 32 minutes when the maximum joint and panel temperatures reach 65°C and 39°C respectively.

5.5.10 Summary

There is no correlation between temperatures taken at the joint or panel by the thermal imaging camera and the compartment temperatures. In all cases the temperature profiles at the joint record higher temperatures than at the panel.

Although the temperature profiles of the joint and panel follow the same pattern as compartment temperature profile, however there is a significant time lag between the two. The time lag in the 95mm samples is an average of 12 minutes and 18 minutes in

the 120mm samples. Therefore temperature information taken at the joint and panel on the external face with thermal imaging camera is not reliable and cannot be used to inform fire fighting decisions making.

In general the temperature divergence of the joint and panel occurs earlier with the 95mm panel samples rather than the 120mm panel samples. The vertically orientated samples achieve temperature divergence quicker that their respective horizontally which can be attributed to the better fitting joint.

However in all of the tests temperature divergence occurs where the compartment has reached temperatures in excess of 600ºC and is at or just past flashover conditions. Therefore divergence can be considered a good indicator of high compartment temperatures. These temperatures are such that fire-fighters would not be committed into these compartments to extinguish the fire or carry out rescues and alternative fire fighting methods would need to be used.

Table 5.5.10 provides a summary of the time that divergence of temperature at the panel and the joint is experience and a comparison of the fire compartment temperature at that time. **It is clear from the analysis summarised in the table above that there is no direct relationship between the external temperature at the point of divergence and the fire compartment temperature at that time.**

However the time to temperature divergence provides a reasonable guide to flashover and early post-flashover periods. Where the conditions within the compartment have reached flashover conditions then it can be assumed that no saveable life or property will exist within the compartment and therefore fire fighting operations will focus on the protection of other surrounding compartments.

The earliest time that the Fire and Rescue Service would be expected to begin fire fighting operations would be 15 minutes after the initial call. From the table above it is clear that divergence is only apparent at this time in one of the sets of tests.

Although divergence is a good indicator of high compartment temperatures it may not be evident until 40 minutes after the initial call. However where the TiC records low temperatures and non-divergence results then flashover has not been reached and a decision to enter the compartment can be made.

Test	Description	Time to flashover (minutes)	Time to divergence (minutes)	External temperature at divergence (°C)	Compartment temperature at divergence (ºC)
1	**95mm vertical joint**	**7**	**10**	**41**	**782**
2	**95mm vertical joint**	**7**	**10**	**32**	**782**
3	**95mm horizontal joint**	**9**	**22**	**36**	**708**
4	**95mm horizontal joint**	**9**	**20**	**33**	**645**
5	**120mm vertical joint**	**18**	**20**	**25**	**728**
6	**120mm vertical joint**	**18**	**20**	**31**	**701**
7	**120mm horizontal joint**	**10**	**28**	**28**	**704**
8	**120mm horizontal joint**	**10**	**38**	**36**	**750**

Table 5.5.10 Comparison of temperature divergence at the unexposed surface

5.6 Analysis of results taken of panel deflection taken from outside of container

5.6.1 Introduction

As discussed in section 4.7 the main purpose of taking panel displacement measurements was primarily to assist the work of Andrew Foster, a PhD student at Manchester University who is assessing temperature profiles within sandwich panel construction by using mathematical modelling methods. The measurements taken in these series of tests are to be used to inform and validate the mathematical model that is being developed.

In the literature review there was no guidance or information identified detailing deflection in sandwich panel construction when subjected to fire conditions. This was an opportunity to examine the defection profiles in each of the fire tests and consider whether any correlation between the deflection on the outer face and the fire compartment temperature conditions could be identified.

Generic guidance exists for UK Fire and Rescue Services in relation to the observation of wall deflection in fire due to heating of the inner face and the potential of creating instability and the associated risks to fire-fighter safety. No guidance or consideration is given to the relating the extent of the deflection and the relationship to the temperature within the compartment. This was therefore considered an opportunity to collect and analysis the results of the defection profiles on the external face of sandwich panels exposed to real fire conditions and comment on whether this information can be used to influence fire fighting decision making.

<u>5.6.2 - 95mm samples with vertical orientated joint</u>

These tests show a maximum deviation of between 15mm and 33mm from the initial position. These maximum deviations occurred at 28 minutes with a compartment temperature of 550°C. The maximum compartment temperature reached was in excess of 800°C at over 8 minutes with a movement deviation recorded as 3mm.

<u>5.6.3 - 95mm samples with horizontally orientated joint</u>

These tests showed a maximum deviation of 27mm at 43 minutes and a compartment temperature at this time of 150°C. The maximum compartment temperature achieved during this test was 720°C at 24 minutes at which time displacement of between 14mm and 20mm was recorded.

The results for test 3 were disregarded as test records confirm that the sample used for this test had become dislodged during this test due to one of the securing clamps becoming displaced. It is therefore regarded that the results are unsuitable to be used for this analysis.

<u>5.6.4 - 120mm samples with vertically orientated joint</u>

These tests recorded maximum deviations of between 36mm and 41mm at 40 minutes with a compartment temperature of 500°C.The maximum compartment temperature recorded was 760°C at a time of just over 36 minutes with maximum deviations of between 3mm and 7mm.

<u>5.6.5 - 120mm samples with horizontally orientated joint</u>

These tests show a maximum deviation of between 8mm and 40mm from the initial position. These maximum deviations occurred at 26 minutes 30 seconds when the compartment temperature was reaching its peak temperature. The maximum compartment temperature reached was 756°C at 26 minutes 40 seconds.

At 45 minutes 30 seconds a maximum deviation between 8mm and 10mm was recorded in the opposite direction to the maximum reached at 26 minutes and 30 seconds. This deviation in the opposite direction was recorded when the compartment temperature reached 495°C.

5.6.6 Summary

Crib Designation	Tests	Panel Thickness (mm)	Joint Orientation	Maximum compartment temperture (°C)	Time of maximum compartmentaion temperture (minutes)	Maximum deviation (mm)	Time of maximum deviation (minutes)
A	1 and 2	95mm	Vertical	800	8	15 – 33	28
B	3 and 4	95mm	Horizontal	720	24	27	43
C	5 and 6	120mm	Vertical	760	33	36 – 41	40
D	7 and 8	120mm	Horizontal	756	26	8 - 40	26

Table 5.6.6 Comparison between maximum compartment temperatures and panel deviation

The results analysed and summarised in the table 5.6.6 above are broadly similar and consistent with measurements taken in other similar tests. The results of Tests 1 – 6 show the strongest similarities in that the maximum deviation on all occasions occurs significantly after the maximum compartments temperatures have been reached and the fire is well into the decay phase.

The 95mm samples experienced the maximum deviation approximately 20 minutes after the maximum compartment temperature had been reached. This figure was similar for both the vertical and horizontally orientated samples.

However this time was much shorter for the 120mm samples. The time from maximum compartment temperature until maximum deviation was observed was 7 minutes for the vertical orientated samples and almost at the same time for the horizontally orientated samples.

The joints in vertical orientation showed a greater average deviation than the joints in horizontal orientation. The can be explained due to the better fit of the joints generally when orientated horizontally rather than in a vertical geometry.

In these tests the extent of the deviations recorded was between 8mm and 40mm. It would only be possible to assess such deviations when the original datum point was known. As the deflections are relatively small it would also be difficult to measure and interpret the significance of such small movement away from the original position.

One of the signs and symptoms of building collapse of traditional buildings bowing out of external walls and this is no different to deflection of sandwich panels in fire. It is important to consider whether this approach to assess deflections in sandwich panel wall construction can be used and applied to practical fire fighting operations. In a typical fire fighting scenario it would be impossible and impractical to set up movement transducers to measure wall deviations. The deviations observed ranged from 3mm up to a maximum of 40mm which would be difficult to detect over a large area. Clearly that information would need to be interpreted and a judgement made on the likely temperature conditions within the compartment. In addition, to observing deviations from the norm requires a datum point to be determined and then the extent of the deflection assessed from that point. This approach would clearly be impractical when dealing with compartment fire fighting.

However on the incident ground, a number of Safety Officers will be appointed with the sole responsibility to check and act upon information relating to safety matters. One of the responsibilities could be to check for panel deviation which would be by observation as fire conditions develop.

There is no clear relationship between compartment temperatures and deflection at the sandwich panel joint. However where maximum deflection occurs it has been established that the fire is past the peak value and often well into the decay phase.

However any deflection at the joint is indicative of high internal compartment temperatures and indicative that the integrity of the sandwich panel joint has become compromised. If the joint integrity has been compromised then this could allow the passage of toxic and un-burnt gases into other adjacent compartments and would bring into question the ability of fire-fighters to carry out other functions in adjacent compartments. In addition where the joint integrity has been compromise due to non-uniform heating then there is a potential for a twisting effect to occur in the panel which could compromise the panel stability.

Any observed or measured deflection could be a indicator of high internal compartment temperatures resulting in a reduction of joint integrity and stability. In this circumstance fire fighting tactics should be reviewed. Consideration should be given to withdrawing Fire-fighters from adjacent compartments and fire fighting should be carried out defensively (i.e. fire fighting from an external position).

5.7 Analysis of results of temperature profile at joint and panel taken 10mm below the surface of unexposed face.

5.7.1 Introduction

This analysis is designed to evaluate the temperature profiles near to the surface of the unexposed face and that at the joint at an equivalent distance from the exposed face.

The literature review identified guidance used by some Fire and Rescue Services that advised peeling back the facing material of the unexposed surface to identify the core material. Where the core material could be identified as combustible or non-combustible then a decision could be taken in relation to potential for fire spread and panel stability.

This analysis extends the above guidance and is designed to determine the value of revealing the core material and joint at 10mm below the surface of the unexposed face and whether the temperature profiles at these points give any better indication of the temperature conditions within the fire compartment.

It is acknowledged that fully opening up a joint or making a penetration into a compartment where sandwich panels form the external envelope would normally be a time consuming activity and would not be the chosen method used by the Fire and Rescue Service in the initial stages of a fire. However prising open the external joint or peeling back the external face to reveal an area of 10mm below the surface of the unexposed face is a relatively simple realistic action that could be taken by the Fire and Rescue Service using basic hand tools.

5.7.2 Test 1 – 95mm thickness with vertical joint orientation

The joint and core material show no difference in temperature until 15 minutes into the test. At the both increase in temperature rapidly. The joint experiences a far rapid increase until a peak temperature if reached at 550°C at 29 minutes. The core temperature rises to over 400°C at around 29 minutes.

Although both have reached their peak temperatures at around 29 minutes the corresponding fire compartment temperature at this time is 600°C. At this time the fire in the compartment is 8 minutes into its decay phase. In the decay phase the joint cools at a far greater rate than the core.

Above ambient temperatures were recorded after 7 minutes into the duration of the test with divergence in temperatures between the joint and panel being observed at 14 minutes. At 7 minutes compartment temperatures had already reached 786ºC.

5.7.3 Test 2 – 95mm thickness with vertical joint orientation

The joint and core material show little rise above ambient temperature until 14 minutes. As in test 1 the joint temperature shows the most rapid rise in temperature until its peak temperature of 550°C is reached at 43 minutes. In this test the core temperature shows a similar but slower temperature increase up until its maximum temperature of 500°C at 36 minutes into the test. The peak temperatures in the panel and joint were reached 21 minutes and 29 minutes respectively after the peak temperature reached in the fire compartment.

Above ambient temperatures were recorded after 8 minutes into the duration of the test with divergence in temperatures between the joint and panel being observed at 11 minutes. At 8 minutes the temperature within the compartment was 816ºC and had already reached its first maximum value.

5.7.4 Test 3 – 95mm thickness with horizontal joint orientation

The joint and core material showed little difference from ambient temperature until 4 minutes into the duration of the test. The fire compartment reached its maximum temperature of 720°C at 22 minutes. At this time both the core and joint temperatures began to rise at the same rate until 28 minutes when both began to rise towards their peak temperatures but with the joint temperature increasing at a greater rate.

Both joint and core temperatures reached their peak temperatures at 480°C and 350°C respectively. Both of these temperatures were reached approximately 8 minutes after the maximum fire compartment temperature had been reached. In the decay phase the joint cooled at a faster rate than the core material.

Above ambient temperatures were recorded after 4 minutes into the duration of the test with divergence in temperatures between the joint and panel being observed at 11 minutes. At 4 minutes the temperature within the compartment was 42ºC. Divergence of temperatures between the joint at panel occurred at 23 minutes, at this time the compartment temperature had reached 715ºC.

5.7.5 Test 4 – 95mm thickness with horizontal joint orientation

Both joint and core showed little change above ambient temperature until 21 minutes into the test. Both then showed increases up to their maximum temperature, with the joint temperature increasing at a greater rate. Both the joint and core material reached their peak temperatures of 400°C and 340°C respectively at 46 minutes into the test. These peak temperatures at 29 minutes when the fire compartment was 20 minutes into its decay phase and recording 400°C at this time. The peak fire compartment temperature of 700°C was reached at around 23 minutes into the test, at this time both core and joint temperatures were marginally above ambient temperature.

Above ambient temperatures were recorded after 6 minutes into the duration of the test with divergence in temperatures between the joint and panel being observed at 23 minutes when the compartment temperature had reached 715ºC. At 6 minutes the temperature within the compartment was 84ºC.

5.7.6 Test 5 – 120mm thickness with vertical joint orientation

Both joint and core showed little change above ambient temperature until 23 minutes into the test. At this time the fire compartment temperature was marginally into its decay phase after having reached a peak temperature of 750°C at 21 minutes. The joint temperature rapidly increased up to its maximum of 580°C at 32 minutes into the test with the core temperature reaching its maximum temperature of 370°C at 38 minutes.

Above ambient temperatures were recorded after 9 minutes into the duration of the test with divergence in temperatures between the joint and panel being observed at 23 minutes when the compartment temperature had reached 715ºC. At 9 minutes the temperature within the compartment was 50ºC.

5.7.7 Test 6 – 120mm thickness with vertical joint orientation

Both joint and core temperatures remained marginally above ambient temperature until 28 minutes into the test. Both the core and joint temperatures increased at a rapid rate until reaching their maximum peak temperatures.

Both joint and core reached their peak temperatures at approximately 43 minutes. The joint temperature at this time was 450°C and the core temperature 360°C. The fire compartment temperature at this time was recorded as 450°C.The maximum temperature of both the joint and core occurred 22 minutes after the peak fire compartment temperature was reached.
Above ambient temperatures were recorded after 22 minutes into the duration of the test with divergence in temperatures between the joint and panel being observed at 27 minutes when the compartment temperature had reached 651ºC and was into the decay phase of the fire. At 22 minutes the temperature within the compartment was 753ºC.

5.7.8 Test 7 – 120mm thickness with horizontal joint orientation

Both joint and core temperatures remained marginally above ambient temperature until 27 minutes into the test. Both the core and joint temperatures increased at a similar rapid rate up until 150°C, with the joint temperature then increasing at a greater rate until reaching peak temperatures.

Both joint and core reached their peak temperatures at approximately 43 minutes. The joint temperature at this time was 400°C and the core temperature 310°C. The fire compartment temperature at this time was recorded as 500°C.

Above ambient temperatures were recorded after 20 minutes into the duration of the test with divergence in temperatures between the joint and panel being observed at 27 minutes when the compartment temperature had reached 651ºC and was into the decay phase of the fire. At 20 minutes the temperature within the compartment was 671ºC.

5.7.9 Test 8 – 120mm thickness with horizontal joint orientation

Both joint and core temperatures remained marginally above ambient temperature until 21 minutes into the test. Both the core and joint temperatures increased at a similar rapid rate with the core temperature increasing at a greater rate than the joint until 300°C. After that time the joint increases at a greater rate until both reach their maximum peak temperatures. Both joint and core reached their peak temperatures at approximately 55 minutes. The joint temperature at this time was 480°C and the core temperature 390°C. The fire compartment temperature at this time was recorded as 400°C.

Above ambient temperatures were recorded after 20 minutes into the duration of the test with divergence in temperatures between the joint and panel being observed at 22 minutes when the compartment temperature had reached 726ºC and was into the decay phase of the fire. At 20 minutes the temperature within the compartment was 732ºC.

5.7.10 Summary

Table 5.7.10 below provides a summary of the time taken for temperatures 10mm from the surface of the unexposed side to achieve above ambient and compares the compartment temperature at that time.

The 95mm samples achieve above ambient temperatures 10mm below the surface significantly sooner than the 120mm samples, which can be attributed to the enhanced insulation qualities due to the greater thickness of the core material.

Although no definitive trend can be established, five of the eight tests have shown that when above ambient temperatures are reached 10mm below the surface of the unexposed face, fire compartment temperatures are in excess of 600ºC. This temperature is significant and is indicative of flashover conditions within the compartment.

Test No	Time to reach above ambient temperature 10mm below surface of unexposed face (minutes)	Time to divergence 10mm below surface of unexposed face (minutes)	Compartment Temperature (ºC)
1	7	13	786
2	8	11	816
3	4	24	42
4	6	25	84
5	9	22	50
6	22	27	753
7	20	21	671
8	20	21	732

Table 5.7.10 Time to reach above ambient temperatures at 10mm below the surface

It is clear that the temperature profiles taken 10mm below the surface of the unexposed face are unreliable when trying to compare with the temperatures within the compartment.

Test No	Time to reach above ambient temperature 10mm below surface of unexposed face (minutes).	Time to reach above ambient temperature on surface of unexposed face (minutes).
1	7	10
2	8	10
3	4	22
4	6	20
5	9	20
6	22	25
7	20	29
8	20	29

Table 5.7.10 (a) Comparison between time to reach above ambient temperatures at 10mm below the surface and at the surface of the unexposed face.

Table 5.7.10 (a) provides a comparison between the time taken to register temperatures above ambient temperature both at the unexposed face and 10mm below the surface. This analysis is designed to consider whether there is any value in the Fire and Rescue Service revealing the joint and panel using hand tools or simply relying on collecting surface temperature information.

As would be expected, in all of the tests the time to achieve above ambient temperatures was earlier 10mm below the surface than on the surface of the unexposed face. **As demonstrated any temperature increases of at least 2°C above ambient temperatures at both the exposed surface and 10mm below are normally indicative of high fire compartment temperatures.** From the analysis it is shown that the temperature 10mm below the surface attains temperatures above ambient between 2 minutes and 16 minutes quicker than at the unexposed surface.

In both sample thicknesses, it took longer for the unexposed surface to reach temperatures above ambient where the joint was in the horizontal orientation as opposed the same thickness in the vertical orientation. As has been stated previously this has been attributed to the better joint integrity achieved when the joint is in the horizontal orientation.

Joints in a horizontal configuration exhibit better joint integrity and therefore take longer to show temperatures above ambient at the surface or just below the surface of the unexposed face. Sandwich panels with joints in the vertical orientation reach temperatures above ambient sooner than the equivalent thickness in a vertical orientation. **Therefore where the option exists it would be better to take measurements at vertically orientated joints than those in a horizontal orientation.**

It is clear that there is value to be gained in revealing the joint and core material at a depth of 10mm beneath the surface of the unexposed face. These tests have revealed that where temperatures greater than ambient are measured then this is indicative of high compartment temperatures and therefore it would be inappropriate to commit fire-fighters into the compartment and an alternative approach should be sought.

In these series of tests, temperatures 10mm below the surface reached above ambient between 2 minutes and 16 minutes quicker than at the unexposed surface. Although revealing the core at this depth is a relatively simple operation the time and resources needed to perform that function may be considered unnecessary given the little benefit that can be achieved. **However, revealing the core and joint at this depth is common practice with most Fire and Rescue Services to establish the core material. Therefore as this function is being performed anyway then guidance could be extended to** include taking temperature measurements as part of this process to determine if above ambient temperatures exists. It is an easy operation to reveal both the joint and core material at this depth below the surface and could potentially give earlier indication of high compartment temperatures.

Given this it may be better to consider temperature divergence rather than just temperature change. Table 5.7.10 (b) below compares temperature divergence at the unexposed surface and 10mm below the surface of the unexposed surface. It is clear that from the table that in the majority of cases temperature divergence occurs sooner at the surface rather than at 10mm below the surface. This would be unexpected and the only explanation for this is the differences in measuring techniques. The below surface temperatures were measured by thermocouples whereas the surface temperatures were measured with the thermal imaging camera. Therefore is unreliable to make the comparison between the two sets of results and further work could be carried out how much sooner temperature divergence occurs and whether this would provide a significant time difference to justify exposing the joint 10mm below the surface and taking temperature measurements.

Test number	Time to temperature divergence at the unexposed surface (minutes)	Time to divergence 10mm below the unexposed surface (minutes)
1	**10**	**13**
2	**10**	**11**
3	**22**	**24**
4	**20**	**25**
5	**20**	**22**
6	**20**	**27**
7	**28**	**21**
8	**38**	**21**

Table 5.7.10(b) Comparison between temperature divergence at the unexposed surface and 10mm below the unexposed surface

Where above ambient temperatures are revealed at 10mm beneath the surface of the unexposed face then this indicates high compartment temperatures. Given these high temperatures it would be inappropriate for offensive fire fighting (i.e. internal fire fighting). However where the joint integrity remains intact then fire-fighters could perform other functions within adjacent compartments.

5.8 Analysis of rate of change of temperature at the joint and panel taken from outside of the compartment with thermal imaging camera

5.8.1 Introduction

The analysis carried out in the previous sections have primarily been concerned with determining whether any relationship exists between the internal compartment temperatures and those on the external face of the panel and at the joint. This section examines the rate of temperature change at the joint and panel taken by the thermal imaging camera on the unexposed face of the sandwich panel samples, to determine if a relationship exists between this rate of change and the fire compartment temperatures. Graphs of this analysis are shown in section 4.9.

5.8.2 - 95 mm samples vertical orientation

In the vertically orientated samples there is little discernible rate of temperature change at the joint until 7 minutes into the test, at this time the peak compartment temperature of 800°C has been reached. The average rate of change across both tests at this time was 5°C/ minute. The most apparent change occurs from around 9 minutes to 18 minutes, a time when compartment temperatures remain in excess of 700°C but approaching the decay phase. After this time there are significant positive and negative fluctuations but the fire is well into its decay phase.

The analysis of the rate of temperature change at the panel revealed that these tests the rates changes were extremely erratic as compared to the other The largest positive rate of change occurred between 17 minutes and 18 minutes into the test duration. The rate of change of temperature was recorded as 34°C / minute when the compartment temperature was in excess of 750°C. In both tests the compartment temperatures had reached maximum values and had just entered the decay phase.

5.8.3 - 95 mm samples horizontal orientation

In the horizontally orientated samples there is little rate in change of temperature at the joint until after 20 minutes into the fire test. At this time the compartment had reached its maximum temperature of over 700°C. The largest rise occurs in both samples between 22 minutes and 35 minutes into the test, at this time compartment temperatures are in decline but still in excess of 540°C.

The largest positive rate of change at the panel occurred between 28 minutes and 32 minutes into the test duration. The rate of temperature change was recorded on average as

3°C / minute across both tests. The compartment temperatures had already reached maximum values at this time and declining with temperatures in the order of 630°C.

5.8.4 - 120 mm samples vertical orientation

In the vertically orientated samples the first discernible rate increase at the joint occurs at 20 minutes, at this time the compartment temperature has reached its maximum temperature of over 700°C. The rate increases positively up until 30 minutes into the test where the compartment temperature has fallen to 545°C. The largest negative temperature rate decrease occurs between 30 minutes and 40 minutes, where the compartment temperature has declined to 450°C.

The largest positive rate of change in panel temperature occurred between 19 minutes and 20 minutes into the test duration. The recorded rate increase was 2°C/ minute averaged across both tests. At this time compartment temperatures had reached their maximum values of 729°C

5.8.5 - 120 mm samples horizontal orientation

In the horizontally orientated samples the first discernible temperature rate change at the joint occurs at 30 minutes into the fire test. At this time the compartment temperatures have reached their maximum value of 742°C. The largest positive increase occurs from 30 minutes to 36 minutes, at this time the fire compartment has reached its maximum temperature and is in the decay phase.

The largest positive rate increase on the panel occurs during the growth phase of the fire was on average between 36 minutes and 39 minutes into the test duration. The recorded rate of temperature increase was 4°C/ minute averaged across both tests. At this time the compartment fire was well into its decay phase with temperatures of 576°C recorded.

5.8.6 - Summary

In the 95mm sample tests perceptible rate changes at the joint occurs after 7 minutes in the vertically orientated samples and after 14 minutes in the horizontally orientated samples. Whereas in the 120mm samples the rate changes occurred after 20 minutes in the vertically orientated joints and 28 minutes in the horizontally orientated samples.

In all of the tests the practical observable change occurs at a time when the compartment temperatures are at or are just past their maximum values but still in excess of 600°C.

The tests have shown that initial rates of observable change occur more readily in vertically orientated joints than in horizontally orientated joints. This is attributed to the greater integrity of the joint in the horizontal orientation. **Therefore vertically orientated joints give earlier indications of high compartment temperatures and this should be reflected in Fire and Rescue Service guidance.**

The most significant rate of temperature change observed at the joint is indicative of high compartment temperatures but in the early post flash over phase of the fire. Where this is apparent the response of the Fire and Rescue Service would be defensive fire fighting (i.e. fire fighting from an external position).

In the 95mm sample tests perceptible rate changes occur at the panel after 18 minutes the vertically orientated samples and after 28 minutes in the horizontally orientated samples. Whereas in the 120mm samples the rate changes occurred after 20 minutes in the vertically orientated joints and 24 minutes in the horizontally orientated samples.

In all of the tests the practical observable rate of temperature change occurs at the panel at a time when the compartment temperatures are at or are just past their maximum values but still in excess of 500°C. The rate of temperature change in the panel core still occurs quicker in the vertical orientation than the horizontal orientation which is attributed to the addition heating effect caused by loss of integrity of the joint.

In both vertical and horizontal orientation, the rate of observable temperature change in the panel core occurs later than the rate of change in the joint temperature. This observation should therefore be reflected in Fire and Rescue Service guidance.

5.9 Analysis of rate of change of temperature at the panel and joint at 10mm below the unexposed surface taken with thermal imaging camera.

5.9.1 Introduction

As described in the previous section the change in temperature at a point 10mm below the surface at both the joint and at the core material has been analysed. It is considered that the Fire and Rescue Service would be able to access this depth below the unexposed surface simply with the use of simple hand tools and is therefore a realistic action that could be easily achieved in the early and dynamic phase of a fire situation.

This section builds on the previous analysis and examines the rates of temperature change at the both the joint and core material taken with the thermal imaging camera at a depth of

10mm unexposed face of the sandwich panel samples. This analysis seeks to determine a relationship between the rate of temperature change at the panel and the temperatures within the compartment. Graphs of the full results are shown in section 4.10.

5.9.2 - Test 1 95mm samples in vertical orientation

The rates of change are predominantly greater in the joint temperatures rather than the core material. The first appreciable change occurred in the joint and core at 1 minute 30 seconds into the test where the rate of change was around 8°C per minute. At this time the temperature of the compartment was recorded as 43°C, over twice the ambient temperature. The first significant rate increase occurred at 15 minutes with the rate of change in the joint recorded as 66°C per minute and the compartment temperature 780°C. At this time the compartment had reached its first maximum peak temperature and approaching its second.

The highest rate of change was recorded as 98°C per minute at 19 minutes. At this time the fire had begun the decay phase with compartment temperatures recorded 742°C.

5.9.3 - Test 2 95mm samples in vertical orientation

The rate of change at the joint is greater than the core in the growth stages of the fire with the opposite occurring in the decay phase. The earliest rate increase occurs at 1 minute 30 seconds as in the first test. At this time the compartment temperature is recorded as 44°C, twice that of ambient temperature. Within the growth phase of the fire the greatest rate of change in the joint temperature is recorded as 62°C/ minute at 13 minutes, where the compartment temperature has reached 768°C. There are greater rate changes in both the joint and panel core temperatures after that time when the fire is into its decay phase.

5.9.4 - Test 3 95mm samples in horizontal orientation

The rate of change of temperature is negligible throughout the growth phase of the fire. The first noticeable rate change of temperature at the joint occurs between 25 minutes and 28 minutes where the rate changes from 4°C/ minute to 43°C/ minute. At this time the compartment temperature declines from 711°C to 672°C and continues to decay. The most significant rate change occurs at the joint between 30 minutes and 32 minutes where the rate changes from 13°C/ minute to 34°C/ minute, however during this period the compartment temperature declines from 630°C to 595°C and continues to decay.

5.9.5 – Test 4 95mm samples in horizontal orientation

Both joint and core material show little rate of temperature change until 20 minutes into the test duration. At this point the first rate change is evident up until 22 minutes where the rate has changed from 1°C/ minute to 2°C/minute, at this time the compartment temperature is 709°C and reaching its maximum temperature. The next significant rate of change in the joint temperature occurs 28 minutes where the rate is 7°C/ minute and the compartment temperature reduced to 672°C. The greatest temperature rate change at the joint is recorded at 16°C/ minute at 32 minutes into the test, at this time the compartment temperature had reduced to 595°C but occurred 10 minutes after the peak compartment temperature had been reached.

5.9.6 – Test 5 120 mm samples in vertical orientation

Both joint and core showed little rate of change in temperature until 18 minutes into the test. At that time the rate of temperature change at the joint was recorded as 271°C/ minute and the panel 216°C/ minute. At 18 minutes the compartment temperature was recorded as 714°C and reached its maximum temperature 4 minutes later. The next and largest rate of temperature change occurred at 31 minutes with rate changes at the joint and core recorded as 534°C/minute and 172°C/ minute respectively. At this time the compartment temperature was recorded as 545°C and was 10 minutes past the peak temperature.

5.9.7 – Test 6 120 mm samples in vertical orientation

The earliest rate change of temperature occurred at 3 minutes into the test when the compartment temperature was recorded as 30°C. The first significant rate of temperature increase in joint and core occurred at 20 minutes into the test. The rates of temperature changes at this time were recorded as 114°C/ minute and 106°C/minute in the joint and core respectively. At this time the compartment temperature was 734°C and approaching the maximum peak value.

The next significant increase occurred at 27 minutes where the rate of temperature change at the joint and core were recorded as 98°C/ minute and 53°C/ minute respectively. The compartment temperature at this time was 639°C and 6 minutes into the decay phase of the fire. After this period the rate changes are sporadic well into the decay phase with no trend being identified.

5.9.8 – Test 7 120 mm samples in horizontal orientation

The first rate of temperature change at both the joint and core was observed at 5 minutes into the test when the compartment temperature reached 57°C. The next significant change occurred at 21 minutes where temperature rate changes at the joint and core reached 57°C/ minute and 55°C/ minute respectively. At this time the compartment temperature recorded 712°C and was approaching the peak compartment temperature. A significant reduction in the temperature rate was observed at 38 minutes in at both the joint and panel, with rates being recorded as -32°C/ minute and -34°C/ minute respectively. This reduction is consistent with the temperature reduction in the decay phase of the fire.

5.9.9 – Test 8 120 mm samples in horizontal orientation

The first rate of temperature change at the joint was recorded as 15°C/minute observed at 10 minutes into the test with, at this time the compartment temperature had risen to 595°C and was approaching the initial temperature peak of 620°C.

The next significant temperature rate increase at the joint was recorded as 34°C/ minute occurred at 27 minutes into the test. At this time the compartment was at its maximum temperature of 754°C. Although there was evidence of other temperature rate rise increases, the third and most prominent was recorded as 112°C/minute at 34 minutes into the test when the compartment temperature had reduced to 642°C and the fire was in the early decay phase.

5.9.10 Summary

Test	Sample description	Time to significant rate of temperature change (minutes)	Rate of temperature change (°C/ minute)	Compartment Temperature (ºC)
1	95mm vertical joint	15	66	780
2	95mm vertical joint	13	62	768
3	95mm horizontal joint	25	43	672
4	95mm horizontal joint	32	46	595
5	120mm vertical joint	18	271	714
6	120mm vertical joint	20	114	732
7	120mm horizontal joint	21	57	717
8	120mm horizontal joint	27	34	748

Table 5.9.10 Comparison of significant rate of temperature change at the unexposed surface

From the above results it can be seen that the significant rate of temperature change occurs earlier in the 95mm samples than in the 120 mm samples. However where these significant rate changes occur, the compartment fire is between 595°C and 780°C and are either at their peak compartment temperatures or in the early decay stages of the fire.

In practical terms, the rate of change of temperature at the joint and core cannot be used to determine the compartment temperature; this is primarily due to the lag in temperature from the exposed side to the unexposed side of the panel. However from the analysis above the information may be used to determine the phase that the fire has reached rather than the temperatures within the compartment. This information may be used to assist in the fire fighting decision making process.

The rates of temperature changes occur sooner in the vertically orientated samples than those in the horizontal ordination. This observation mirrors the results of previous analyses and attributed to the better integrity of the horizontally orientated joint arrangement and should be incorporated into guidance for Fire and Rescue Services.

Test	Sample description	Time to significant rate of temperature change (minutes) 10mm below surface	Time to significant rate of temperature change (minutes) at unexposed surface
1	95mm vertical joint	15	17
2	95mm vertical joint	13	14
3	95mm horizontal joint	25	28
4	95mm horizontal joint	25	28
5	120mm vertical joint	18	25
6	120mm vertical joint	20	27
7	120mm horizontal joint	21	28
8	120mm horizontal joint	27	36

Table 5.9.10 (a) Comparison of significant rate of temperature change 10mm below surface of unexposed surface

The purpose of this section was to analyse the rates of temperature changes at the joint and core 10mm below the surface of the unexposed face. The significance of this analysis was to determine the benefits of using basic hand tools to expose the joint and panel and taking temperature measurements 10mm below the surface of the unexposed face, as opposed to taking measurements at the exposed face only. The table above compares the time taken before for significant rates of temperature changes to be apparent at both the surface and 10mm below the surface of the unexposed face.

From the table above it is evident that the time taken for the a significant rate of change of temperature to take place in the 95mm samples occurs between 1 minute and 3 minutes sooner 10mm below the surface as opposed to on the exposed face. In the 120mm sample this occurs between 7 minutes and 9 minutes sooner at 10mm below the surface.

It is clearly beneficial to collect as much information about potential fire conditions within a compartment as soon as possible. However, as shown above there is minimal time difference in temperature rate changes between at the exposed surface and 10mm below the exposed surface. **Therefore the value of taking time to expose the joint 10mm below the surface, taking temperature measurements and evaluating the relationship with the internal compartment temperature is insignificant. This approach would not provide any advantage to fire fighting decision making over that provided from using thermal imaging camera on the surface.**

5.10 Analysis of temperatures at external face of test container

During the fire tests the temperature profile of the external face of the container at roof height was collected using a thermal imaging camera. The purpose of collecting this information was to compare temperatures on the external face with internal compartment temperatures. Insulated building envelopes would be unlikely to have any metallic connections as this would act as a bridge between the internal and external environment and reduce the effectiveness of the insulation, however it is useful to analyse the results. Graphs showing these results can be found in Appendix A.

In all of the tests the peak internal temperatures are approximately twice as high as the temperatures on the external façade. Although this is purely a feature of the test facility it is a valid observation and provides an indication of high internal compartment temperatures.

5.11 Conclusions

The above section has analysed fire data results and considered temperature conditions at the unexposed surface, 10mm below the surface and 10mm from the exposed surface. All of the evidence suggests that it is impossible to determine internal compartment temperature other than by drilling into or removing the panel to assess by direct observation. This would be considered an appropriate fire fighting tactic but would take time to achieve whereas other indicators may provide a more immediate gauge to compartment conditions.

Temperature divergence between the joint and panel measured externally is a good indicator of high compartment temperatures. There is a good correlation between the time of divergence and flashover or early post flashover conditions.

Any panel deflection observed or measured externally is a good indicator of high compartment temperature. Maximum deviation occurs between flashover and into the decay stage of the fire. Although this is considered reliable it is acknowledged that it would be difficult to assess such small deflections during fire fighting operations.

Any degree of deflection or temperature divergence between the panel and joint may mean loss of integrity or stability of the panel. Therefore the adjacent compartment may become compromised and fire fighting operations may need to be conducted from a compartment that has not been compromised

There is a good correlation between the rate of temperature change at the joint taken at the unexposed surface and the early post flashover period. No correlation was identified between the rate of temperature change at the panel and compartment conditions.

Where flashover or early post flashover conditions have been attained then this has a significant implication to fire fighting tactics. When flashover has occurred within a compartment then it can be assumed that any lives or contents have already been lost and therefore there would be no benefit to fire-fighters entering the compartment to carry out search and rescue operations or initial fire fighting attack. Where temperature divergence occurs then the integrity of the joint may be lost, therefore compromising adjacent compartments

In the circumstances described above the appropriate fire fighting response would be to fight the compartment fire defensively (an external attack) and provide protection to adjacent compartments to prevent fire spread. Where flashover or early post flashover conditions have not been identified then fire-fighters could enter the compartment to fight the fire offensively (internal attack) ensuring gas cooling techniques to ensure that the compartment does not reach flashover conditions.

CHAPTER 6: SUMMARY AND DISCUSSION

6.1 Introduction

As an aid to the reader, this final chapter of the dissertation restates the research problem and reviews the major methods used in this study. The major sections of this chapter provide a summary of the results and discuss their implications.

6.2 Statement of the problem

It is acknowledged within the UK Fire and Rescue Services that fires involving buildings containing sandwich panel construction present special problems to the fire crews attending the incident. The problems are essentially one of speed of fire development, concealed fire spread and a build-up of dangerous conditions within compartments. Given the insulated qualities of these panels it is difficult to determine the temperature conditions that exist from the unexposed face. These fires behave in the same way as those in other buildings but far faster, with rapidly changing and deteriorating conditions. This presents the Fire Incident Commander with a number of problems when attempting to assess internal temperatures conditions allow him/ her to choose the best tactics to successfully resolve the incident.

With traditional buildings it is easier to make an assessment of temperature conditions within compartments as the walls do not have the thermal insulation qualities associated with sandwich panel construction. There is no practical requirement to provide such a degree of insulation and also traditional buildings will have various openings and communication that allows a reasonable assessment of internal temperature to be made by thermal imaging cameras and other means. By making this assessment from outside of a compartment allows informed decisions to be made on the best and safest way to conduct fire fighting operations.

However buildings of sandwich panel construction do not allow these assessments to be made and therefore informed decisions are not able to be made. The literature review chapter identifies a number of high profile fires within sandwich panel buildings which have resulted in fire-fighter fatalities and injuries. Following these incidents and in the absence of any meaningful research or practical advice on the best approach to take in tackling these fires, some Fire and Rescue Services within the UK took the decision not to enter sandwich panelled buildings that were involved in fire.

This purpose of this study is to review existing literature to identify methods and techniques used by the Fire and Rescue Services to determine fire conditions within a building of sandwich panel construction. In addition a series of small scale fire tests were conducted using sandwich panel samples of differing thickness and joint configuration and subjected to realistic fire conditions.

Temperatures profiles within the fire compartment, sandwich panel core, within the joint profile and on the outer faces of the panels were taken using thermocouples and thermal imaging cameras. The results of the tests were analysed to determine whether any relationship exists between the temperature profiles and the temperatures within the fire compartment and whether this information could be used to advise fire fighting decision making.

6.3 Review of the methodology

This study entailed a comprehensive literature review to determine the approaches taken by UK Fire and Rescue Services to fire fighting in buildings of sandwich panel construction. The literature review revealed that there was very little guidance to assist Fire and Rescue Services in interpreting results from thermal imaging cameras. The literature review identified a number of Fire and Rescue Service that had adapted their standard operating procedures; however these minor adaptations were only changes to tactics and not designed to assist in interpretation of results.

A detailed experimental programme was developed to conduct real fire testing on small sample of sandwich panels, using pallet stacks as the real fire source.

The tests were carried out on sandwich panel samples with steel facing and PIR cores with the joints in the horizontal and vertical geometry. The chosen thicknesses of sandwich panel were 95mm and 120mm as these are most commonly used in external wall applications. The 95mm thickness is the most commonly used and the 120mm product is the newest product type. Thermocouples were placed within the fire compartment, throughout the body of the sandwich panel and at critical points in and surrounding the joint detail. The temperature measurements recorded at 10 seconds intervals via a data recorder.

Temperatures at the unexposed face were taken using thermal imaging cameras commonly used by the UK Fire and Rescue Services and the measurements manually recorded at appropriate temperature intervals.

6.4 Fire fighting Options

6.4.1 Fire fighting Response

In considering the results of the analysis and comment on how this information may be used to inform fire fighting decision making it is important to take into account the Fire and Rescue Service risk philosophy and what fire fighting options may be available.

The risk philosophy adopted by the UK Fire and Rescue Service and supported within a national framework provides a generic approach to risk follows:

- The Fire and Rescue Service may risk our lives a lot, in a highly calculated manner, to protect saveable lives.
- The Fire and Rescue Service may risk our lives a little, in a highly calculated manner, to protect saveable property.
- The Fire and Rescue Service will not risk our lives at all for lives or property that are already lost.

6.4.2 Fire Service Intervention

There is a commonly used model to describe Fire Service Intervention. The model is based upon a number of sub systems that describe a timeline of events from a time of call to the Fire Service to the commencement of fire fighting operations. Although the model is generic it can be modified to introduce other sub systems to address more specific activities.

Historically the requirements for Fire Service attendance times were nationally agreed standards based upon factory such as building types population density. Since 2004 Fire Authorities have been required to develop local Integrated Risk Management Plans (IRMPs) based upon local risk and this drives the locally set attendance standards. Therefore travel time in the model is variable depending upon locality.

Within the context of the risk philosophy stated above it is important to consider what fire fighting options are available when having made an assessment of the fire conditions within a compartment. In broad terms the following tactics are available when considering compartment fire fighting:

- If the conditions within the compartment are too severe then it may be accepted that any persons or property within the compartment have already been lost. Where the severity has the potential to affect the structure and the stability of the compartment defensive fire fighting (i.e. fire fighting from an external position) would be the chosen fire fighting tactic.

- If conditions within the compartment are too severe it may be accepted that person or properties within the compartment have already been lost. However, if the integrity and stability of the compartment is unaffected, then it may be acceptable to operate within an adjacent compartment. This may be to prevent fire spread into other adjacent compartments or to perform some other function.

- If conditions within the compartment are favourable and an effective attack on the fire could be performed to protect saveable life or property. Offensive fire fighting (i.e. fire fighting from an internal position) would be an acceptable tactic; however the position would need to be constantly reassessed to ensure that the internal conditions remain tenable.

6.4.3 Summary of the results and analysis

As there are no longer set attendance times across the UK then it is difficult to establish how long it would take for a Fire and Rescue attendance to be made to a fire incident. Having reviewed the Integrated Risk Management Plans (IRMP) for all of the Fire and Rescue Services within the UK a reasonable attendance time of 10 minutes is common with a further 5 minutes inspection time. This means that it would take a minimum of 15 minutes from a time of call to a fire to some form of intervention. The analysis of the results considers the general profiles across the range of tests but also considers conditions at 15 minutes into the test to assess conditions when the Fire and Rescue Service may be making an entry into a compartment.

<u>6.4.3.1 Measurement and collection of temperature profiles within the fire compartment measured by plate thermocouples.</u>

The configuration of the fire load used for each of the tests was identical. In order to conduct the tests, four crib fires were used. The peak compartment temperatures ranged between 755°C and 825°C. One of the crib fires reached its peak temperature after 8 minutes whereas the other three reached maximum temperatures between 21 and 26 minutes into the test duration. **At 15 minutes into the test three of the fires had reached their maximum temperatures and one was in the growth phase. The fire loads and configuration were not designed to replicate any other test but planned to be as consistent as possible across all four of the design fires.**

<u>6.4.3.2 Analysis of temperature profiles in the panel core.</u>

Temperatures recorded at slice 1(closest to the exposed face) being slightly above ambient and yet the compartment temperature is between 300ºC and 500ºC, approaching flashover conditions. At 15 minutes duration there are significant differences between core and compartment temperatures however there is a greater degree of confidence that high temperatures exist within the compartment.

It is not possible to use this information directly to determine compartment temperatures. During fire fighting operations the only way to determine exact internal compartment temperatures would be by direct observation by drilling through or removing part of the panel and taking direct measurements.

6.4.3.3 Analysis of temperature profiles within the panel joints.

At 15 minutes into the test, temperatures at slice 1(closest to the exposed face) range from 272°C to 662°C whereas the compartment temperatures range from 352°C to 795°C which provides a reasonable correlation of temperature.

However a more practical approach would be to observe joint temperatures at the unexposed surface. **At 15 minutes these temperatures range from 28°C to 325°C whereas the compartment temperatures range between 352°C to 795°C. At present, there is no clear quantifiable correlation between compartment temperatures and the surface joint temperatures and the information is therefore not directly usable.**

6.4.3.4 Analysis of the temperature profiles at the unexposed panel face taken with the thermal imaging camera.

Although the temperature profiles of the joint and panel follow the same pattern as compartment temperature profile, there is a significant time lag between the two. The time lag in the 95mm samples is an average of 12 minutes and 18 minutes in the 120mm samples.

Therefore temperature information taken at the joint and panel on the external face with thermal imaging camera does not provide an accurate guide to temperatures within the compartment.

6.4.3.5 Divergence of panel and joint temperatures on the unexposed panel face taken with the thermal imaging camera.

Due to joint opening up as the foam material degrades, the panel surface temperature and the joint temperature on the unexposed side initially are very similar but diverge after a period of time. This time of divergence is reasonably close to the flashover time. Thus, if temperature divergence has not happened, the fire may be considered to be in the pre-flashover stage.

The sooner that temperature divergence can be recognised the sooner that those high compartment temperatures can be assumed. In all of the tests temperature divergence occurred before 15 minutes duration. Therefore this is a realistic indicator of a high temperature compartment fire.

Where a compartment fire has not reached flashover conditions then an assumption may be made that salvable lives and property exist within the compartment and an offensive (internal) fire fighting attack may be made. Where temperature divergence is identified then flashover has occurred and it can be assumed that there is no savable life or property within the compartment. In these circumstances the appropriate fire fighting tactic would be to provide a defensive approach (external attack) providing protection to adjacent compartments.

6.4.3.6 Analysis of the panel displacement taken at the unexposed face with linear displacement transducers.

At 15 minutes into the test the panel deviation ranges from 10 mm to 25mm. although it would be difficult to detect such minimal panel movement. Where maximum displacement is observed or measured occurs then the compartment fire has reached flashover and the fire is often well into the decay phase.

Any observed or measured displacement is an indicator of high internal compartment temperatures and therefore an external attack with protection to adjacent compartments is the appropriate fire fighting response. Such displacement could result in loss of joint integrity and panel stability, fire fighting tactics should constantly be reviewed to ensure that adjacent compartments are not compromised. It is acknowledged that it would be difficult to make an assessment of displacement but this is a good indicator and worthy of further work to develop better practical techniques to make that assessment.

6.4.3.7 Analysis of the temperature profile of the panel core and joint taken 10mm below the surface of the unexposed face.

From the analysis it is shown that the temperature 10mm below the surface attains temperatures of 2°C above ambient temperature between 2 minutes and 16 minutes quicker than at the unexposed surface.

It is clear that there is value to be gained in revealing the joint and core material at a depth of 10mm beneath the surface of the unexposed face. These tests have revealed that where temperatures greater than ambient are measured then this is indicative of high compartment temperatures and therefore it would be inappropriate to commit fire-fighters into the compartment and an alternative approach should be sought.

However, revealing the core and joint at this depth is common practice with most Fire and Rescue Services to establish the core material. Therefore as this function is being performed anyway then guidance could be extended to include taking temperature measurements as part of this process to determine if temperatures of at least 2°C above ambient exist. It is an easy operation to reveal both the joint and core material at this depth below the surface and could potentially give earlier indication of high compartment temperatures.

Where above ambient temperatures are revealed at 10mm beneath the surface of the unexposed face then this indicates high compartment temperatures. Given these high temperatures it would be inappropriate for offensive fire fighting (i.e. internal fire fighting). However where the joint integrity remains intact then fire-fighters could perform other functions within adjacent compartments.

<u>6.4.3.8 Analysis of the rate of temperature change at the joint and panel taken at the unexposed face with the thermal imaging camera.</u>

In all of the tests the practical observable change in temperature at the joint occurs at a time when the compartment temperatures are at or are just past their maximum values but still in excess of 600°C. Vertically orientated joints give earlier indications of high compartment temperatures than horizontally orientated joints.

No reliable correlation could be identified in relation to the rate of temperature change at the panel and compartment conditions.

The rate in change of temperature at the joint reveals that the rate of temperature change at the joint can be related to the early post flashover conditions which can be used to inform fire fighting tactics. The fire fighting response would be defensive fire fighting (external attack) providing protection to surrounding compartments.

<u>6.4.3.9 Analysis of the rate of change of temperature at the panel core and joint at 10mm below the surface of the unexposed face, taken with the thermal imaging camera.</u>

The rates of temperature changes occur at a quicker the vertically orientated samples than those in the horizontal ordination. This observation mirrors the results of previous analyses and attributed to the better integrity of the horizontally orientated joint arrangement and should be incorporated into guidance for Fire and Rescue Services. However generally the rates of temperature change taken 10 mm below the unexposed surface provide do not provide as clear a relationship as those taken on the unexposed surface.

Therefore the value of taking time to expose the joint 10mm below the surface, taking temperature measurements and evaluating the relationship with the internal compartment temperature is insignificant. This approach would not provide any advantage to fire fighting decision making.

6.5 Conclusions

The analysis above has determined that there is no reliable way of determining internal temperature conditions within a compartment from the outside. However there are a number of indictors that can be used to determine that high temperature conditions exist within the compartment. Where it has been determined that high temperature exists then a course of actions is proposed.

6.6 Limitations

This work has been focussed on exposing the sample sandwich panels and joints to the maximum possible real fire conditions in order to analyse the temperature developments. In order to achieve this maximum exposure, the fire size and location was selected in order to test the panel and the joint under the most extreme fire conditions that could be achieved.

Although these tests were not designed to replicate any other test regime every effort has been made to ensure that the tests are as reproducible as possible. The test fires have all been identically positioned using the same mass of wooden pallets; however as identified it has been difficult to achieve exactly the same fire profiles as the pallets were of different ages and had been subjected to different environmental conditions. Analysis of the fire curves reveals variance of over 8% between the different fire test curves.

However it is acknowledged that the compartment size, fire size and proximity of the test sample to the fire source used in these tests do not provide realistic conditions and be unlikely that these similar conditions would be met in a real building fire. Buildings of sandwich panel construction are normally large volume un-compartmented buildings with high ceilings and it would be unlikely that a fire of the magnitude used in these tests would provide the same level of intensity due to the increased building volume and ceiling height.

In addition it is common for buildings of this type to be provided with physical protection against mechanical damage 2m from the floor on the internal face and therefore the heat flux from a fire at floor level would not affect the sandwich panel in the same way as in the test conditions.

The work carried out in this thesis has used a limited number of test samples and relied on using a fully developed crib fire as the fire source. It is acknowledged that not all fires behave in this way and it would be useful to carry out similar tests using a smouldering fire as the fire source.

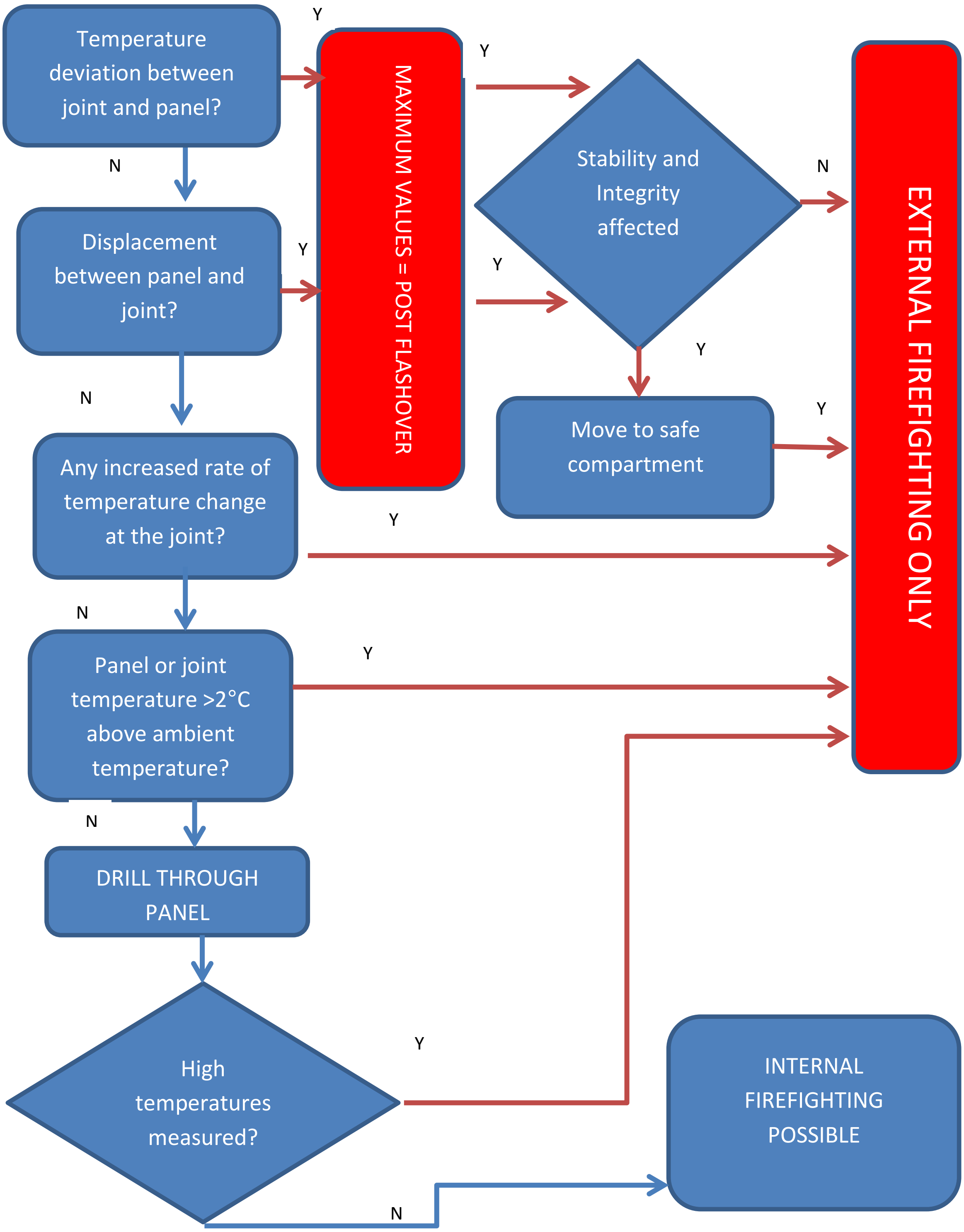
6.7 Guidance for Fire and Rescue Services

The checks below that can be made from outside of a compartment are recommended to determine whether high compartment temperatures exists are as follows:

- Is the temperature on the unexposed surface greater than 2°C above ambient temperature? If yes then high compartment temperatures exist.
- Is there an increased rate of temperature change at the joint? If yes then high compartment temperatures exist. When the maximum rate of temperature change occurs then flashover conditions have been reached.
- Is there displacement at the joint? If yes then high compartment temperatures exist. The maximum displacement occurs after flashover conditions have been reached (it is acknowledged that this may be difficult to assess during firefighting operations).
- Is there temperature deviation between the panel and joint? If yes then high temperatures exist and the compartment has already reached flashover conditions.
- Where the above checks are made and the answer to the questions is yes then it can be reasoned that high compartment temperatures exist, saveable life and property has already been lost and only defensive (external firefighting operations) is appropriate. Depending upon the outcomes from a dynamic risk assessment this may mean carrying out operations from outside compartment or preventing fire spread to other compartments.

However where the answer to the questions is no then then this does not provide reliable information and further investigation would be necessary to determine compartment conditions. The further investigation would require the compartment to be opened or a hole drilled through the panel to determine the temperature conditions inside. Once this has been carried out then direct temperature measurements can be taken. A dynamic risk assessment will then determine the appropriate firefighting response which would either be an internal attack (offensive) or an external attack (defensive). A practical easy to use guide is provided in section 6.7.1.

6.7.1 Visual guidance



6.8 Further Work

These small scale tests have been designed to expose small test samples of sandwich panel to significant exposure from real crib fires and analysis the temperature development within. It is acknowledged that there is little similarity between these tests and real life building fires and further work should be carried out with greater alignment to the conditions that may be found within the built environment. Although it would be impractical to carry out full scale testing due to limited resources it may be possible to provide an analysis of typical compartment sizes and fires sizes experienced within these building types. A scaled down test regime could then be developed which would be better aligned to real building fire conditions.

Given the highly insulated qualities of the insulated panels it will always be difficult to get an accurate determination of internal temperatures from outside of the compartment with current technology. It would be useful to explore possibilities of having a passive method that could be integral to the construction that would provide temperature information outside of the compartment. This could be a system of installed integral thermocouples, a form of colouration strip or paint that changes colour when a certain temperature is reached.

Due to time limit, this study has only examined temperature developments in sandwich panel construction at different locations. An analysis of profiles within the thickness of sandwich panels may allow the fire temperature to be extrapolated from temperatures on the unexposed surface and another point deep inside the panel. This may be possible because sandwich panel construction is lightweight in nature. Therefore, heat absorption by the panel is relatively small compared to heat conduction. Hence, heat transfer in the sandwich panel approaches steady state. If the temperature dependent thermal conductivity of the foam is known, then extrapolation of temperatures to the exposed surface may be possible. The exposed surface temperatures are usually close to the fire temperatures.

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