University of Central Lancashire

Phenomenological Studies of Fires on Recycling Materials

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by

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Abstract

This thesis provides the scientific basis for the waste management industries best practice guidance. The findings have been published by the Waste Industries Safety and Health Forum Guidance 28- Reducing Fire Risk at Waste Management Sites. It details the development of fire in a range of common waste materials at large scale and under realistic storage conditions. This data was used to develop and demonstrate new firefighter tactics now employed by the British Fire Service.

The research was based on a series 27 full scale experiments on common waste materials stored in both loose piled conditions and compressed bales stacked up to 4 m high in line with the UK regulations. The fire tests ranged in masses between 3 tonnes and 18 tonnes of material. The piles were tested in both a fully open condition and within a bunker. The material was ignited on the surface and measures using a bespoke thermocouple array. A series if deep seated ignitions were also examined. A set of self-heating test were conducted concurrently with these fire tests. A previously undocumented vortex fire behaviour was discovered during these experiments. CFD was used to confirm the phenomenon associated with the stacked bale fire experiments. The findings were used to develop a new set of firefighting tactics using water, compress air foam system and surfactant water additive these were tested at full scale by members of the fire service from Essex and East Sussex fire and rescue services. A range of different scientific methods were employed to obtain data including thermal imagery along with more traditional thermocouple approach. Video smoke and thermal imagery systems provided very early detection of fire in fuel bed matrix that allow the passage of convection currents such as pre crushed wood but did not prove any more effective than conventional detection technologies in impervious fuel beds. The LEGIO block passive fire separation system was also tested to evaluate the use of movable concrete blocks in the waste environment. K type thermocouples were positioned are regular intervals throughout the depth of the blocks at different points to evaluate conductive heat transfer.

The experiments were used to define the fire development in stored waste materials and provided a range of fire engineering parameters. These include a full analysis of the separation distance using a computer model to establish boundary distances based on the analysis of radiated heat transfer from a range of geometrical orientations of both transmitters and receivers. To provide safe separation distances for stored waste based on the materials and storage conditions. Due to the size of the piles, it was not possible to conduct the tests on a load cell to calculate mass loss. Instead, mass loss was estimated by analysis of the volume loss that could be measured form this mass loss rate and heat release rates were calculated for RDF, SRF, Shredded Tyres, pre crushed timber, wood fines and HDPE bales in ventilated

and unventilated conditions. The firefighting tactics explored in the paper have been used to develop the Waste Fire Tactical Advisor role by the National Fire Chiefs Council UK.

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Where a candidate's research programme is part of a collaborative project, the thesis must indicate in addition clearly the candidate's individual contribution and the extent of the collaboration. Please state below:

1. Section 10 is based on a report for the WISH group (6) conducted on radiation modelling which was a joint project (71) with Marios Alexandro who re ran my radiation models and co authored TN 15799-02b which is a commercial report for inclusion within the Waste industries Safety and Health forum guidance in line with IFC ltd peer review process.

2. Section 11.1 analysis of the real fire data provided by PHE is based on a report conducted for the WISH group (6) and was a joint project (93) with Ben Simmons who re-examined my review of real fire data and co-authored TN 15799-06 which is a commercial report for inclusion within the Waste industries Safety and Health forum guidance in line with IFC ltd peer review process.

4. Use of a Proof-reader

No proof-reading service was used in the compilation of this thesis.

Signature of Candidate

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List of Symbols and Abbreviations

BRE	Building Research Establishment
BSI	British Standards Institution
CFD	Computational Fluid Dynamic simulation
CFOA	Chief Fire Officers Association
CIWM	Chartered Institution of Waste Managers
EA	Environment Agency (England)
EAW	Environment Agency Wales now Natural Resources Wales
ESA	Environmental Services Association
FLIR	Forward Looking InfraRed
FPA	Fire Prevention Association
HDPE	High Density Polyethylene
HSE	Health and Safety Executive
HSL	Health and Safety Laboratory
HRR	Heat Release Rate
LDPE	Low Density Polyethylene
LFB	London Fire Brigade
NIEA	Northern Island Environment Agency
NFCC	National Fire Chief Council
PAS	Publicly Available Standard
PHE	Public Health England
PVC	Polyvinyl Chloride
RDF	Refuse Derived Fuel
SEPA	Scottish Environmental Protection Agency
SRF	Solid Recovered Fuel
TRA	Tyre Recyclers Association
WEEE	Waste Electrical and Electronic equipment
WISH	Waste Industries Safety and Health Forum
WRA	Wood Recyclers Association
	Waste & Resources Action Programme

Nomenclature

A	Area
A_f	Area of flame
c	Specific heat capacity
CH_{crit}	Critical column height
D	Diameter
f_{mass}	The fraction an individual material makes up of a multi material pile by mass.
J	Joules
L_f	Flame length
L^*	Flame Height
L^*_{crit}	Critical flame height
M	mass
q	Heat flux
q^E	Enthalpy of change kg.m.s^{-2}.k^{-1}
q^E_{crit}	Critical Enthalpy of change kg.m.s^{-2}.k^{-1}
Q	Heat flux per metre square
r	radius
S	Second
T	Time
U	Velocity
V	Volume
∂T	Change in time
∂T_{crit}	Critical change in time
∂u_{vapw}	Change in enthalpy of vaporisation of water
ε	Emissivity
ρ	Density
$\tilde{\varphi}$	The cross sectional area hole formed by reposing fragment in a pile of material
$\tilde{\varphi}_{ave}$	The average of the sum of the cross sectional area holes formed by reposing fragment in a pile of material

List of terms

Black bag	This is a term used in the industry to describe waste collected for household street collection rather that commercial waste collections. Black bag waste tends to have a more random content and contains more contaminants and hazardous materials that commercial waste.
Branch	A devise attached at the end of firefighting hose to increase the pressure and focus of the water jet. These devises often have valves to control the flow of the water jets to product a range of effects from focused jets to broad sprays.
Burn back	This described the propensity for material to re-ignite when a firefighting medium is moved away from the area.
Gate Fee	The land fill tax levy is applied to all waste entering a waste management site. Every lorry entering a waste management site must be weighed. Recycled "products" are weighed on exit and this mass is deducted from the input waste mass. Tax is paid on the difference as it is assumed to be destined for landfill.
Hard suction hose	A type of firefighting hose that is designed to resist atmospheric pressure in order to allow the fire pump to generate a partial vacuum which in turn allows the atmospheric pressure to force water into the fire pump. This allows the fire service to pump water from open water sources such as rivers and lakes.
Heavy plant	This is the generic term for forklift trucks, bull dozers, backhoes and diggers etc, used at waste management sites to handle waste.
Leachate	Water that has percolated through waste and has become polluted with high levels of proteins and other

	contaminants in the material. This will result in unnatural bacteriological and algae growth causing persistent ecological damage to the environment if released.
Municipal waste /Municipal derived waste	An interchangeable term with RDF commonly used in the USA and Australia
Puddly Clay	This is a type of clay sourced from the bottom of open water sourced. It is saturated which makes it watertight. This material has the consistency of very wet potting clay.
recyclates	This is a collective term that refers to the potential recycled products that can be produced from any given waste stream. For example, glass can be used to produce a range of sand substitutes for construction or raw glass for bottle production depending on need and commercial viability. For ease the waste management industry will refer to recycled products as recyclates rather than the individual product.
Salvage sheet	This is a sheet often made of woven or continuous plastic that commonly 3 or 4 m square area and is used to provide weather protection for fire damaged building or content to prevent water damage.
Tracking	The term used when heavy plant drives over a pile of waste.
Throw	In this document throw refers to the effective range of firefighting media projected from the branch of firefighting delivery hose.
Triple extension ladder	This a type of firefighting ladder that has three section each approximately 2 m long and is easily separated into individual section. The fire service use these in a variety of different applications from makeshift

	stretchers to the construction of small ponds to allow fire pump to pump from them.
Windrow	A term used to describe composting of organic material in elongated piles

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Chapter 1 Introduction

1. Introduction

This project was set up in December 2013 in response to a significant rise in the number of serious and protracted fires involving waste and recycling industrial sector. It had become apparent that the fires were too large for fire and Rescue services to extinguish in what would be considered a reasonable time scale. The Environment agency issues a guidance document PPG07 (1) which would see a number of amendments before being withdrawn and replaced with Fire Prevention Plan guidance (2) in 2014 which specified that a period of 4 hours after the arrival of the fire service would be enforced. This guidance was intended to provide fire prevention advise in line with Government Policy (3). Analysis of FDR1 (the home office fire report form used by fire and rescue services in England and Wales to collect real fire data) (4) indicated that deliberate application of a naked flame or self-heating was attributed to causing a very significant proportion of waste fires and consequently much of the existing fire prevention measures concentrated on security measures to prevent unauthorized access to the site. The Chief Fire Officers Association (CFOA now NFCC) was instructed by the Fire Minister Rt Hon Brandon Lewis MP to assist the Waste Industry Safety and Health Forum (WISH) to formulate a set of Industry Best practice guidance (5). The author joined the group that included representatives for the Health and Safety Executive (HSE), Health and safety Laboratories (HSL), The Environment Agency (EA), Public Health England (PHE), The Environmental Service Association (ESA), The Wood Recyclers Association (WRA) and the Tyre Recyclers Association (TRA). This group formed the WISH 28 committee (6) that was tasked with producing industry best practice guidance base on the HSL literature review (6). The committee critiqued this literature review and jointly concluded that the research was of little relevance (6). What research was available at the time was either based on fire tests involving caravans or wooden cribs or small-scale laboratory fire tests conducted on small scale samples that had been specifically prepared to evaluate their heat release rate as coal substitutes in energy from waste (EFW) power generation and were not representative of realistic storage conditions.

The real fire data was limited by a number of factors firstly the FDR1 (4) is only commonly completed for building fire. Rubbish/open ground fires were generally reported using an FDR2 (4) process which contains considerably less information. The origin of the fire was not observed and therefore, the origin was listed as unknown or recorded as application of naked flame.

As a result, in 2013 there was a perception within industry that the primary causes of fire in waste and recycling site were attributed to deliberate ignition of the surface of the material followed by self-heating. If deliberate ignition was truly the prime cause of fire, there had to be a mechanism for a surface fire to migrate to the interior of the mass of material without involvement of the bulk of the intermediate materials as a significant proportion of the fires documented had an element of deep seated fire. This would require, an as yet, unidentified fire phenomenon. The tests were developed to detect fire spread along the boundaries between the material and the surface upon which it was sitting and a possible burrowing behaviour.

As this was an entirely new area of research the early results highlighted the lack of understanding with regard to how fires progress in piles of lose fragments of material. The physical theory of fire progression through the mass of piled fragment/particle of material has largely been proved with the use of thermocouple data tracking the temperature variations within the mass of the material, excavation of a deliberately wet pile of material to suppress the fire in order to make observation of the early progression of deep seated ignition progress. The suggested theory has been compared with real fire data and has effectively explained all the observed fire behaviours.

1.1 Background and Context

The fire research project was designated the "Waste Industries Safety and Health Forum real fire test project" (7). WISH is the organisation that was set up to produce industry best practice and comprises the HSE, the EA, SEPA, Environment Agency Wales (EAW) Northern Island Environment Agency (NIEA), National Fire Chief Council (NFCC) formally (CFOA), ESA, CIWM, HSE, HSL WRA and TRA. Fires in waste management sites had become a growing problem as started above. Government targets and societal expectation has to some extent outstripped the technology to cope with reprocessing waste materials. As a result, rather than being dumped into land fill sites waste has been processed into a range of "products" some obvious ones that are recycled as new raw materials such as metals and to a degree paper and plastic that have a value as a commodity. Others that have no commodity value or are not economically viable to recycle are turned in to a new generation of solid fuels for power generation of fuels for kilns. These are broadly categorised as Refuse Derived Fuels (RDF) and Secondary Recovered Fuels (SRF).

For much of the year RDF has little or negative value and the larger operators process the material because the finished fuel is considerably less expensive to supply to power generators than it is to send to land fill. It is interesting to note that EFW operators charge the waste management companies around 40% to 60% of the land fill tax to burn their RFD, consequently there is very little margin for profit in the waste management sector in the UK markets. Recycled wood and SRF also have little or no value in the summer however, they do increase in value in winter when demand for power generation peaks. The low value and dependency on the commodity market have resulted in two very distinct business models. The first model is generally adopted by companies that concentrate in waste management for their turnover. These companies produce recycled materials as a means of minimising their onward costs of final disposal of the waste when compared with the tax imposed upon them for sending waste materials to landfill sites. These companies make a profit on the fees they charge for each tonne of waste delivered. They tend to be very compact sites to minimise building rental and running costs. The second business model is where the company will retain the material in anticipation of a peak in demand for their product. These companies are much more dependent on the sale of the finished product as well as the "gate fee", they are typically very extensive sites with large over heads.

Due to their dependency on the commodity markets, which has led to stock piling and the large areas of combustible materials the incident of fires as waste management sites has increase dramatically. The problem is not just the number of significant fires (those requiring the attendance of the fire service) but also the severity and protracted nature of fires at waste sites. Such fires can last for week or months. It is also painfully apparent that our current understanding of these fires and firefighting tactics are inadequate.

1.2 Scope and Objective

The aim of this research is to gain a better understanding of waste fires with a view to informing industry best practice and regulation. An initial literature review revealed that there had not been any specific research conducted on waste fires in realistic storage conditions. The control measures put in place prior to this research is extrapolated from

BRE experiments on caravan fire spread (8) As a result, a 6 m separation distance between storage piles was adopted by the EA (2). The test data that is available is small sample testing to evaluate the materials suitability as a power generation fuel or thin samples to determine the susceptibility of the material to ignite due to exposure to a radiated heat flux. These tests have little relevance as the test samples are shredded and dried prior to testing.

The available real fire test data taken from fire reports and collated and provided by the EA indicates that the majority of waste fires are caused by the application of naked flame. This data was provided by the local fire services in the form of FDR1 data supplied by the Office for National statistic now published online (4). The second most common cause stated was biological self-heating. Fire Services report that these fires become deep seated and as a result can take weeks and sometime months to extinguish. Based on this these report the test are designed to identify the following:

- Can a surface fire find a pathway from the surface to a point deep within the pile without involving the majority of the mass of the pile?
- How credible is ignition by a naked flame?
- Establish accurate separation distances for the safe storage of waste materials based on the empirical heat flux data obtained.
- What impact does the storage conditions have on fire properties of the stored materials?
- Establish alternative solutions to prevent fire spread between piles of waste?
- How much influence does the material properties have on fire growth?
- Can this lead to improved fire suppression and detection?
- Improved firefighting methods to minimise water contamination.

There were clearly other factors involved in waste fires that have a direct influence on the magnitude and severity of fires at waste management facilities. The most likely explanations for this were issues with scale, Fluid Dynamics and the effects of a yet undefined fire behaviour.

As this research progressed it became apparent that in the new context of the fire phenomenon that has been defined by this project that much of the previous research has new relevance when applied in the correct context. This will be discussed at length in the literature review.

1.3 Achievements

There have been 27 large scale fire tests. As a result of the analysis of these tests it has been discovered that there are 6 general fire types involving the waste tested these are:

- Impermeable surface fuel bed fire
- Semi-permeable surface fuel bed fire
- Impermeable deep seated fuel bed fire
- Semi-permeable deep seated fuel bed fire
- Permeable fuel bed fire
- Fluid dynamically driven surface fuel bed fire

These can be characterised into four theoretical models

1. Permeable fires: where the gaps between the individual particles in the pile are sufficiently wide to allow flame and air to pass through the mass of the pile.
2. Surface fires (semi permeable and impermeable fuel beds): where the gaps between the individual particles are insufficient to allow flame to pass through the mass of the fuel bed. The fire remains on the surface.
3. Deep seated fires where the ignition is generated within the mass of the material and migrates to the exterior this process is accelerated in semi-permeable fuel beds and the fire gains a greater access to air as it progresses towards the surface of the material and as a result are more acute than impermeable deep seated fuel bed fires.
4. Fluid dynamically driven surface fire: this is a unique fire behaviour observed in compressed baled materials stacked in multiple pillars which is common practice in the waste management industry but may have implications for other industries that store materials in this configuration.

5. Baseline fire engineering parameters including mass loss rates, heat release rates and heat flux.

Chapter 2 Literature Review

2. Literature Review

This chapter discussed the range of literature that was reviewed prior to and during this project. This information was used to influence the design and scope of the fire tests. Some references are not reviewed here but these are confined to sources of a particular photograph used to illustrate an argument for example the photograph of a glacier calving or instruction manuals or BS standard to which a piece of equipment was built or operated, but did not directly influence the design of the teas.

2.1 Characterising the problem of surface fires

The waste materials used in this project are all derived from "black bag" waste. The composition of this material varies according to national, regional and seasonal factors. Throughout the western world governments have sort various way to increase recycling and reduce lands fill and dumping of waste at sea. However, there are two facts that must be considered. Firstly, the storage of massive piles of waste is a relatively new phenomenon. Until 1990 the UK was still dumping waste at sea, *Hansard, Waste Dumping (North Sea) Hansard, Waste Dumping (North Sea) (1990)* (9) or straight into land fill. Bulk storage of waste at waste management sites for any length of time has been driven by the scaling back of landfill as an option around the developed world since the mid 2000's so this is a relatively new problem. In the UK the market is driven by the landfill tax (3). All material being sent to landfill is weighed and a substantial levy applied. Consequently, waste management companies endeavour to find alternatives for land fill. Once the tax (obvious recyclates such as paper, card, glass, wood, metal and recyclable plastics have been removed to be sold for recycling. The residual waste, which still forms the bulk of the waste by mass, is further refined. The UK EFW infrastructure is decades behind much of Europe. The UK produce a fuel for export to Europe. This is largely a material that is called SRF. SRF has strict set of standards BS EN 15357 (10) now superseded by BS EN 21637:2020 (11), BS EN 15358 (12) and BS EN 15359 (13) controlling the composition of the fuel. It has the chlorinating compound removed to reduce the risk of dioxin production. It is shredded and dried to produce a more consistent combustion profile. BS EN 15358 (12) is particularly useful as it specifies composition and calorific values for the product and therefore, lends itself to testing as there is considerably more reliability with regard to the repeatability of the fire tests. This makes the design of the power station simpler as both the furnace design and emissions scrubbing system are simpler. As the SRF market is well established on Continental Europe when the UK EFW power stations were designed, they were designed to burn RDF. PAS 111:2012 (14) was used to specify the wood grades used in the series of expeiments. PAS 107 (15) was used for the shredded tyre specification and WRAP web base guidance (16) was use for plastic. There were other materials such as low grade plastic where there was not specific national or industry guidance avalible. But where possible the material selection utilized these standard approaches inorder to retain a degree of repeatability

Refuse derived fuels are more challenging to define. Russel, S.H. (1976) Refuse Derived Fuel (17), a study of the use of RDF as a fuel for power generation. The study is still useful as it broadly describes power generation today and describes the typical shredding processes used and the general size of the treated fuel. However, this report defined output in terms of boiler design data. Vesilind P.A., Uli M.E., Gullett B.K. & Elsevier E. (1983) Characterization of Refuse Derived Fuel by Large Scale Continuous Calorimetry (18) tackled the problem of a lack of consistency of RDF and they went on to define the contents of municipal waste.

Vesilind P.A. & Rimmer A.E. (1981) Unit operations in resource recovery engineering, (19) The test samples used in the series of experiments are stated to be large RDF pellets that have been soaked in charcol lighter fluid and in the samples were in the region of 14kg. This paper provides some useful data but can only be considered indiative due to the sample size and the particular preperation of the samples for testing. The composition cited in (19) is also questionable given the age of the data and the national variation in recycling activities. In the study *Piao G., Aono S., Kondoh M., Yamazaki R. & Mori S., (2000) Combustion test of refuse derived fuel in a fluidized bed* (20) two compositions of RDF were tested. These results are comproble to the free buring phase of the experiments conducted during this project, and provide simular values observed during the peak heat of the fires. Other than this the results are of limited use to this project as the sample size was stated to be $0.3m^2$ and subject to a continuous supply of air forced through the fluidised RDF bed and therefore inconsistent with the proposition of RDF in storage .

It was apparent from these papers that the materials were challenging to iginte, this was apparent from the various pre treatment that the material was subjected to prior to testing. For example fluidised beds and soaking in charcol lighter fuel. *Hirunpradithoon S., Dlugogorski B.Z., Kennedy E.M. (2008) Fire properties of refuse derived fuels: measurements of temperature profiles and mass* (21) the material was screened according to ASTM E828 RDF-3 (22) standard. Th samples are very small in the range of a few grams and are exposed to a radiant heat source. The experiments were measure in a cone calorimeter. Although some useful data was obtained. It was unclear what was burning as the sample size was so small that it was possible that the test was of single items rather than a typical RDF mixture. It was also noted that ASTM E828 (22) was withdrawn in 2009 "Withdrawn Rationale:

This test method of designating the size of refuse-derived fuel from its sieve analysis was applicable to the classified light fraction (RDF-3) (22) of shredded municipal or industrial waste materials less than 0.15 m (6 in.) in size.

Formerly under the jurisdiction of Committee D34 on Waste and Subcommittee D34.03.02 on Municipal Recovery and Reuse, this test method was withdrawn in September 2009 because it was a standard procedure method which did not pertain to the waste materials for which it is titled. This standard was a basic sieve analysis method and does not designate the size of RDF-3 as indicated by the title (23).
Wagland S.T., Kilgallon P., Coveney R., Garg A., Smith R., Longhurst P.J., Pollard S.J.T. & Simms N. (2011) Comparison of coal/solid recovered fuel (SRF) with coal/refuse derived fuel (RDF) in a fluidised bed reactor (24), describes a comparison between the emissions from a system that liquifies the fuel and injects it into a boiler. This is, therefore, irrelevant in terms of the physics behind the combustion processes involved in the experiments. It was also noted that none of the SRF and RDF fire achieved the same combustion temperatures and as a result the emissions are not comparable. However, the comparison of coal with SRF and RDF did provide a branch of research that with the potential to be very useful in understanding deep seated fire progression.
Johari A., Haja A., Haslenda H. & Ramli M. (2014) Combustion Characteristics of Refuse Derived Fuel (RDF) in a fluidized bed combustor (25) *cover similar ground and treatment of RDF. This is typical of a number of test reports which are typically aimed at defining a mix and treatment of RDF for a particular furnace design.* All of the papers indicated that the materials were pre-dried and shredded. It is also apparent that RDF has a modest heat release rate in the region of 0.5 MW. Many of the other materials are easier to quantify *Babrauskas V., (2015) Ignition of wood: A review of the state of the Art*, (26) paper for example summarises the state of the art on fire testing on wood. This paper provided a range of factors used to produce two papers specifing separation distanced. The paramiters ranged from 4 KW/m^2 to 12.6 KW/m^2

used in this paper. *Mc Allister S. & Finney M. (2015) Burning rates of wood crib with implications for Wildland fires, (27)* Delichatsios M.A (1976) Fire growth rates in wood cribs (28) and Smith P.G. & Thomy P.H. (1970) The rate of burning of wood cribs (29) all provide a good correlation with *Edward G. (2015) Investigation into the characterisation of burning for a range of recycled waste products (30).* This paper (30) was conducted as part of the larger WISH project was in agreement with this Babrauskas. Indeed, the finding of the FPA report (30) were consistent with the majority of the materials reviewed. The exception being RDF where further research to quantify the likely fire behaviour was considered. However, after some debate at the WISH committee (6) the decision was made not to pursue this line of research as it was anticipated that the result would take a year to sample the full annual cycle and would result is such a wide range of data points as to make its use impracticable.

2.2 Characterising the problem of deep seated fires

By mid February 2016 it was apparent that there was no evidence supporting the migration of fire from the surface to a location within the pile without involving the intermediate materials. The only conclusion, therefore, was that the records of deep seated fires were fires that originated within the material and not due to surface ignition as previously reported (4). This then directed the expansion of the research to investigate the origins of deep seated ignition and to understand how fires with an origin deep within the pile progressed through the pile. Two lines of research were developed. The first was to initiate the fire at the base of the pile of material and the second was to construct a pile of RDF and one of wood fines with a view to observing a spontaneous ignition event. The Manual of Firemanship part 6b Chapter 1 describes a range of rural fire type including silo and hay stake fires (31). The risk factors identified in this text were aeration, cuts size and moisture content. *Ramirez A., Garcia-Torrent J. & Tascon A.(2010), Experimental determination of self-heating and self ignition associated with dusts of agricultural materials commonly stored in silos (32),* discussed the application of the method detailed in EN 15188:2007(33) again concluding particle size moisture content and aeration as primary risk factors. *Krigstin S., Helmeste C., Wetzel S. & Volpe S. (2020). Managing self-heating & quality changes in forest residue wood waste piles, (34)* discuss self-heating of biomass residue. Wood fines were placed in a pile and monitored to map the heat transfer using thermocouples. They conducted two tests neither of which resulted in a fire. These were almost identical to the wood fines test No.18. However, the test detailed in this report (34) examined the sugar content of the waste to establish is this was a contributing factor. Apparently, the sugar content had little or no observable impact. *Ryckeboer J., Mergaert J., Vaes K., Klammer S., De Clercq D., Coosemans J., Insam H. & Swing J. (2003) A survey of bacteria and fungi occurring during composting and self-heating* processes (35) discusses the biological and fungal regimes involved in composting. The paper states composting temperature up to 900c, moisture content and aeration as critical factors in the production of compost. A repeating theme is the need for a high moisture content and regular aeration to support microbiology in a compost pile, both of which are potentially missing in waste piles. The dilemma for spontaneous combustion is the fact that the moisture content needs to be reduced below 20% or the water content suppresses combustion. However, microorganisms in compost require a moisture content of around 30%. It was also observed that temperature of 60^{0}c can only be maintained for short periods as the temperature effectively sterilizes the material. *Sidhu H.S., Nelson M.I. & Chen X.D. (2006) A simple spatial model for self-heating compost piles* (36) state a range of ignition temperatures for a "windrow" in a range from 150^{0c}c to 250^{0}c. I would, therefore, appear that biology alone would not account for spontaneous combustion in waste piles.

A waste pile tends to lack aeration especially considering the fact that over time the pile compacts excluding air pockets. A moisture content of 35% or over is not uncommon. It would not be unreasonable to assume that an RDF pile has areas of dry pocket adjacent to wet areas. Therefore, logically the piles would be most vulnerable to self-heating events when disturbed by turning over and thus introducing the third of the risk factors, aeration. Jones J., William A., Saddawi A., Dooley B., Mitchell E., Werner J. & Chilton, (2015), Low Temperature ignition of biomass (37) and *Quintiere S.G., Warden J.T., Tamburello S.M., & Minnich T.E. (2008) Spontaneous Ignition, (38)* both identify that waste is capable of self-heating given the right conditions. The question is just how realistic is it to expect waste piles to reach these conditions under real storage conditions. *Woodward I, (2015) Fire safety assessment at UK & Hadfield wood recycling Middlesbrough (39)* who collaborated with *WISH (6)* were able to obtain measurements of significant temperature rises as heavy plant was tracking around the edges of the test bed being constructed in order to conduct the tests for the paper (38 cause (40)). This is interesting as this is the first documented evidence to support the long held belief that tracking over waste is a bad practice that increases the risk of self-heating fires. Obviously by tracking over the waste pile vessels such as aerosols, batteries and chemical containers are likely to rupture and generate a fire due to chemical reaction. However, this introduces the possibility of heating by compression as a possible cause of fire. Industry and EA guidance strongly advises against this practice it is, therefore, likely that the practice of tracking will no longer be an issue.

Tinsley A., Icove D.J. & Whaley M.W. (2010) Analysis of hay clinker as an indicator fire cause (40). It is unlikely that this would be applicable to waste as the composition varies significantly from pile to pile. Even timber has elements of manmade boards so there is a plastic and glue component to each pile that would be difficult to repeat. De Boer H. (2008) Hay fires and self-heating (41), does at face value have so striking similarities with stacked bale storage. However, there is much more air captured within a hay bale. It is also noted that baled waste is compressed to over 50 tonnes pressure and the bales are effectively solid blocks compared to hay.

Hewings G., Griffiths T. & Williams (2018) Meeting UK catering waste processing requirements in forced aerated batch composting systems (42), Hemm G., (2013) The composting conundrum: Just how aerobic is aerobic (43), European Environment Agency (2013) Open Burning of Waste (44) and FEMA (1998) Special report: The hazards associated with agricultural silo fires (45) all confirm the risk factors of moisture air and particle sizes. Tuomisaari M., Baroudi D & Latva R (1998) Extinguishing smouldering fire in silos (46) and Ogle R., Dillon., S.E. & Feche M. (2013) Explosions from a smouldering silo fire (47) were interesting however, the two scenarios are very different as waste fire are generally quite open compared with the enclosed type of fire detailed in this report. *Hellerand H.J. Schade G.W. Idler C.H. & Kern J (2006) Carbon monoxide of biomass: An additional pathway for CO in agricultural and forest ecosystems (48) highlights the non-fire related production of carbon monoxide associated with decomposition of agricultural and forest by products. This indicates the breakdown of hydrocarbon chains also associated with combustion.*

The main impediment to spontaneous combustion in waste materials from purely biological action would appear to be the moisture content not unlike the Three Bears in the fairy tale, the metaphorical porridge has to be just right. While it cannot be ruled out completely it would appear from the evidence that spontaneous combustion in waste is more likely to be the result of biological heating interacting with a contaminant such as a battery.

2.3 Deep seated fire development.

Sloss L. & Lesley D.R. (2015) Assessing and managing spontaneous combustion of coal (49), details the progression of a fire through a coal pile. This description mirrored the direct observations of the progress of the fire that were initiated at Barling.
A review of the following papers all revealed tantalizing parallels with waste fires. All of these coal events were initiated by the introduction of an oxidizer to trigger the chain reaction that led to the fire. Indeed, to trigger the waste fires it was necessary to introduce oxygen and an external fuel source. Unlike coal where the reactions appear to only need a very small quantity of air to trigger the chain reaction even in wet conditions waste was considerably more difficult to ignite. It was often necessary to introduce hydrocarbon fuels and forced air into the base of the pile for up to 20 minutes.
Fabianska M.J., Ciesielczuk J., Kruszewski L., Misz-Kennan M., Blake D. R., Stracher G. & Moszumanska I (2013) Gaseous compounds and efflorescence generated in self heating coal waste dumps – A case study from Upper and Lower Silesian coal basins (50), Singh R. V. K. (2013) Spontaneous heating and fire in coal mines (51), Weishauptova Z., Pribyl O., Sykorova I. & Machovic V,(2015) Effect of bituminous coal properties on carbon dioxide and methane high pressure sorption (52), Zhan J., Wang H., Zhu F. & Song S. (2014) Analysis on the governing reactions in coal oxidation at temperatures up to 400^{0}c, (53) Ray S. K., Panigrahi D. C. & VA. K., (2014) , An electro-chemical method for determining the susceptibility of Indian coals to spontaneous heating, (54) Restuccia F., Ptak N. & Rein G., (2017) , Self-heating and ignition of shale rock, (55) ,US Department of Energy (1993) Spontaneous combustion in coal , Environment Safety & Health Bulletin (56), Kaminsky V. A., Obvintseva N. Y. & Epshtein S. A. (2017) The estimation of the kinetic parameters of Low temperature coal oxidation, (57),International Research for Sustainable Control and Management, International Conference Beijing 2005, Spontaneous Coal Seam Fires: Mitigating a global disaster, (58) and Sasahi K., Wang Y & Zhung X (2014) Numerical Modelling of low rank coal for spontaneous combustion, (59)
In conclusion it can be seen that a deep seated fire in an impermeable waste pile will behave in the same was as a coal heap. However, the moisture content remains the limiting factor for spontaneous fires by biological action in waste piles.

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2.4 Stacked bale fire development

Xiong, Gang & Zeng, Dong & Krisman, Alex & Wang, Yi. (2020). On the burning behaviour of thermoplastics at large scale: Uncartoned unexpanded plastic commodity. (60). This paper details a fire test of plastic pallets stacked with a gap which at first glance resembles the stacked baled fire tests completed in October of 2017. While the flame spread was significant with areas of flame attachment to the columns formed by the structure of the stacked pallets the fire did not form the vortex behaviour and although the heat release rate was significant it followed the typical burning pattern for plastic eloquently detailed by Sherratt J. (2001) the effects of thermoplastic melt flow on behaviour on the dynamics of fire growth (61). Norichika Kakae, Harada K. & Ohmiya (2004) A simplified calculation method for heat release rate of thermoplastic combustible materials (62), identifies a model with is consistent with the preceding papers. Gollner M.J., Williams F.A. & Rangwala A.S. (2011) Upward flame spread over corrugated cardboard (63), further emphasizes the flame behaviour that would be expected from a relatively flat vertical surface. This behaviour is described in Hurley M.J. et al (Ed) (2016) SFPE Handbook of Fire Protection Engineering 5th ed (64) and Drysdale D., (2011), An introduction to Fire Dynamics 3rd (65) neither of which detail the formation of vortices in the way observed during the fire tests. A review of a range of paper relating to liquid hydrocarbon papers did reveal parameters that were closer to the early stages of the baled plastic fires. Mealy C.L., Benfor M.E. & Gottuk D.T., (2011) Fire dynamics and forensic analysis of liquid fuel fires (66) and Mohamed M. & Salem H. (2014) Combustion characteristics for turbulent premixed flame using commercial light diesel and kerosene fuels, (67). Marsden J.A. (2005) Experimental and Numerical studies of whirling fires (68), describes vortex fire behaviour but this paper details deflectors to induce the rotation. Although the random surfaces of the pile could be acting as deflectors it was noted that when the vortex would change direction of rotation when material became dislodged. During a conversation relating to a PhD submission for a colleague we discussed a series of fire tests conducted by FPA (69) in which an identical fire behaviour to that detailed in section 8 were produced in almost identical geometries. The results were never made public due to non-disclosure agreements with the client.

It was observed that staked bales are more suspectable to ignition than the same material in a lose pile. Ibrhim M. A, Hogland W., Appel G. & Persson H., (2013) Combustion Characteristics of Municipal solid waste Bales, (70), conducted a study on the ignition profile of the polythene wrapping that is commonly used as a protective covering for baled materials. Given the data observed and calculated in the paper Alexandrou M. & Sangster A.J. radiation model using WISH targets (71) it can be concluded that this is a credible source of ignition. Linteris G.T. & Rafferty I.P. (2008) Flame size, heat release and smoke points in material flammability (72) and Vermesi I., Roenner N., Pironi P., Hadden R.M & Rein G (2016) pyrolysis and ignition of a polymer by transient irradiation (73). Provide additional data sets for transient radiation.

2.5 Summary of the Literature Review

In summation it can be seen that many of the materials can be categorised using existing Literature. The exception being RDF mainly because of the wide variations in the composition of the material. The first series of test dealt with the effects of deliberate surface ignition of a pile of material. The intension of which was to obtain peak heat release rates to derive safe separation distances and secondly to explore the possibility of migration of the flame front into the pile to form a deep seated fire. Having established that true deep seated fire originates in the depths of the pile and not as the result of surface ignition a further review of literature was undertaken to define deep seated fires.

Deep seated ignition as a result of biological heating is anecdotally evident. The literature relating to the potential for spontaneous ignition, fall in to two categories those that prepare the sample by pre drying it and often shredding the sample before heating the small sample in an oven until it self heats. The second set of experiments examine large samples in realistic conditions. Although there is no doubt that these materials are capable of spontaneous ignition these conditions were not observed in realistic storage conditions. There are striking similarities between coal fires and waste fires. The question is how the fires are obtaining sufficient oxidiser to reach self sustained fire growth. The method selected in this project i.e., forming a pile of wood with thermocouple positioned in the pile to record a self-heating event leading to a fire was repeated independently with a slightly difference wood by product (34) but with equally disappointing results. These results clearly indicate there is much more to the self-heating problem in waste than biological heating and the fact that a material is capable of runaway self-heating is not necessarily a good measure of the risk of self-heating ignition. Further research is required and it would appear the potential critical factors are the chemical changes that the material undergoes as a result of a biological break-down to the material together localized drying over time.

The baled fires are not fully documented in any literature found to data, but the conversation (68) is reassuring that this is a function of the geometry of the system and not the result of the experimental method. It was anticipated that the flame would accelerate up the surface of the stack and the material would burn at the peak heat release rate expected for that material based on the review of literature. What was not anticipate was the interaction of the flames to form a vortex. This resulted in heat release rates that exceeded those stated for a normal accelerated flame front across the vertical surface of the fuel bed. This phenomenon was examined using Fluid dynamic simulator modelling and repeated on a range of materials to establish material or geometrical dependency. The limits were tested by staggering the bales to a brick lay pattern and by initiating a fire against one flammable and one non-flammable surface.

Chapter 3 Experimental Program

This project builds on the Laboratory tests (30) that were scope by the author and conducted by the FPA (30). The aim of the project was to establish the fundamental understanding of fires in and on waste materials and their common derivatives. This chapter provides an overview of the fire tests conducted as part of the WISH work packages 2 & 3. The original scope was to conduct a series of test on piled and baled materials subjected to surface ignition. There was further test development during the program as the existing tests did not fully replicate real fire data and experiences.

3. Fire Tests: Discussion on Methods and Materials

3.1 Introduction to the Test Methodology

The test method was originally developed based on the assumption that the official explanations for the sourced of ignition of deep seated fires was the application of a naked flame on the surface of the pile (4). The WISH Committee (6) who were tasked with producing industry best practice guidance set the parameters for a series of experiment to provide empirical evidence of fire behaviour of common waste materials stored under realistic storage conditions. This project (7) was organized into 4 work packages. The first of which was to conduct a series of laboratory experiments performed on $1m^3$ samples to provide some baseline data such as mass loss rates heat flux etc. (30). This thesis covers work packages 2-4.

It was observed that for a surface fire to generate a deep seated fire without the involvement of the intermediate material, would require an undefined process by which a flame may migrate through the pile without the involvement of the mass of the material that forms the pile of waste to a point buried deep within its mass. The working hypothesis for the development of the test rig is summarised thus:

- A clear open pathway such as a hole burrowed by rodents or other pests of sufficient size to allow the passage of flame.
- Fire spread at the boundary between the fuel bed and the ground or wall on or against which it is resting.

The first rig was designed to provide sufficient data points to record temperature fluctuation throughout the pile mass to detect fire passage by other method. The fire tests were all video recorded and local weather monitoring was also undertaken to evaluate the effect of the weather on the fire test.

The materials to be tested were selected based upon the real storage condition. The materials being SRF, RDF, Pre crushed wood chip, Pre crushed wood chip screened for ferrous metals, "Raw wood", Wood fines, Shredded Rubber and fragmentiser fluff. Paper and Card and textiles were not tested as their fire properties are sufficiently similar to wood to assume that the wood results are an acceptable correlation to this material. The tests were subject to the Permitting Regulations 2010 (74). Permits for the fire testing was granted under an exemption within the regulations for Fire Service training and research. However, this was on the basis that waste electrical and electronic equipment (WEEE) would not be tested. A method of suppressing the test fires was available to prevent nuisance and that the principal of as low as reasonably practicable would be adopted with regard to pollution caused. This principal was the primary driver in omitting textiles and the various card and paper recyclates.

It became apparent as the fire tests progressed, that fire spread through the medium to create a deep seated fire did not occur as the original hypothesis predicted, except in a very particular case. Therefore, a new piled fire test was developed during the series of fire test being undertaken at the Barling test site. This test variant involved setting a fire deep within the mass of the pile. A number of small tests were conducted to establish a practicable ignition source. This will be covered in a separate section. Sustaining a deep seated fire proved challenging and was only achieved at Barling by providing a permanent air supply. However, the resulting fires did provide a good correlation with real fire data. Obtaining useful thermocouple data was not perfected until work package 4 fire tests at Morton in the Marsh.

3.2 The tested materials and test sequence

Material	Particle size	Description	Standards
Raw wood	Up to 5m	Mixture of salvaged construction timber man made timber furniture pallets etc.	BSI PAS 111:2012(14)
Pre-crushed wood un-screened	50 mm - 150mm	Raw wood shredded not screened for ferrous metals	BSI PAS 111:2012(14)
Pre-crushed wood un-screened	50mm - 150mm	Raw wood shredded screened for ferrous metals	BSI PAS 111:2012(14)

Wood fines	5mm – 30mm	Raw wood shredded screened for ferrous metals ready for incineration or bio-pellet production	BSI PAS 111:2012(14)
RDF	Not specified	RDF is made up of any material that is uneconomical to recycle	No agreed industry standard
SRF	5mm – 30mm	SRF is made up of similar material to RDF however, there are strict limits on the materials that this can contain, and it is dried and shredded to provide a more consistent fuel	BS 15358 (12)
Shredded Tyres	60mm-150mm	Used tyres are shredded either for recycling into liquid fuels or production of rubber crumb.	PAS 107 (15)
Fragmentizer fluff	30mm-60mm	Shredded car interiors with the ferrous metals screened used as a capping layer in land fill.	No agreed industry standard
HDPE	N/A	Crushed plastic drinks bottles	WRAP guidance (16)
Low grade plastic	N/A	Mostly single use plastic bags, microwave trays and single use film there was also a high content of paper, food waste and fragments of aluminium cans estimated mixed plastic content 85 % by weight	No agreed industry standard

Table 1: List of materials used in the test series.

Fire Prevention association Laboratory tests work Package 1(30)

- Surface fire test on standard transport consignment bale circa $1m^3$ or loose material in $1m^3$ basket.
- Data obtained; heat flux mass, loss rate, surface temperatures to establish base lines and safety protocols for open fire test as waste management sites

Pollington fire tests Work package 2

- Untreated wood test. Baseline test for the series to validate comparisons with existing wood fire test data.
- First test examining the possibility of transition to deep seated fire from surface fires.

Barling Magna fire tests work package 2

- Repeat surface ignition tests on the full range of selected loose piled material to obtain fire data to establish safe separation distances
- Conduct surface ignition fire tests on selected baled materials

Barling Magna fire tests work package 2 A

- Initial fire tests to reproduce deep seated ignition. Technical difficulties limited data capture.
- Residence tests the material with the worst history of self-heating ignition selected and piled test constructed in order to capture the point of deep seated ignition.
- Vortex fire behaviour first observed in WP2. Repeat tests and brick laid bales test conducted to establish limit of this behaviour.

Fire Service College work package 3

- Fire test data was analysed and the vortex behaviour modelled using FDS from this the firefighting tactics for vortex fire was developed
- Best practice from the fire service was collated through the NFCC committee (80) this learning was formalised into the "Muddy Puddle" process.
- Portable concrete block wall systems were scope for analysis and sponsored by LEGIO.
- The Deep seated fire test process was developed and repeated.

Figure 1 project development flow chart

Fire Test Description	Date of test	Test Objective	Photograph of Test
Test 1 Pollington North Yorkshire. A 1 tonne sample of the raw material. In this case a mixture of reconstituted timber boards and building and pallet timbers	19/11/2015	1. Obtain HRR for the untreated wood. 2. Establish emissions in the near field. 3. Obtain mass loss rate 4. Compart data with standard wood crib fires to obtain a baseline data set to compare future results (25)	
Test 2 Pollington North Yorkshire. A 1 tonne sample of the pre crushed wood material. The same material as test 1 but shredded to 50mm-150mm and not screened to remove ferrous metals	19/11/2015 to 21/11/2015	1. Obtain HRR 2. Establish emissions in the near field. 3. Obtain mass loss rate 4. Explore fire boundary creep along the floor 5. Look for localized fire penetration to account for deep seated fires	
Test 3 Barling Magna Essex repeat of test 2 to confirm results and examine the effect of different weather conditions	21/1/2016	1. Obtain HRR 2. Obtain mass loss rate 3. Explore fire boundary creep along the floor and look for localized fire penetration to account for deep seated fires	

Test 4 Barling Magna Essex wood fines. Material as above but shredded to 10mm or less ready for incineration as a fuel for power generation.	25/1/2016	1. Obtain HRR 2. Obtain mass loss rate 3. Explore fire boundary creep along the floor and look for localized fire penetration to account for deep seated fires	
Test 5 Barling Magna Essex repeat of test 2 but substituting RDF for wood.	28/1/2016	1. Obtain HRR 2. Obtain mass loss rate 3. Explore fire boundary creep along the floor and look for localized fire penetration to account for deep seated fires	
Test 6 Barling Magna Essex repeat of test 2 but substituting 6 tonnes of wood for the previous 3 tonnes to establish any sensitivity to scaling of the pile size	4/2/2016	1. Obtain HRR 2. Obtain mass loss rate 3. Explore fire boundary creep along the floor and look for localized fire penetration to account for deep seated fires	

Test 7 Barling Magna Essex repeat of test 2 but substituting SRF (4) for wood.	4/2/2016	1. Obtain HRR 2. Obtain mass loss rate 3. Explore fire boundary creep along the floor and look for localized fire penetration to account for deep seated fires	
Test 8 Barling Magna Essex repeat of test 2 but substituting shredded rubber tyres for wood. This material is shredded tyres the particles are 60mm to 150 mm and contain steel wire reinforcement.	9/2/2016	1. Obtain HRR 2. Obtain mass loss rate 3. Explore fire boundary creep along the floor and look for localized fire penetration to account for deep seated fires	
Test 9 Barling Magna Essex repeat of test 2 but substituting Fragmentiser Fluff for wood. Shredded vehicle interiors	18/2/2016	1. Obtain HRR 2. Obtain mass loss rate 3. Explore fire boundary creep along the floor and look for localized fire penetration to account for deep seated fires	

Test 10 Barling Magna Essex Baled RDF stack fire. Bales are compressed to 40-50 tonnes per square meter bound with steel straps and wrapped for weather protection	17/5/2016	1. Obtain HRR 2. Obtain mass loss rate 3. Ignitability 4. Flame acceleration due to extended vertical orientation of fuel.	
Test 11 Barling Magna Essex first test to simulate a fire with a deep seated ignition in pre-crushed wood pile dimensions is a repeat of test 2	17/5/2016	1. Obtain HRR 2. Obtain mass loss rate 3. Explore fire boundary creep along the floor and look for localized fire penetration to account for deep seated fires	
Test 12 Barling Magna Essex repeat of test 5 with a deep seated ignition point with RDF.	17/5/2016	1. Obtain HRR 2. Obtain mass loss rate 3. Explore fire boundary creep along the floor and look for localized fire penetration to account for deep seated fires	

Test 13 Barling Magna Essex Baled RDF stack fire. Bales are compressed to 40-50 tonnes per square meter bound with steel straps	19/5/2016	1. Obtain HRR 2. Obtain mass loss rate 3. Ignitability 4. Flame acceleration due to extended vertical orientation of fuel.	
Test 14 Barling Magna Essex Baled SRF stack fire. Bales are compressed to 40-50 tonnes per square meter bound with steel straps	15/6/2016	1. Obtain HRR 2. Obtain mass loss rate 3. Ignitability 4. Flame acceleration due to extended vertical orientation of fuel.	
Test 15 Barling Magna Essex repeat of deep seated fire test with SRF (4).	15/6/2016	1. Obtain HRR 2. Obtain mass loss rate 3. Explore fire boundary creep along the floor and look for localized fire penetration to account for deep seated fires	

Test 16 Barling Magna Essex repeat of deep seated fire test with double the quantity of wood to check scale sensitively.	16/6/2016	1. Obtain HRR 2. Obtain mass loss rate 3. Explore fire boundary creep along the floor and look for localized fire penetration to account for deep seated fires	
Test 17 Barling Magna Essex Baled SRF (4). Test to establish if interrupting the fire column would limit the effect of the fire vortex.	15/6/2016	1. Obtain HRR 2. Obtain mass loss rate 3. Explore the limits of the generation of the fire vortex observed in earlier baled material tests.	
Test 18 Barling Magna Essex Wood fines self-heating test	March 2016 – June 2017	1. Observe self-heating within the pile. 2. Take gas samples to establish possible mechanisms that could generate self-heating fire. 3. Track a naturally occurring self-heating fire	

Test 19 The Fire Service College Morton in Marsh Glos. Pre crushed wood fire at commercial scale.	3/10/2017	1. Ensure effective method of igniting a deep seated fire. 2. Confirm scaling 3. Test Legio blocks in a realistic condition.	
Test 20 The Fire Service College Morton in Marsh Glos. Low grade mixed plastic bales for firefighting tactics test using water only	24/10/2017	1. Confirm behaviour of the fire vortex in low grade plastic. 2. Provide a test bed for firefighters to extinguish the fire using the Authors suggested theoretical model	
Test 21 The Fire Service College Morton in Marsh Glos. Low grade mixed plastic bales for firefighting tactics test using Compressed Air Foam System (CAFS)	24/10/2017	1. Confirm behaviour of the fire vortex in low grade plastic. 2. Provide a test bed for firefighters to extinguish the fire using the Authors suggested theoretical model	

Test 23 The Fire Service College Morton in Marsh Glos. Low grade mixed plastic bales for firefighting tactics test using surfactant (0.3%) and water	25/10/2017	1. Confirm behaviour of the fire vortex in low grade plastic. 2. Provide a test bed for firefighters to extinguish the fire using the Authors suggested theoretical model. 3. Observed fire spread between evenly spaced targets.	
Test 24-26 The Fire Service College Morton in Marsh Glos. Low grade mixed plastic bales for firefighting tactics repeat of Water/ CAFS and surfactant tests	25/10/2017 To 26/10/2017	1. Confirmation of results 2. Training opportunity for the fire service	
Test 27 The Fire Service College Morton in Marsh Glos. Low grade mixed plastic bales for firefighting tactics confined in a bunker	26/10/2017	1. Observe the effects of confinement on the bales fire 2. Provide a test bed for the firefighting tactics tests	

Test 28 a & b	24/10/2017 To 26/10/2017	1. Trace progress of deep seated fire through the pile. 2. Establish a time scale for fire propagation through the pile. 3. Obtain data to form a theoretical model for deep seated fires in impermeable fuel beds	

Table 2: Tests in Chronological order

3.3 Materials Excluded from these tests

The tests are subject to the Environmental Permitting Regulations (England and Wales) 2010 (74). As part of the permitting process, it was necessary to demonstrate that the pollution cause was as low as reasonably practicable. Therefore, a range of materials were eliminated due to their similarity to other materials, relative rarity in the UK marketplace, cost or refusal of the Environment agency to issue a permit.

3.1.1 Textiles:

The majority of textiles are collected and exported to the third world in relatively small lots. The low value of the materials results in textiles being added to RDF by the vast majority of the UK waste management companies. Consequently, this material is not held in large quantities in the UK and was not selected for testing.

3.1.2 Paper & Card:

Card was tested during the FPA Laboratory tests (30), and these demonstrate that paper and card unsurprisingly have very similar combustion properties to wood. Therefore, this material was eliminated from the full-size test as the results from the wood tests could be extrapolated to include card. Card also has a very high residual value compared to recycled wood.

3.1.3 Waste Electrical and Electronic Equipment:

Despite a case being made for this material the Environment Agency refused to issue a permit to test this material due to the potential environmental impacts.

3.1.4 End of life vehicles:

Despite a case being made for this material the Environment Agency refused to issue a permit to test this material due to the potential environmental impacts.

3.1.5 Hazardous Waste:

Despite a case being made for this material the Environment Agency refused to issue a permit to test this material due to the potential environmental impacts.

Chapter 4 Surface Fires

This chapter details the tests conducted on loose piled materials subjected to surface ignition. A test rig was developed for these tests where the thermocouples were buried in the material. This eliminated any possibility of the fire flowing the thermocouple into the fuel bed. One of the outcomes was to establish the mechanisms for deep seated fires.

4. Pollington North Yorkshire Test type 1 Untreated Wood

Pollington Airfield North Yorkshire is a site that is sensitive due to water abstraction. Consequently, the Permit to burn had a number of restrictions these being,
the fire test had to be conducted on a bed of "puddle clay" to prevent contamination entering the water aquifer. Only wood could be burnt on this site.
Fire test 1: Untreated wood waste was piled to an approximate height of 1 m and diameter of 3 m. The random nature of the size and configuration of the waste material together with the masses involved make the use of the primary test rig described below impracticable. Two heat flux meters one upwind and the second downwind are positioned at 2 m from the edge of the test bed and 1.2 m vertically. The test was video recorded from the 4 cardinal directions equal distances apart.

4.1 Analysis

As stated, the fire test did not have the thermocouple test rig. This test was intended to be used as a benchmark fire model by which to compare the subsequent wood test. The fire started relatively easily and with the aid of the wind the fire quickly spread through the matrix of the pile. The heat flux data followed a typical fire curve as would be expected and observation made during the experiment provided a benchmark of a free burning waste wood fire. The objective of this experiment was to establish the effect of the presence of contamination such as plastic lamination present in manmade timber boards, with a view to eliminating materials effects on the subsequent fire tests. As all the timber tested had very similar compositions the effect observed in later test can be attributed to physical condition rather than changes in materials.

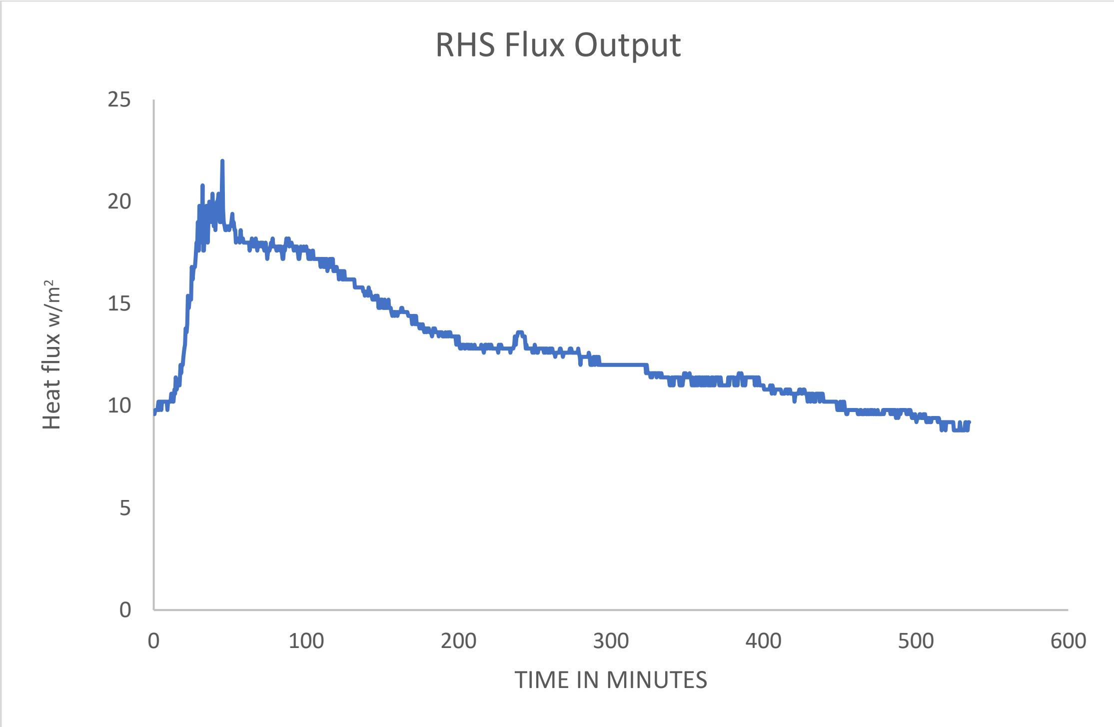


Figure 2: Heat flux meter data for test No1 (table 2) Permeable fire.

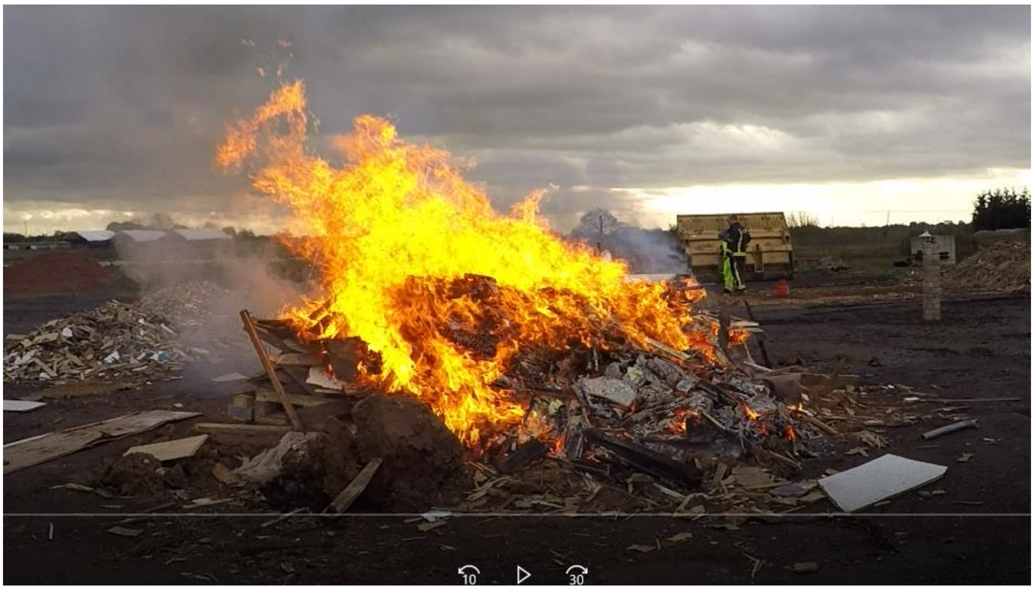


Figure 3: Test 1 (table2); 11:30 am 19 November 2015

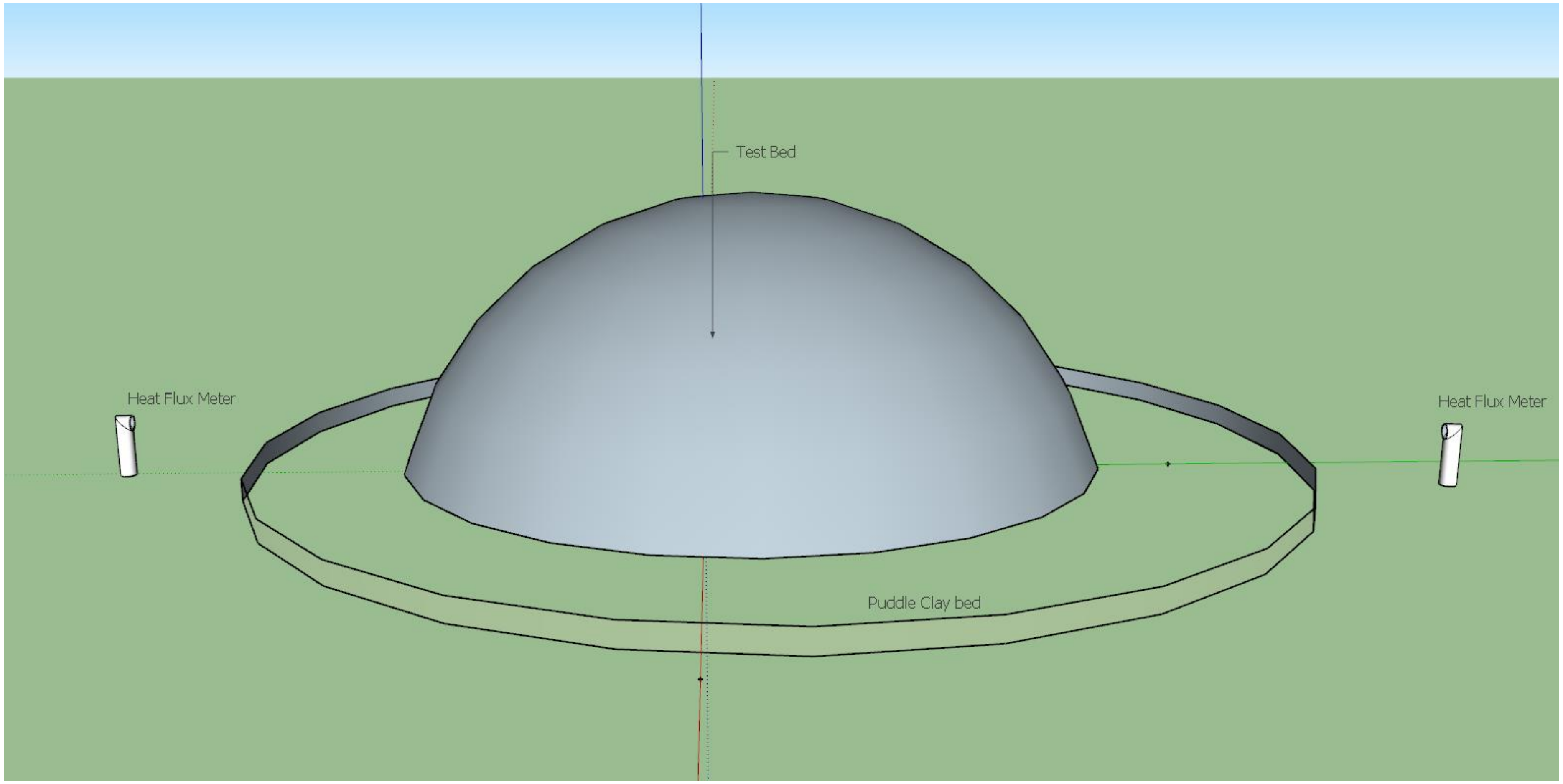


Figure 4: 3D diagram of test 1 (table2)

4.2 Pollington North Yorkshire Test 2 Pre-crushed unscreened wood.

Piled materials test 2 use of K type thermocouples 6 m long with 4 m of stainless-steel sheathing protecting the power coated electrical wires and 2 m of PVC sheathed wire for weather protection. The Thermocouples are tailor made 3 mm diameter with a margin of error of +- 0.2 degrees Celsius. 100 such thermocouples were supplied by Bureau Veritas from their London office as part of their contract with London Fire Brigade.

These are in tern sheathed in ceramic tubs of varying lengths indicated in the table below and arranged according to the diagram and arranged at 45^0, 90^0 and 45^0 angles to provide an array of sensor points to map the temperature profile of the fire throughout the test. The thermocouples are housed within an oblong steel framed box which was clad in 10 mm superlux heat resistant boards and the gaps sealed with fireplace cement. The box was 3 m long with a cross sectional area of 300mm by 300mm. The box and the piled material are placed on a 100mm puddle clay. To provide protection to the thermocouple leads they are buried in sharp and a small concrete block wall was constructed such that the data logger can be located close to the test bead but provided with protection from the radiated heat from the test fire

An additional K type thermocouple was positioned along the side of the test rig to obtain the temperature at the base of the fire. A camera was buried on the side of the test rig at a depth of 200 mm, with a view to capture any flame passage along the boundary between the fuel bed and the ground. Lighting was provided a series of white LED's powered by 6v battery pack. A static Heat flux meter was positions at 2 m from the initial fire bed.

The wood was piled carefully around the rig to avoid displacing or damaging the thermocouples. The waste material was allowed to find its own level and piled to a minimum height of 1m and allowed to find its own resting angle which was assumed to be 45^0. This assumption was based upon preliminary testing which indicates a general tendency for loose waste material to settle at an angle between 40^0 and 48^0. This was a property which was of relevance to the siting of the static heat flux meter. This angle has a tendency to decrease as the materials settle. As a result, the heat flux meters may need to be adjusted to ensure they are 2 m from the plan being observed if there was significant delay between the material being piled up and the start of the test. The results from the heat flux metres are therefore dependant on the view factor of the radiation emissions from the test far more than the other test equipment and the results from the heat flux meters this must be considered when analysing these results.

Figure 5: Test No 2 (table 2) semi permeable fire

The fuel bed was ignited using a 25 mm propane blow torch conforming to BE EN 9012:2011 (75). The flame was played on the upwind side of the pile at the base of the pile around a $1m^2$ area. For a maximum of 20 minutes. The weather conditions were monitored using a mobile weather station. The test was recorded using cameras set 45^0 angles from each other. The thermocouple data was captured together with the heat flux data on a data logger and exported to an excel spread sheet Eltek Squirrel 1000 series (76).

Test criteria:

Materials that take less than 10 minutes to reach a self-sustaining fire – easily ignited materials

Materials that between 10 and 20 minutes to reach self-sustained fire- combustible materials

Materials that take longer than 20 minutes to reach self-sustained combustion – limited combustibility

The application of this criteria is strictly limited to this test methodology for practical reasons.

4.1.1 Analysis

The initial test conducted at Pollington Airfield North Yorkshire on the 19th of November 2015 is discussed below. The pile consisting of 2.25 metric tonnes of pre-crushed wood was piled as described above.

Using basic mathematics, the approximate density and volume are calculated as 238.85 kg/m^3 and 9.42 m^3.

Where the volume of the cone formed is calculated as set out below given a radius of 1.5 m and height of 1 metre

$$V = \pi r^2 H/3$$

Equation 1: Volume of a cone

Therefore,

$$DENSITY = \frac{MASS}{VOLUME}$$

Equation 2: Density

Thermocouple Number	Logger	Channel	Sheath Length/ cm
1	A	1	100
2	A	2	100
3	A	3	100
4	A	4	80
5	A	5	60
6	A	6	40
7	A	7	20
8	A	8	50
9	A	9	85
10	A	10	85
11	A	11	85
12	A	12	40
13	A	13	70
14	B	1	70
15	B	2	70
16	B	3	30
17	B	4	50
18	B	5	50
19	B	6	50
20	B	7	20
21	B	8	40
22	B	9	40
23	B	10	40
24	B	11	20
25	B	12	20
26	B	13	20

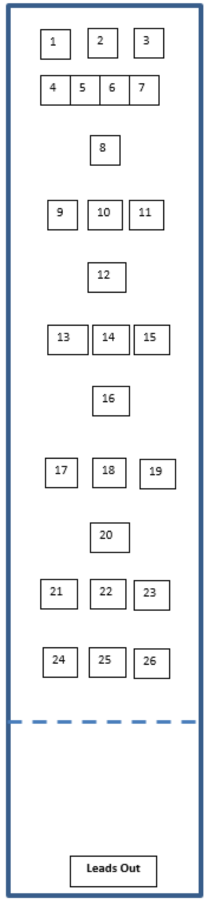


Figure 6: Thermocouple Map and height table for the generic test rig

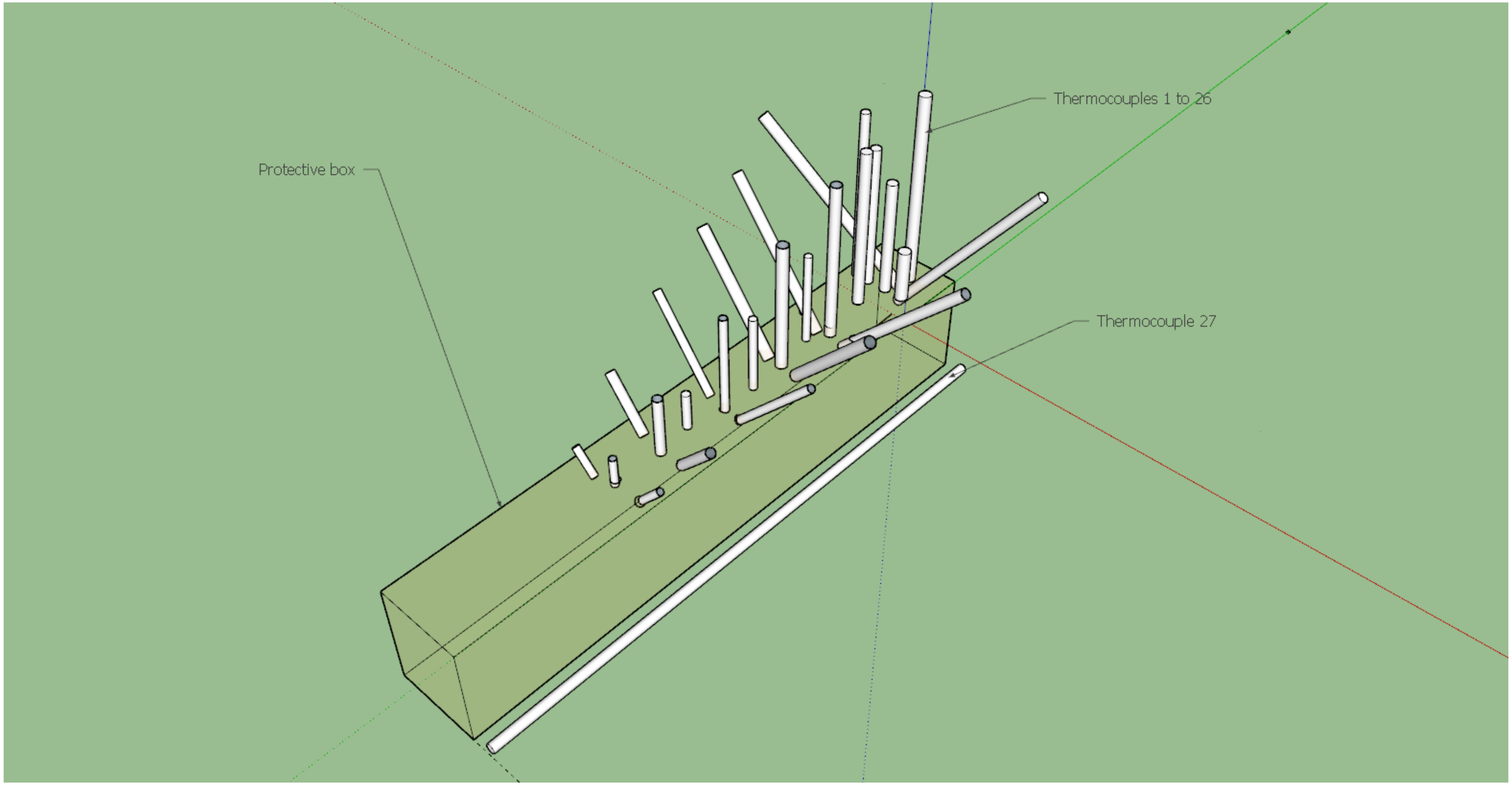


Figure 7: 3D impression of thermocouple arrangement of the generic test rig

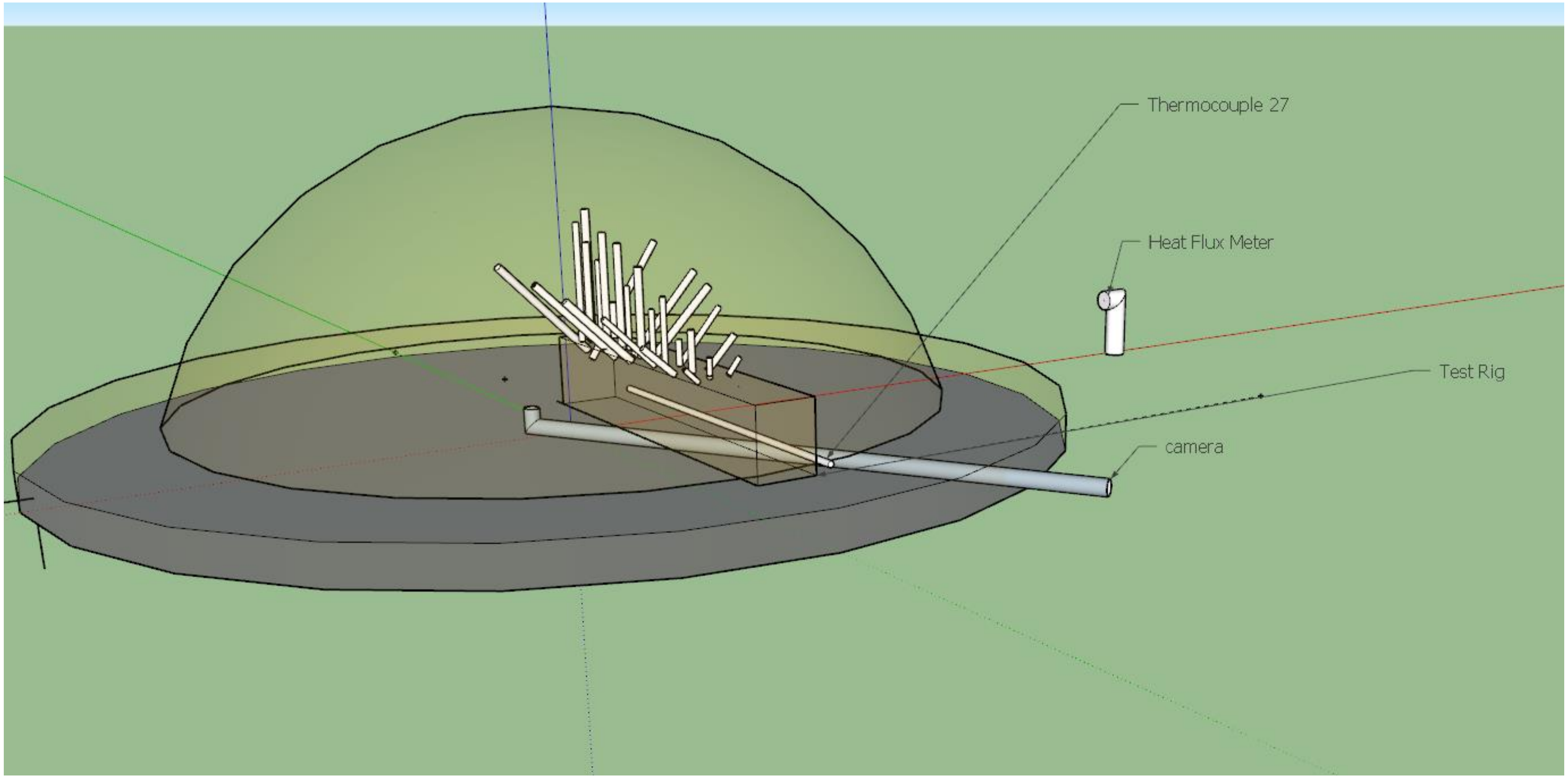


Figure 8: 3D diagram of test method 2

The fire was observed to display a short period of initial surface flaming which was followed by a steady state of smouldering combustion. Given this fire's behaviour, the most interesting parameters from the point of view of fire engineering are the mass loss rate and heat release rate. Taking the first of these parameters it is possible to derive the mass loss rate by considering the progress of the combustion zone in the vertical plain through the middle of the pile. Thermocouples 2,4,5,6 & 7 are arranged at 200mm intervals in the vertical plain. Assuming that the reduction in the height of the material is reciprocated in all directions the height and radius is reduced by 0.2 m are each interval in the table below to calculate the volume at that point. The thermo-couple data for these measurement points are detailed in Figure 7 . The weather data was limited due to extreme weather conditions. The initial fire stages were conducted in wind conditions of a constant easterly breeze of 5 knots however, by 16:00 the site was exposed to storm Barney with wind speeds gusting to 60 mph and heavy driving rain with a measure 33 mm on site in 18 hours. However, the majority of the weather data was lost due to damaged equipment. The strong wind was observed to strip the layer of ash from the surface of the test bed and consequently the surface fire resumed the free burning nature of the initial stages of the experiment.

Figure 9: Test No 2 (table 2) 12:15 PM

Figure 10: Test No 2 (table 2) 17:30 PM

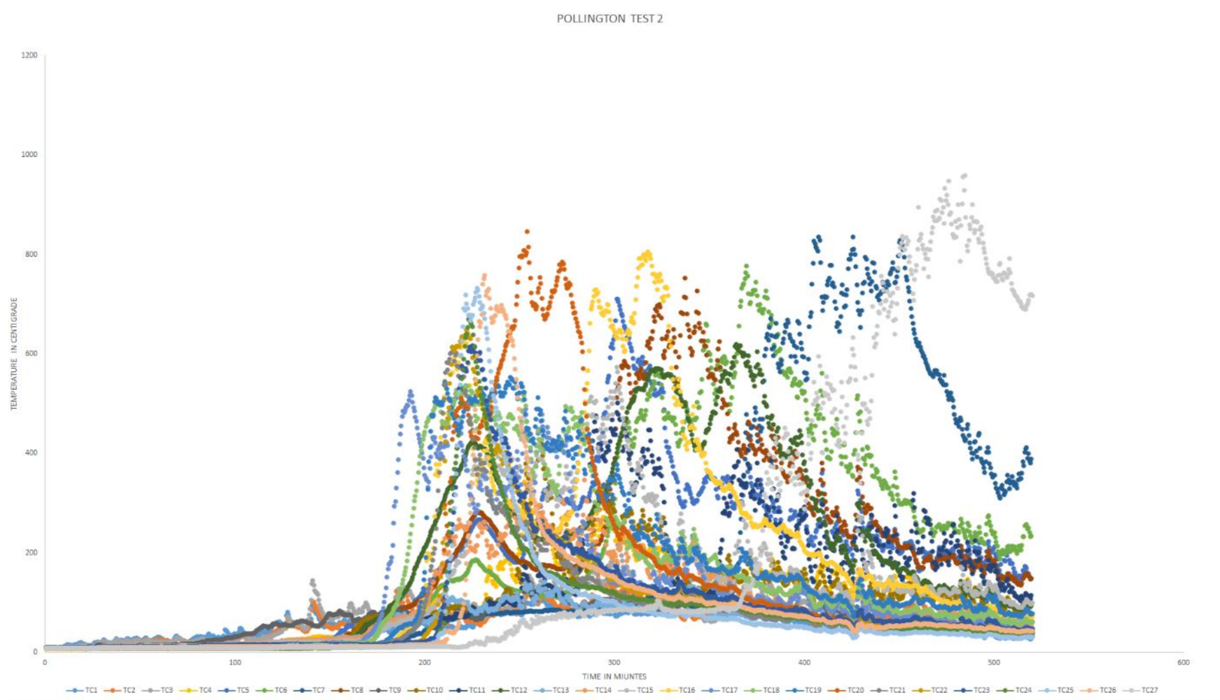


Figure 11: Test No 2 (table 2) thermocouple data graph

By taking these measurements and analysing them in graphical form it is apparent that the combustion layer burns through the material at a very consistent rate. It was not practical to use a load cell to measure the mass loss directly due to the use of puddle clay, the masses of materials and the remote locations and lack of power supplies.

Therefore, it was necessary to develop a practical method for estimating the mass loss of the pile of material. To simplify this process a single plain was considered for each of the experiments this plain uses date from thermocouples 2, 4, 5, 6 and 7.

Therefore, a correlation between the rate of burn and the reduction in volume can both be observed as the pile reduces in size and the measurements taken at fixed points is a valid approach to calculating mass loss. This assumption is based on a constant density of 238.85 kg/m^3. From this assumption the following table has been derived.

Time (s) form highest recorded temperature at TC2	Volume (m^3)	Mass (kg)
0	9.42	2249.97
4080	6.57	1569.25
7050	4.25	1015.11
11040	2.41	575.63
13350	1.01	241.24

Table 3: Mass loss table Test No 2 (table 2)

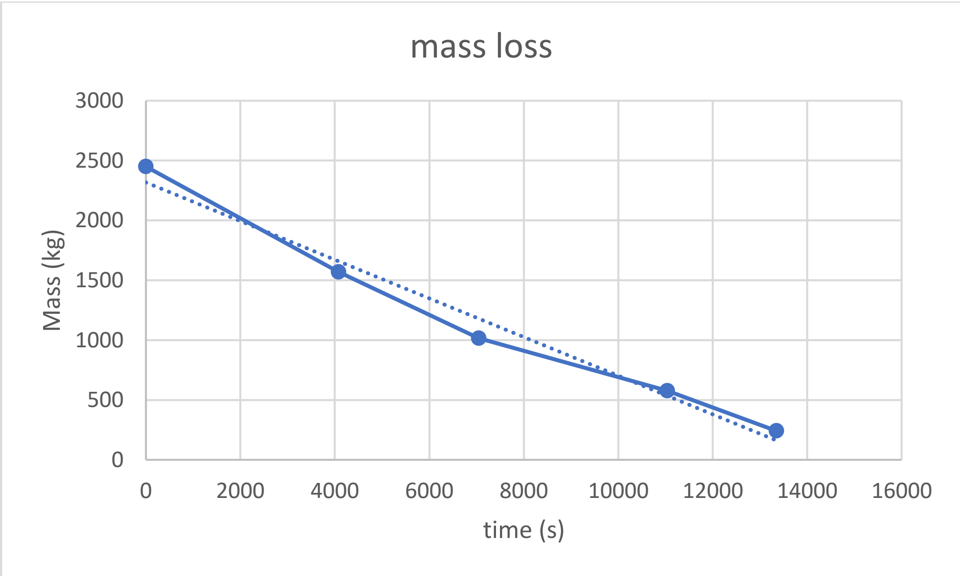


Figure 12: Test No 2 (table 2) Mass loss graph

The resulting graph shows a surprisingly linear relationship between the mass loss rate, loss of volume. It was observed that the flame height and temperatures recorded at the surface showed significant variation throughout the test as the fire was driven by wind and suppressed with rain. Therefore, the consistency of the mass loss rate is unexpected.

Mass loss (2450 kg – 241.24 kg) / 13350 s

Equation 3: Mass loss rate

Overall, the mass loss rate was found to be 0.15 kg/s (total mass loss/ time).
The tests at Pollington established that fire do not penetrate the matrix of a pile without involving all the materials that form the matrix. The thermocouple data clearly demonstrated that the fire on the surface of a pile burns from the outside inwards. This was confirmed by the camera located under the pile. The series of screen shots from a small video camera positioned under the pile of wood facing up to the left of the middle of the pile. As the fire progressed the camera recorded condensation forming in the glass screen as the fire burnt towards the camera location. The camera failed once the fire reached the glass screen. One of the limitations of the small action cameras used for this project was the action of the fisheye lens focusing radiated heat onto the microprocessor causing it to overheat and shutting down the camera. Having eliminated the postulate of some yet unobserved process of fire spread from a surface fire to a deep seated fire. The submerged camera was omitted from further tests.

Figure 13: Underside of the test No2 12:00 PM

Figure 14: Underside of the test No2 15:30 PM condensation can be observed

As expected, the heat flux from the piled material was considerably lower that the free burning wood test 1. Peaking at 70 w/m^2 compared to 321.4 w/m^2 of the free burning test 1 results.

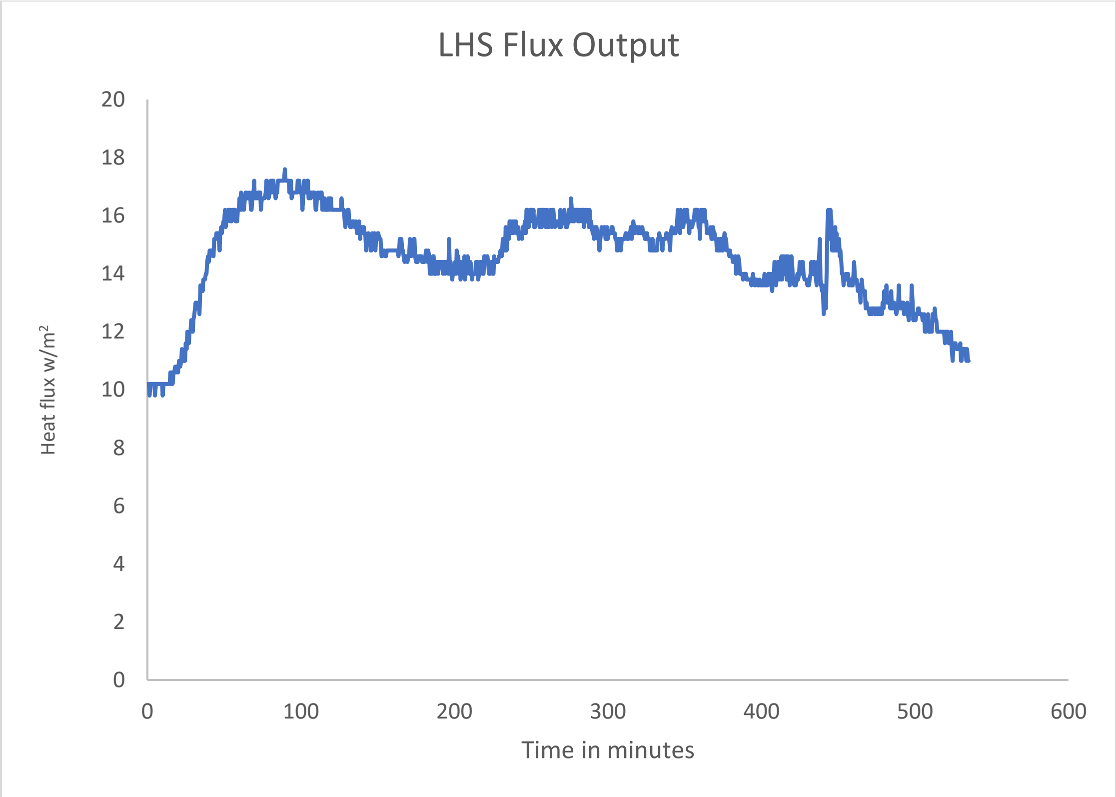


Figure 15: Heat flux data for pile wood test No2 (table 2).

5. Tests Barling test type 3

3- pre-crushed wood, 4- wood fines, 5- piled RDF, 6- double sized pre-crushed wood, 7-Piled SRF, 8- Shredded Rubber Tyres and 9- Fragmentised Fluff

5.1 Test Methodology

These piled material tests use K type thermocouples 6 m long with 4 m of stainless-steel sheathing protecting the power coated electrical wires and 2 m of PVC sheathed wire for weather protection. The Thermocouples are tailor made 3 mm diameter with a margin of error of +- 0.2 degrees Celsius. 100 such thermocouples were supplied by Bureau Veritas from their London office as part of their contract with London Fire Brigade. The main test rig was identical to that used in section 4 see figures 5 and 6. However, the Barling site was prone to flooding so the test beds were raised up on a bed of hard core 150 mm deep and finished with 200 mm of course sand. The camera was also omitted from this series of tests as no evidence of boundary spread was found. The first piled pre-crushed wood test was repeated to ensure that the variation of test bed did not affect the results.

The Material was piled carefully around the rig to avoid displacing or damaging the thermocouples. The waste material was allowed to find its own level and piled to a minimum height of 1m and allowed to find its own resting angle which was assumed to be 45^0. The exception being test 6 where the only parameter changed was the volume and mass of the material being tested. This test was performed as a sensitivity study to provide an increased level of confidence in validity of the test results.

This assumption was based upon preliminary testing which indicates a general tendency for loose waste material to settle at an angle between 40^0 and 48^0. This is a property which is of relevance to the siting of the static heat flux meter. This angle has a tendency to decrease as the materials settle. As a result, the heat flux meters may need to be adjusted to ensure they are 2 m from the plan being observed if there was significant delay between the material being piled up and the start of the test. The results from the heat flux metres are therefore dependant on the view factor of the radiation emissions from the test far more than the other test equipment and the results from the heat flux meters this must be considered when analysing these results.

The fuel bed was ignited using a 25 mm propane blow torch. The flame was played on the upwind side of the pile at the base of the pile around a $1m^2$ area. For a maximum of 20 minutes. The weather conditions were monitored using the waste sites weather station. The test was recorded using cameras set 45^0 angles from each other. The thermocouple data was captured together with the heat flux data on a data logger and exported to an excel spread sheet (Eltek Squirrel 1000 series) (76).

Test criteria:

Materials that take less than 10 minutes to reach a self-sustaining fire – easily ignited materials

Materials that between 10 and 20 minutes to reach self-sustained fire- combustible materials

Materials that take longer than 20 minutes to reach self-sustained combustion – limited combustibility

The application of this Criteria is strictly limited to this test methodology for practical reasons.

The tests are also observed using a FLIR (77) thermal image camera. Wherever possible temperature readings are measured using two sets of instruments and preferably two independent technologies. All test equipment to be calibrated to between 0^0 and 1200^0c. Prior to ignition a sample of the material was taken and stored in a sealed steel sample can. Further samples are taken at key points during the test. This will be discussed in detail in the discussion of results.

The conditions of the Environmental permit for this site were that Leachate must not exceed the limits for the existing landfill site where the fire tests were to be conducted. The maximum pile size should not exceed 10 tonnes and the fire tests could only be conducted when the wind was from a range of SSW to W. It the wind veered around the test would have to be terminated. For this reason, damp sand was selected as the fire suppression system (78) and it had an instant knock down of the flames and instant suppression of smoke.

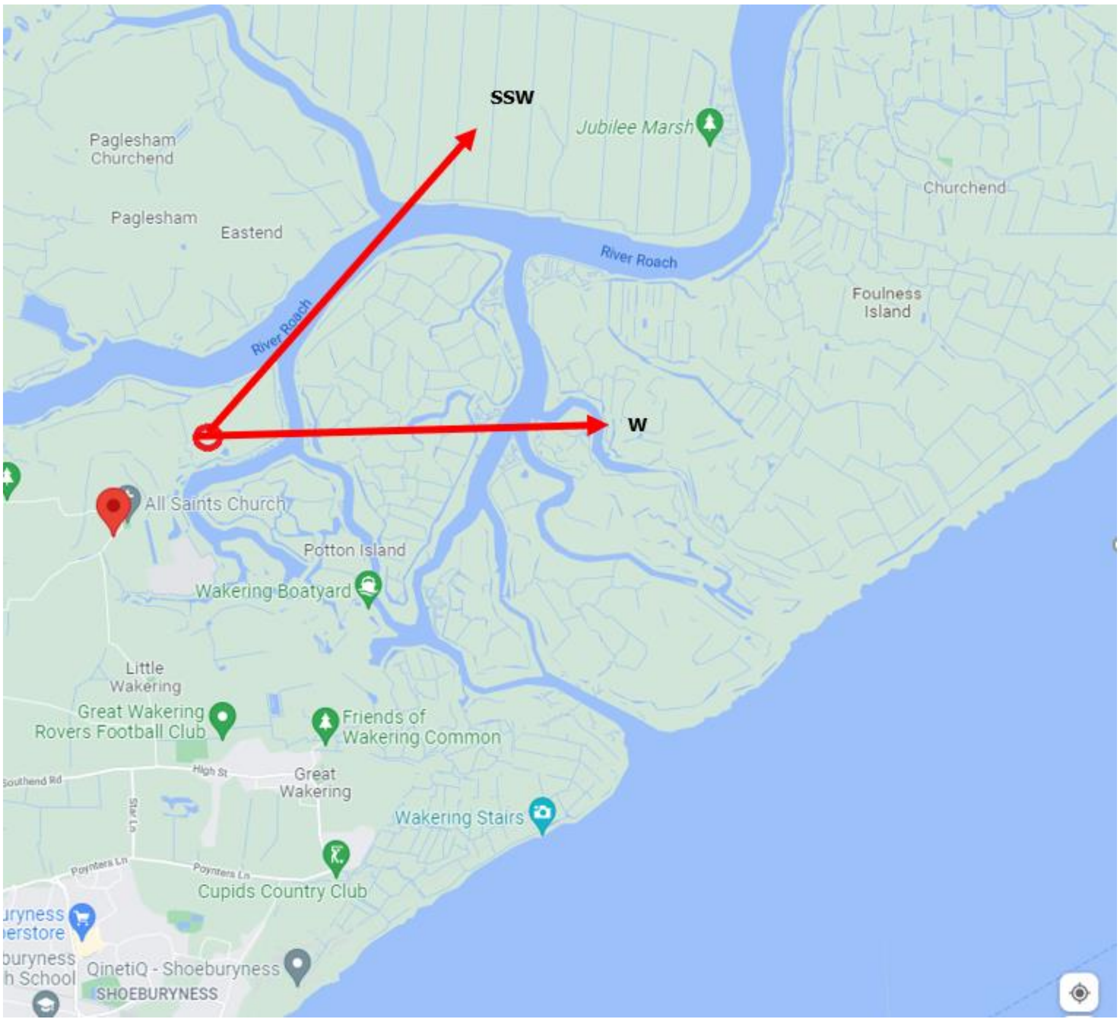


Figure 16: Plan (79) indicating wind restrictions

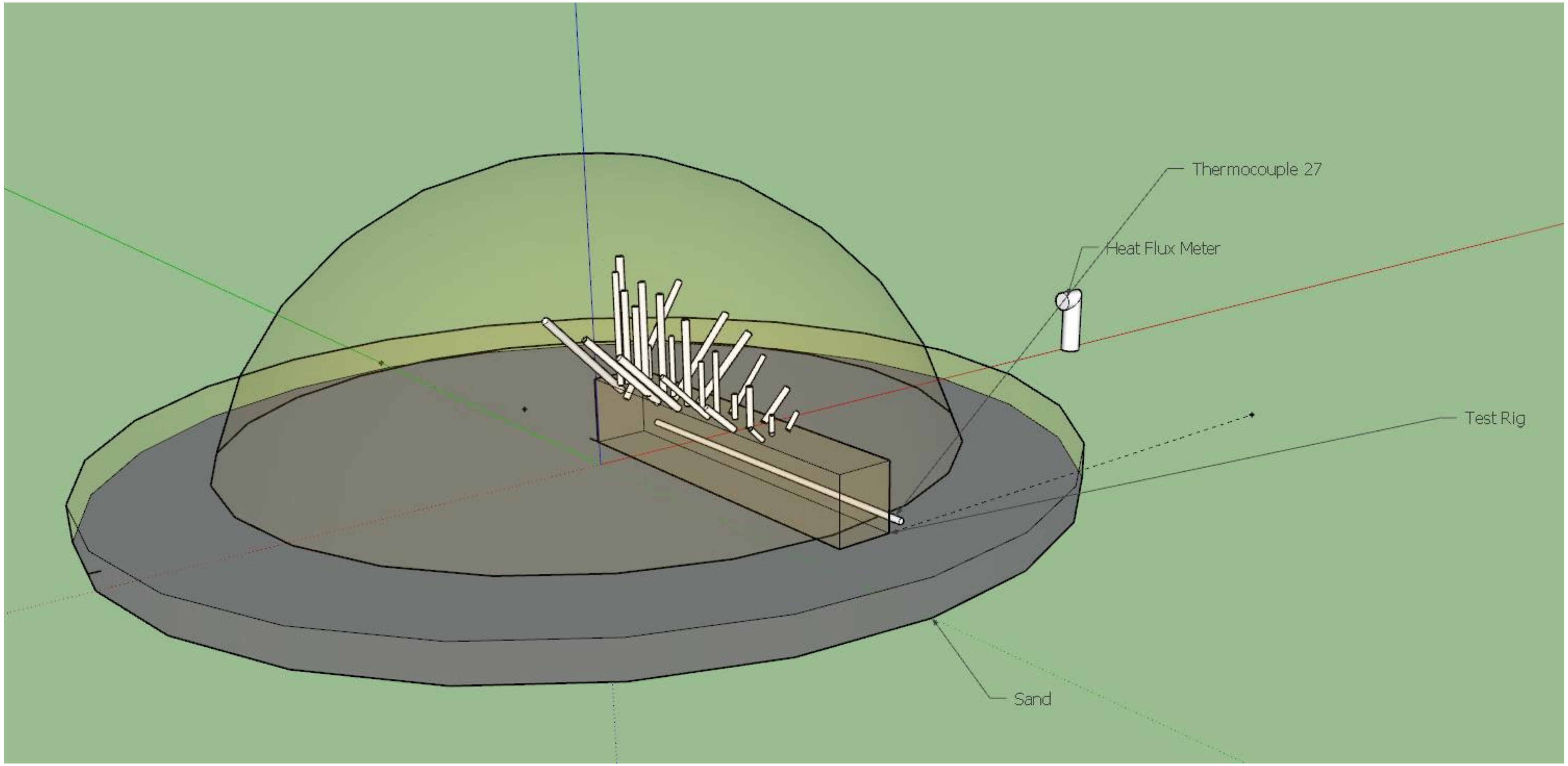


Figure 17: 3D image of test type 3 with no buried camera

5.1.1 Analysis

The second piled wood test conducted at Barling in Essex on the 20th January 2016 is discussed below. The pile consisting of 2.25 metric tonnes of pre-crushed wood was piled as described above.

Using basic mathematics detailed in equations 1,2 & 3 the approximate density and volume are calculated as 238.85 kg/m^3 and 9.42 m^3.

The fire was observed to display a short period of initial surface flaming which was followed by a steady state of smouldering combustion. Thermocouples 2,4,5,6 & 7 are arranged at 200mm intervals in the vertical plain. The thermocouple data for these measurement points are detailed below.

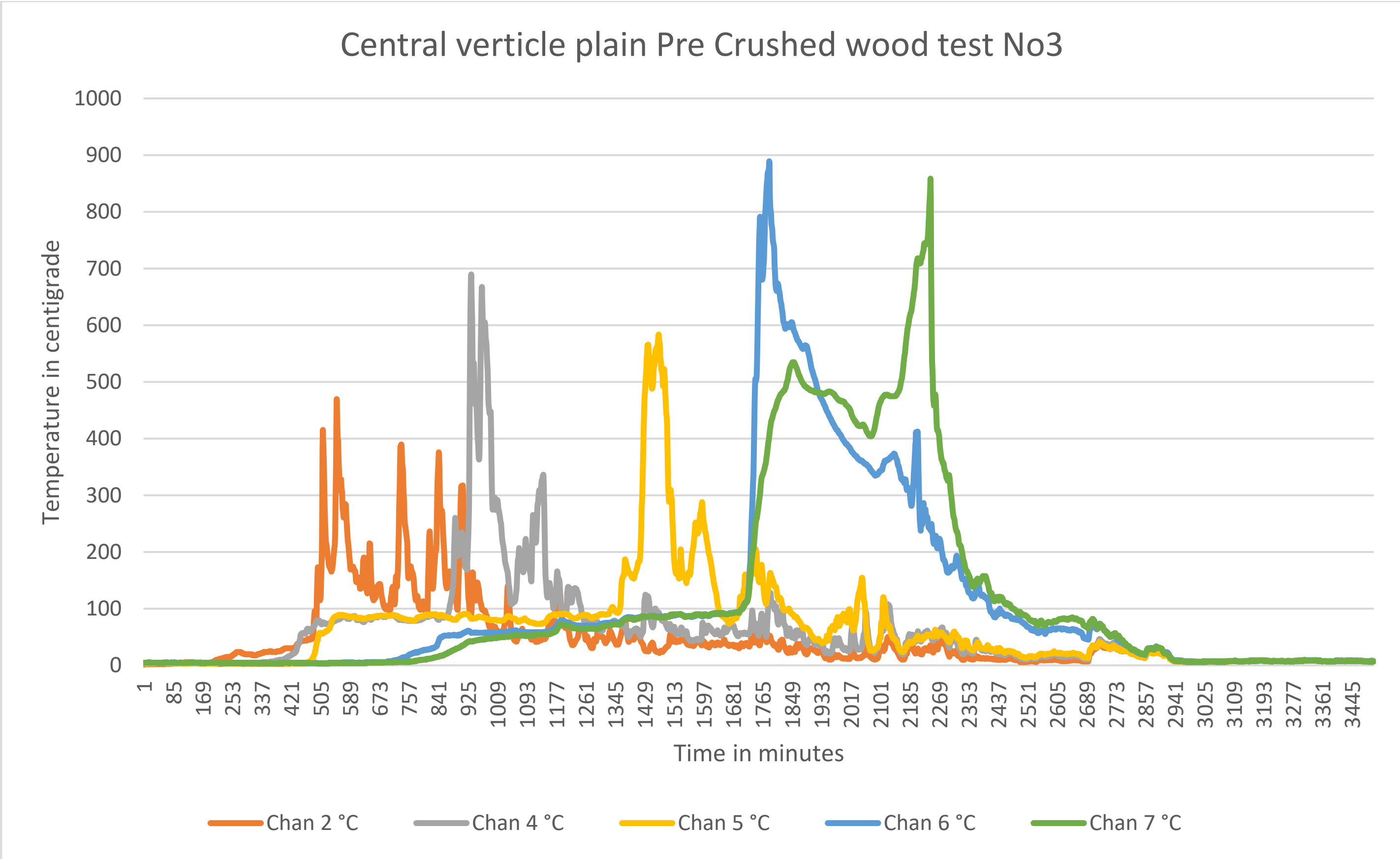


Figure 18: Test No 3 central plain thermocouple graph

By taking these measurements and analysing them in graphical form it is apparent that the combustion layer burns through the material at a very consistent rate. Therefore, a correlation between the rate of burn and the reduction in volume can both be observed as the pile reduces in size and the measurements taken at fixed points is a valid approach to calculating mass loss. This assumption is based on a constant density of 238.85 kg/m^3. From this assumption the following table has been derived.

Time (s) intervals between TC's at 200mm intervals	Volume (m^3)	Mass (kg)
0	9.42	2249.97
11400	6.57	1569.25
27660	4.25	1015.11
36990	2.41	575.63
50640	1.01	241.24

Table 4: Test No3 Mass loss table

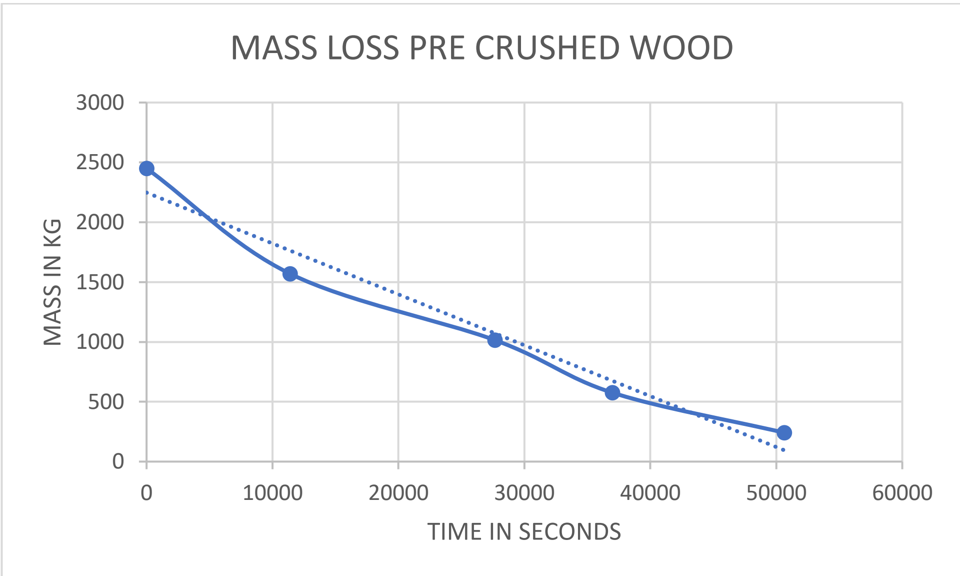


Figure 19: Test No3 mass loss graph

The resulting graph is consistent with the general shape and trends observed in the empirical data and is therefore considered accurate. Therefore, the consistency of the mass loss rate is expected given the results of test 2. Overall, the mass loss rate was found to be 0.04 kg/s (total mass loss/ time). By comparison with the first test (0.15

kg/s) this is a significantly lower mass loss rate. It is apparent that the ash layer that remained intact on this fire test has a significant retarding effect on the combustion processes resulting in a slower mass loss rate.

Figure 20: Test No3 (table 2) smouldering phase

The weather data has also been considered within the time period of this analysis the weather conditions were relatively stable with a temperature variation of 7 degrees Celsius and light precipitation form 19:00 hours none of which was observed to have any significant impact.

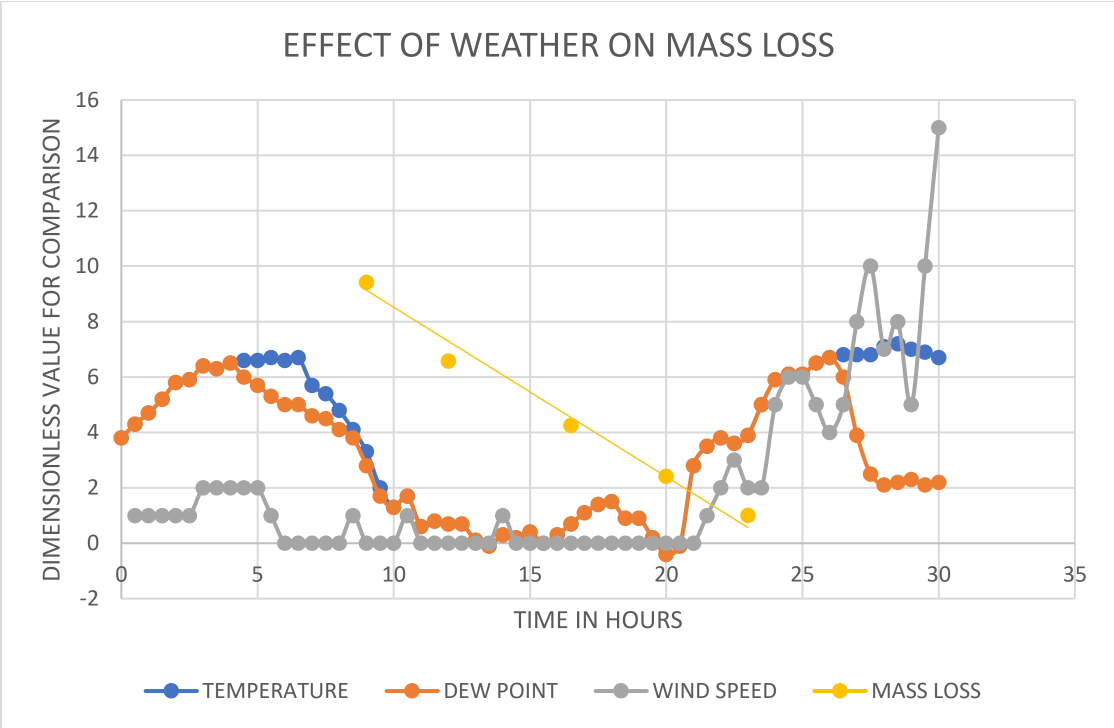


Figure 21: Weather /Mass loss comparison graph for test No3 (table 2)

Heat flux measurements are not available for this test due to equipment failure Although the peak Heat flux observed with all the surface fire involving wood was found to be 70w/m^2 +- 10%. Typically, on calm days once the initial flame had passed over the surface and the ash layer were undisturbed this reduced to almost unrecordable level with the field equipment available. Readings with the thermal image camera were typically showing temperatures around 100^{0}c with an occasional hot spot. Given that the brief of this project from the waste industry is to establish the risk of fire spread due to radiated heat even in the worst conditions 70 w/m^2 does not pose a major radiated heat hazard.

5.1.2 Wood fines test 4

Figure 22 Test No4 (table 2) Wood fines 25 January 2016 10:34AM

The pile consisting of 3.42 metric tonnes of pre-crushed wood was piled as described above.

Using equations 1,2 & 3, the approximate density and volume are calculated as 363.06 kg/m^3 and 9.42 m^3.

The fire was observed to display a short period of initial surface flaming which was followed by a steady state of smouldering combustion. Thermocouples 2,4,5,6 & 7 are arranged at 200mm intervals in the vertical plain. The thermocouple data for these measurement points are detailed below.

Time intervals between TC's at 200mm intervals	Volume (m^3)	Mass (kg)
0	9.42	3400
14370	6.57	2385.3
17610	4.25	1543
83702	2.41	874.97
87962	1.01	366.69

Table 5: Test No4 mass loss table

From the data the results for wood fines appears at first sight to be very different from the first two piles wood tests. This is primarily due to the physical nature of the fines which are finely cut shreds of wood reminiscent of saw dust as shavings. This makes a pile of this material both denser than the larger cut waste woods but also more susceptible to self-heating and the effects of wind. It was observed that the material had a core temperature considerable above ambient with a localised temperature of 80^{0}c observed on during and equipment test on the morning of the 25th January 2016. Although this temperature was observed to reduce to below 30^{0}c prior to the commencement of the test.

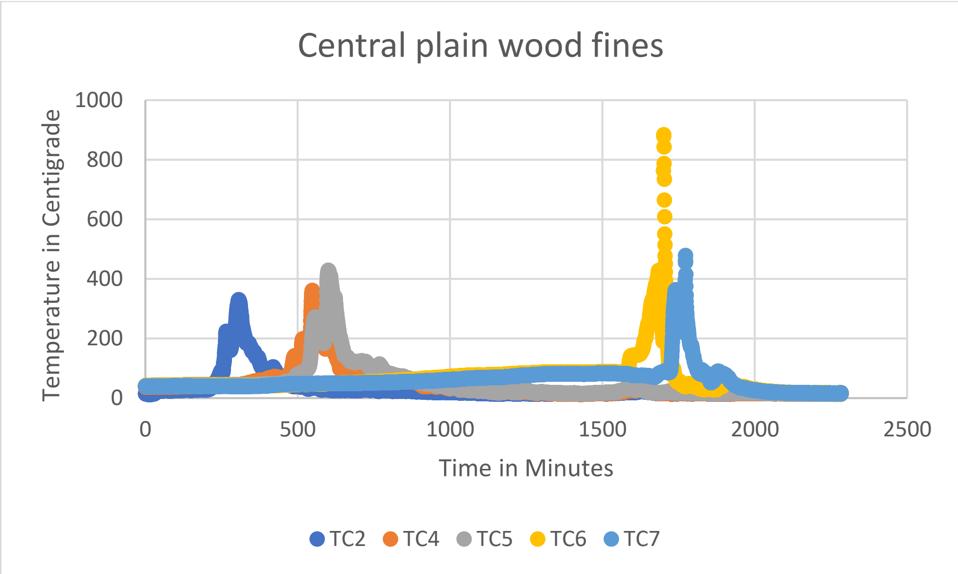


Figure 23: Test No4 (table 2) thermocouple data

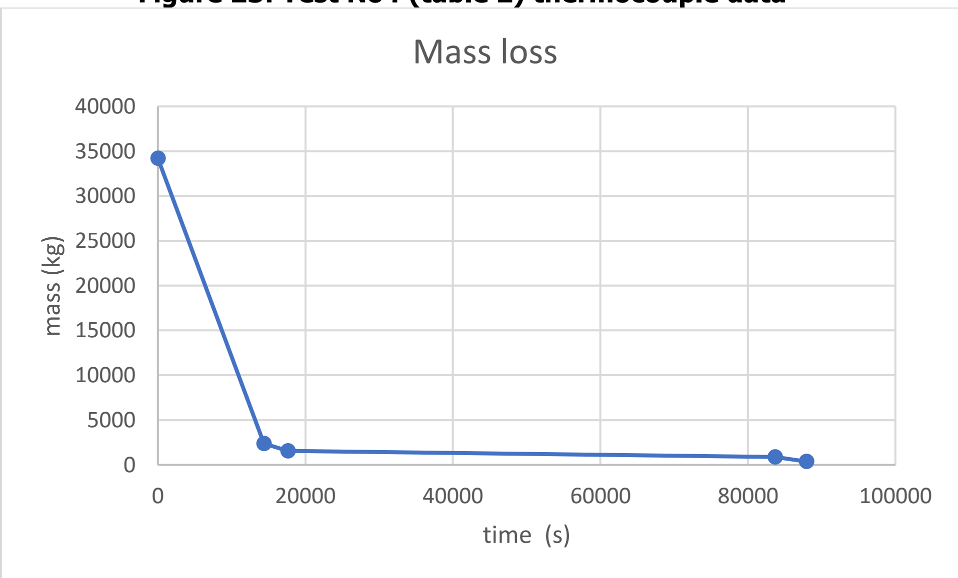


Figure 24:Test No4 (table 2) mass loss rate

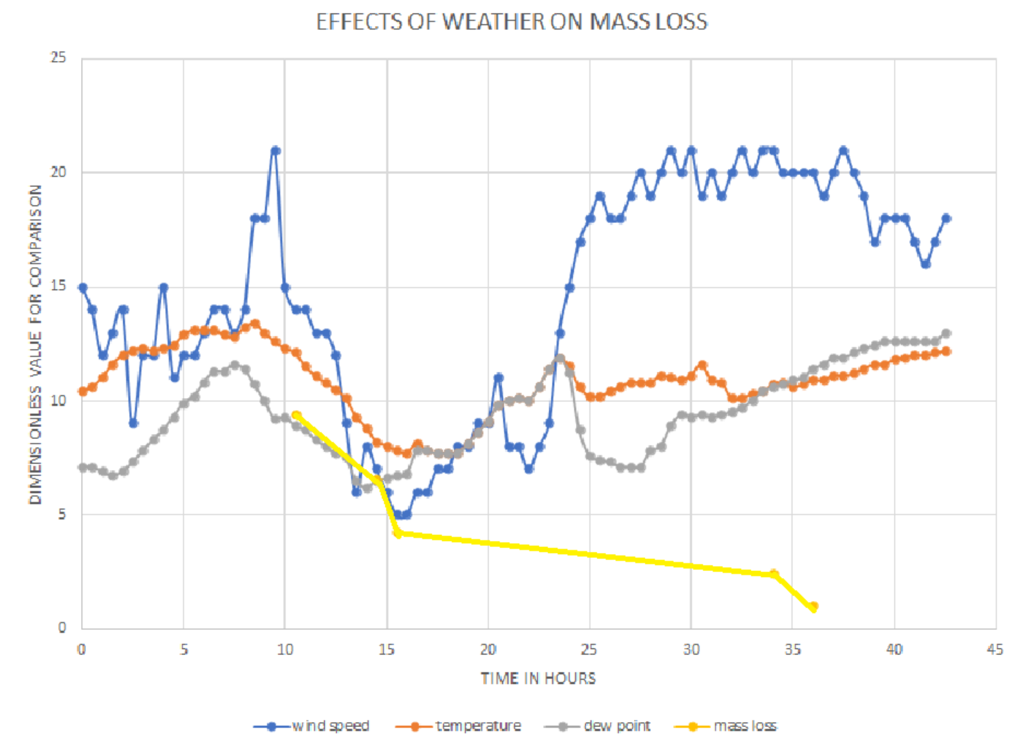


Figure 25 Weather / Mass loss comparison graph for test No4 (table 2)

From the graphs above it can be observed that the high mass loss rates and corresponding peak in temperatures is a direct result of wind erosion of the ash layer as observed in test 2. As the wind subsided a layer of ash and char was observed to form over the surface of the pile. This layer once formed proved quite robust and provided very effective protection to the combustion zone. As can be seen in the graph above this crust rendered the fire effectively impervious to the effects of the weather for the remainder of the test. The second peak in heat flux was interesting as there was no corresponding increase in mass loss. From the point of view of mass loss, the rate of burning appeared to slow. It was also noted that the residue of the pile displayed open flaming. The reduction in mass loss could be attributed to the loss of moisture from the remaining fuel and the loss of the bulk of the pile which would have acted as a heat sink. The last of the fuel was close to the test bed that had already been heated and therefore, the last vestiges of heat release would largely be reflected producing this last period of flaming combustion that broke through the car layer. This final phase of burning was observed in the test 1 and 3 which were allowed to burnout naturally.

(3400kg-1543kg) / 17610 s = 0.105 kg/s

Stable ash layer period between 17610 s and 83702 s

670kg / 66092s= 0.01

Final phase between 83702 s and 87962 s

508 /4260 = 0.112 kg/s

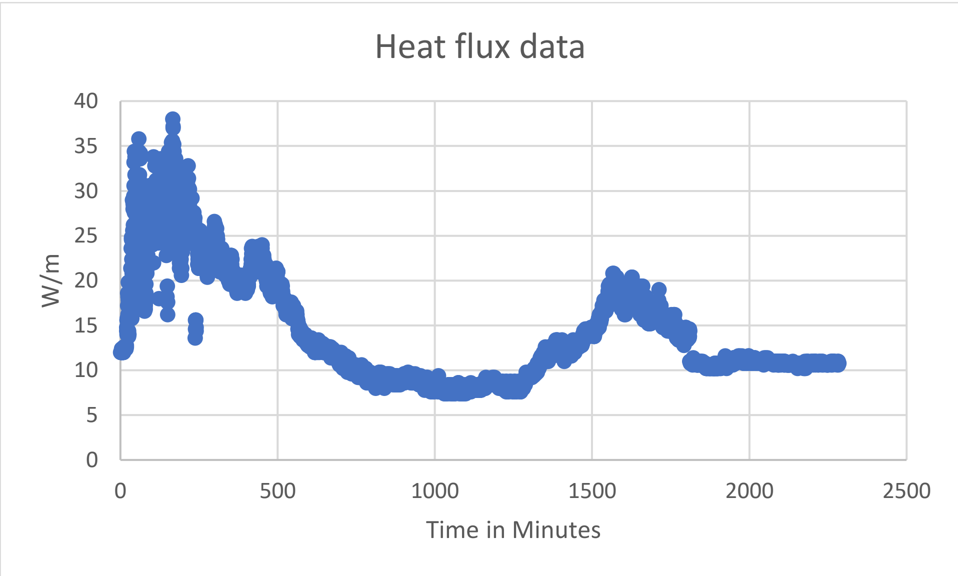


Figure 26 :Test No4 (table 2) heat flux data

The heat flux data at 2 metres is consistent with the other findings.

5.1.3 Piles RDF Test 5

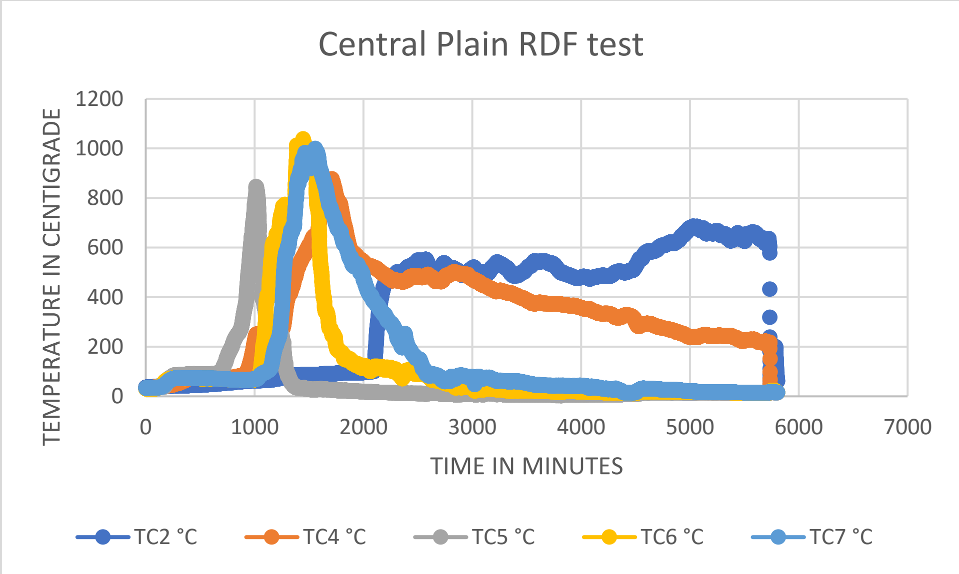


Figure 27: Test No5 (table 2) RDF test data

Note- it was apparent for the results that the thermocouples were connected to the data logger incorrectly. The analysis of the results has been corrected to account of this.

The pile consisting of 2.7 metric tonnes of pre-crushed wood was piled as described above.

Using Equations 1,2 & 3, the approximate density and volume are calculated as 286.62 kg/m^3 and 9.42 m^3.

The fire was observed to display a short period of initial surface flaming which was followed by a steady state of smouldering combustion. Given this fire behaviour the most interesting parameters from the point of view of fire engineering are the mass loss rate and heat release rate this was calculated using the method set out earlier in this section . The thermocouple data for these measurement points are detailed above.

Time intervals between TC's at 200mm intervals	Volume (m^3)	Mass (kg)
0	9.42	2699.96
15780	6.57	1883.09
33150	4.25	1218.14
41820	2.41	690.75
82230	1.01	289.49

Table 6 : Test No5 (table 2) mass /volume table

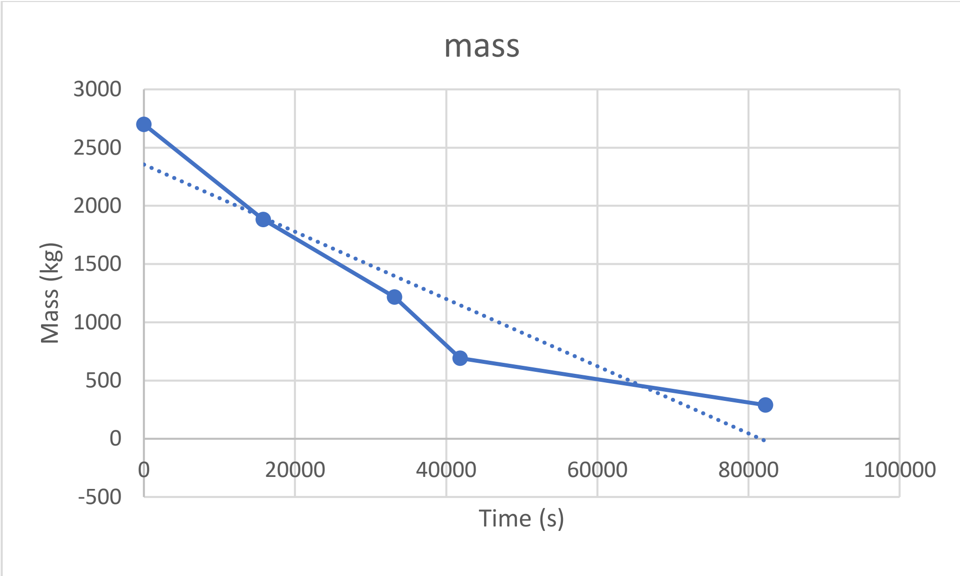


Figure 28 : Test No5 (table 2) mass loss

The wide variation in mass loss is expected give the very random composition of the material which consist of residual waste after the recyclable material has been extracted. As can be seen from the wind data there is no apparent correlation between the weather conditions and the burn rate in this experiment.

The mass loss rate is a therefore indicative.

2419.47 kg /82230 s = 0.03 kg/s.

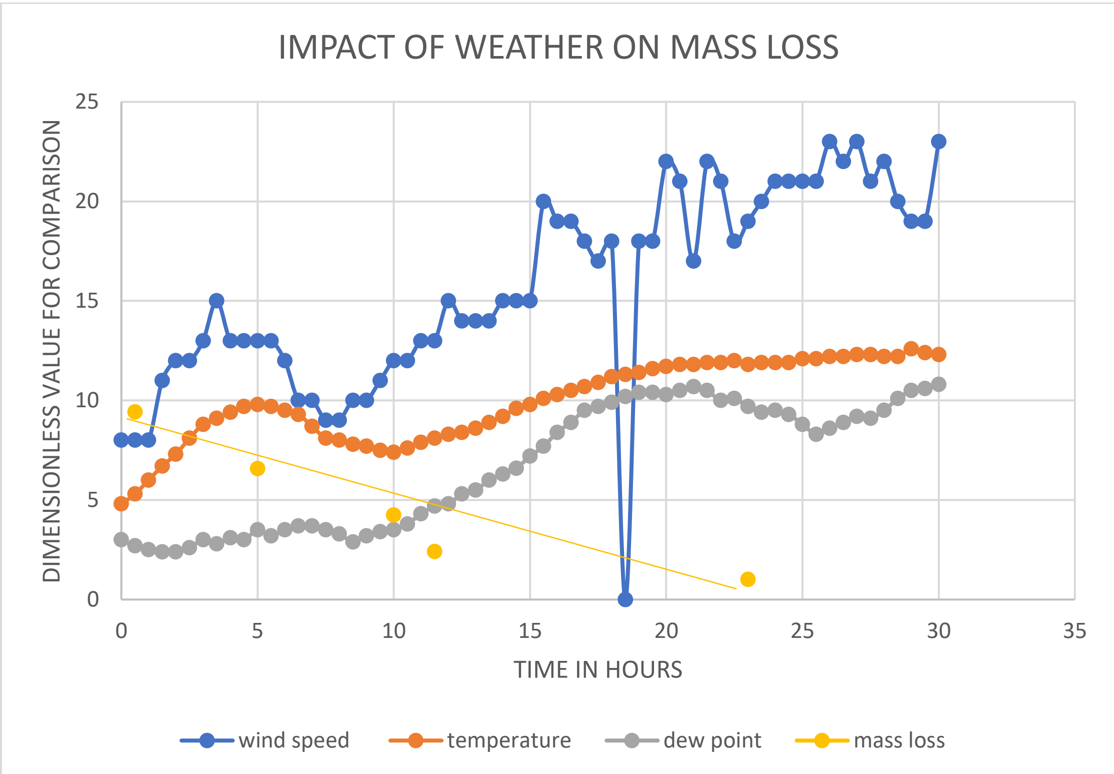


Figure 29: Weather /Mass loss comparison graph for test No5 (table 2)

5.1.4 Double sized pre-crushed wood test

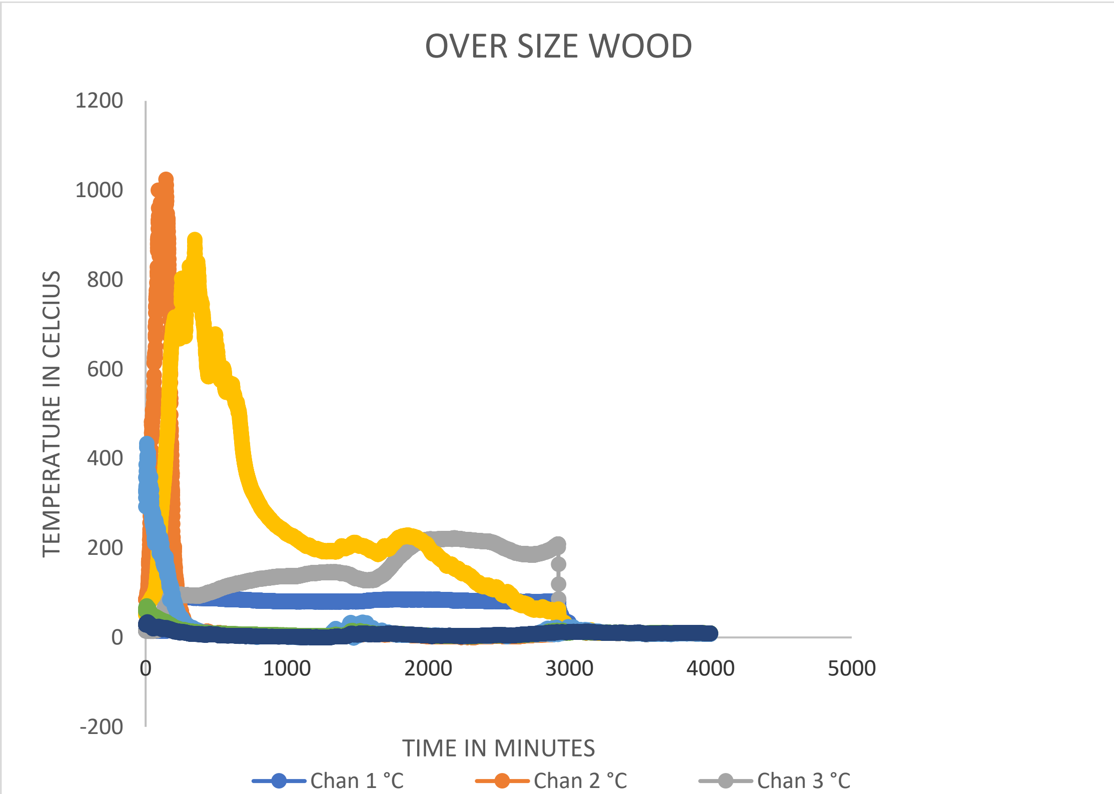


Figure 30: Test No6 (table 2) thermocouple Data

The pile consisting of 5.68 metric tonnes of pre-crushed wood was piled as described above.

Using Equations 1,2 & 3, the approximate density and volume are calculated as 238.85 kg/m^3 and 23.8 m^3. Although the diameter and height of the cone was 2 m the test rig was not scale up therefore the relative volumes are still valid validating direct comparisons.

The fire was observed to display a short period of initial surface flaming which was followed by a steady state of smouldering combustion. Given this fire behaviour the most interesting parameters from the point of view of fire engineering are the mass loss rate and heat release rate this was calculated using the method set out earlier in this section. The thermocouple data for these measurement points are detailed **Error! Reference source not found.**above.

Time intervals between TC's at 200mm intervals	Volume (m^3)	Mass (kg)
0	9.42	2249.97
4740	6.57	1569.25
12000	4.25	1015.11

Table 7: Test No6 (table 2) mass loss table

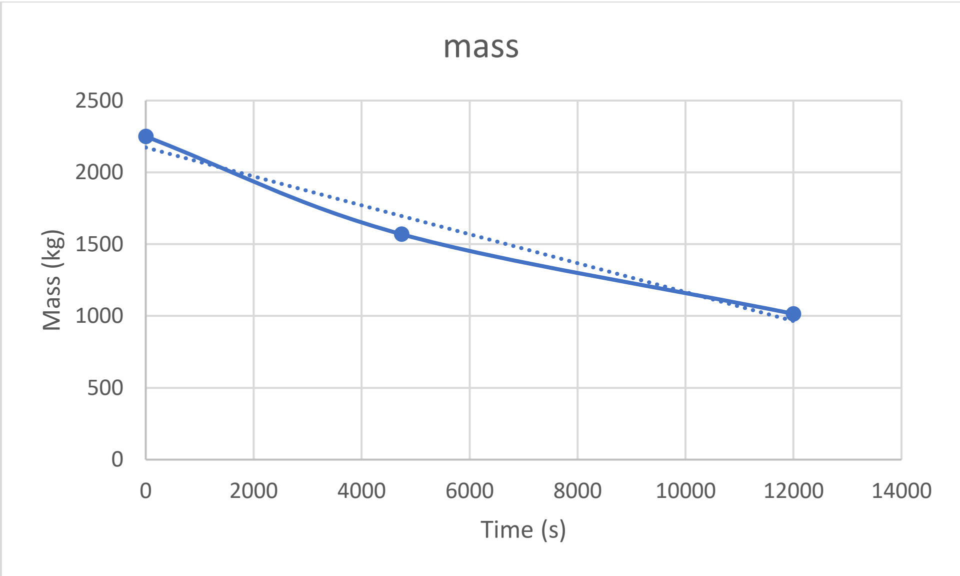


Figure 31: Test No6 (table 2) mass loss graph

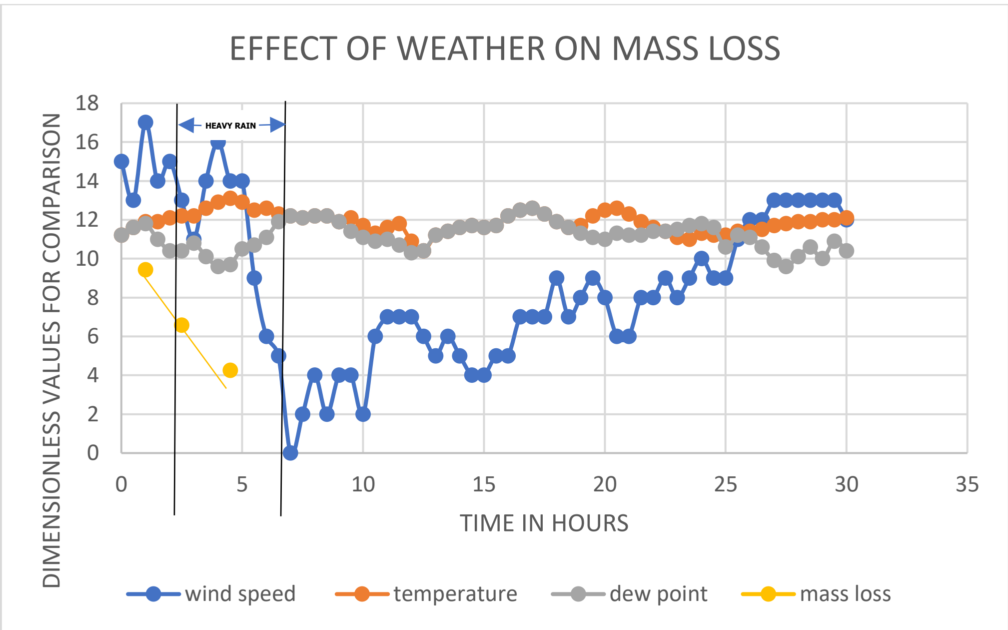


Figure 32: Weather/Mass loss comparison graph for test No6 (table 2)

Mass loss

1234.86 kg /12000 s = 0.1 kg/s

The data logger had become waterlogged and consequently many of the channels were not registering data. It should also be noted that this test used the same test rig and the smaller scale tests, so measurements were only recorded once the pile had reduced in size to that approximately the same dimensions as the smaller test. However, the test data obtained is consistent with the earlier wood test data. The ability of the ash and char layer to shield the combustion zone from the effects of the weather conditions is evident from the mass loss graph over laid with the weather data. There was a period of 5 hours of heavy rain that damaged the data logger despite the weather protection provided to it. However, this extended period of rain had little effect on the rate of combustion as indicated by the mass loss data.

5.1.5 SRF test 7

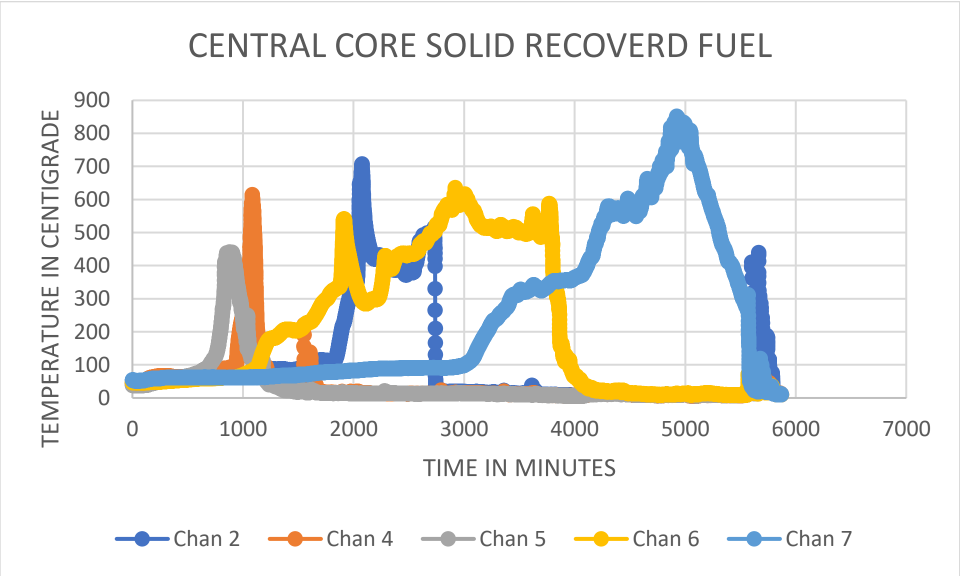


Figure 33: Test No7 (table 2) thermocouple data

The pile consisting of 3.06 metric tonnes of pre-crushed wood was piled as described above.

Using Equations 1, 2 & 3, the approximate density and volume are calculated as 324.84 kg/m^3 and 9.42 m^3.

Where the volume of the cone formed is calculated as set out below given a radius of 1.5 m and height of 1 metre

The fire was observed to display a short period of initial surface flaming which was followed by a steady state of smouldering combustion. Thermocouples 2,4,5,6 & 7 are arranged at 200mm intervals in the vertical plain. The thermocouple data for these measurement points are detailed above. This test had been assembled at the same time as the large scale pre-crushed wood test and consequently the material was very wet. This wetting had generated a considerable degree of biological activity resulting in the pile of waste reaching temperatures of between 38^0c to 55^0c prior to the experiment. Similar surface temperatures were observed on the compress bales of SRF although the interior of the bales remained around ambient. In setting up the fire test on piles loose SRF the material had been broken up introducing large quantities of air into the matrix of the pile and providing greater surface area on which heating could take place. In the very compact form of a compressed bale the bale becomes effectively a single solid object.

Time intervals between TC's at 200mm intervals	Volume m^3	Mass kg
0	9.42	3060
9480	6.57	2134.2
23884	4.25	1380.57
31084	2.41	782.86
116374	1.01	328.1

Table 8: Mass loss table test No 7

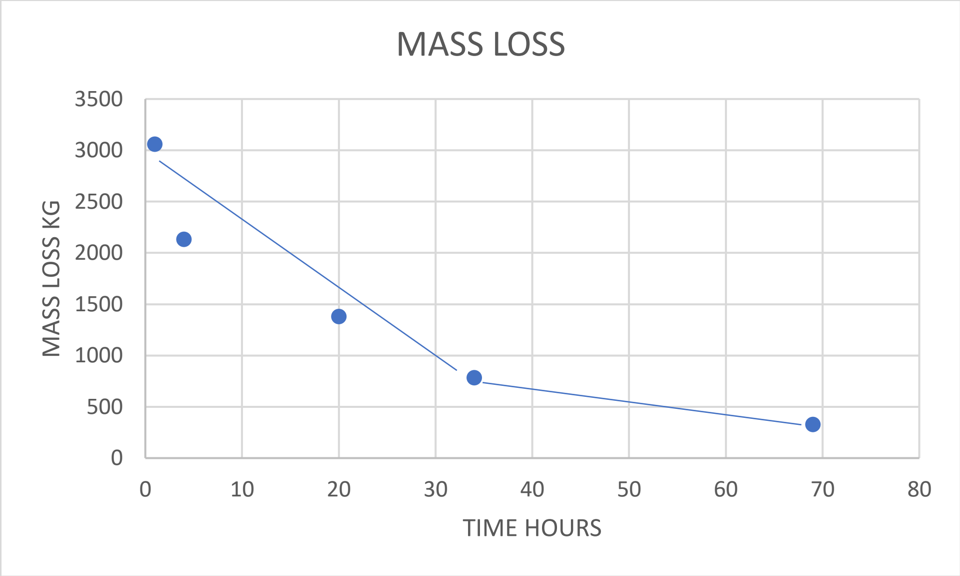


Figure 34: Mass loss graph for test No.7 (table 2)

Mass loss rate: 2277.14 kg /31084 s = 0.07 kg/s

2nd mass loss rate 455kg/85290s= 0.005 kg/s

It should be noted that this material was unusually wet even, so this is consistent with the mass loss rates observed in the work package 1 results where the peak mass loss rate was 0.04 kg/s and steady state was 0.01 kg/s (23). The second period of the experiment where the mass loss rate was significantly reduced is probably due to the presence of water. Prior to the test there was a period of torrential rain and consequently there was standing water around the level of the test bed for the duration of the experiments. The second significant peak recorded by TC 2 coincides with the experiment being buried in sand. This method of extension was specified in the Environmental Permit in order to prevent the production of leachate as a result of using water to extinguish the test fires. This obviously captured the heat being produced by the remaining fuel resulting is all the thermocouples recording a rise in temperature.

5.1.6 Tyre shred Fire test 8

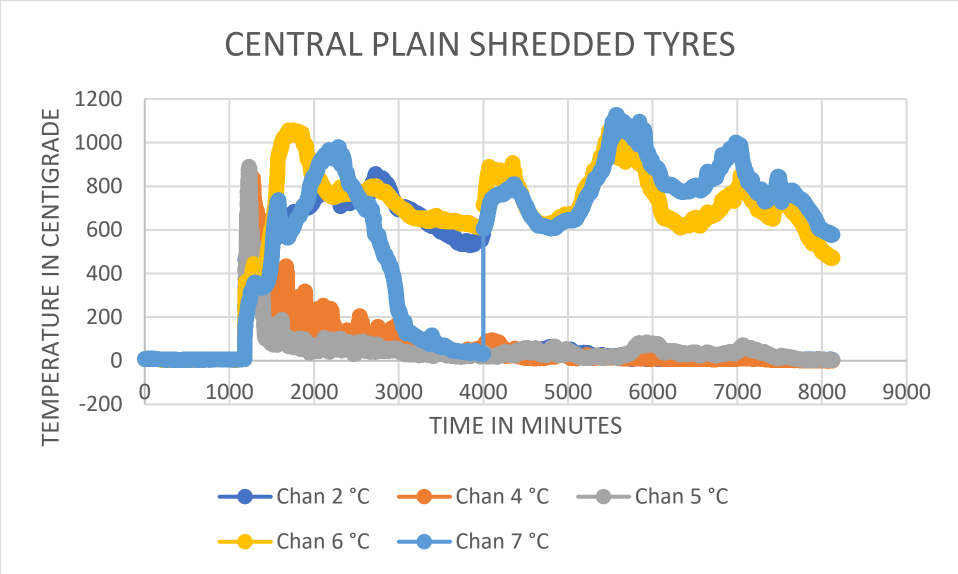


Figure 35:Test 8 (table 2) thermocouple data

The pile consisting of 3.42 metric tonnes of pre-crushed wood was piled as described above.

Using Equations 1, 2 &3, the approximate density and volume are calculated as 363.06 kg/m^3 and 9.42 m^3.

The fire was observed to display an extended period of initial surface flaming which was followed by a steady state of smouldering combustion. Given this fire behaviour the most interesting parameters from the point of view of fire engineering are the mass loss rate and heat release rate. Thermocouples 2,4,5,6 & 7 are arranged at 200mm intervals in the vertical plain.

Time intervals between TC's at 200mm intervals	Volume (m^3)	Mass (kg)
0	9.42	3420
1231	6.57	2385.3
2800	4.25	1543
5580	2.41	874.97
8123	1.01	366.69

Table 9: Mass loss table Test No8

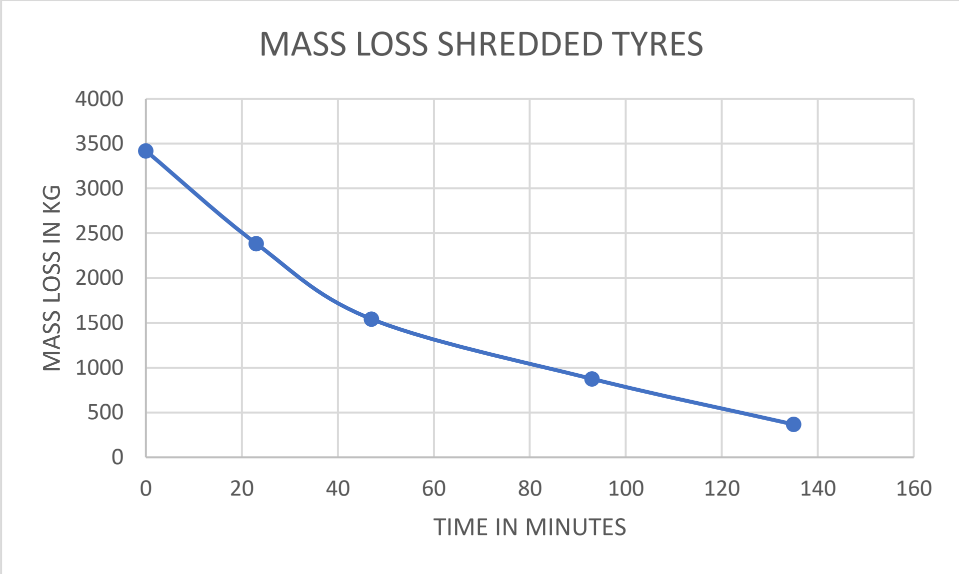


Figure 36: Test No8 (table 2) mass loss graph

It is apparent from the preceding graph and table that this fire test was behaving very differently from the other piled materials.

Figure 37: Test No8 (table 2) mass loss graph

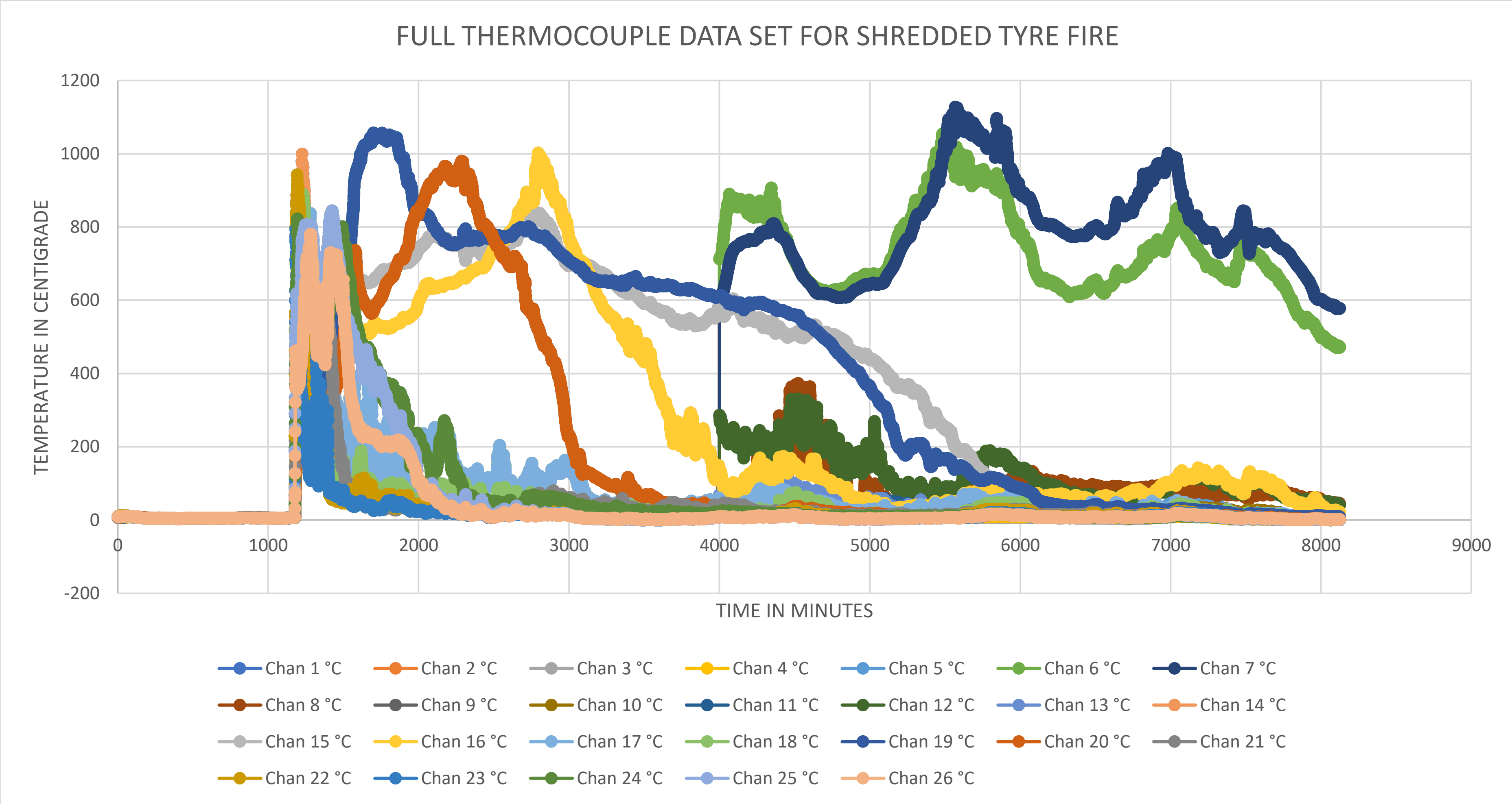


Figure 38: Test 8 (table 2) full thermocouple data

The fire apparently followed the general pattern of a surface fire involving piled materials. However, the matrix of the fuel bed formed by the piled shredded rubber tyres presented large holes.

Figure 39: Test 8 (table 2) view of shredded tyre.

The fire was able to penetrate the core of the matrix as indicated by the thermocouple data. From the observes point of view within 47 minutes of the initiation the fire followed the same pattern as an impermeable fuel bed. However, it was clear from the thermocouple data that this initial phase had generated deep seated combustion prior to being smothered by the ash layer that the fire created. This test fire represents the bridge between an impermeable fuel bed fire and a permeable fuel bed fire and may account for some of the apparent confusion that was apparent in the reporting of the causes of deep seated fires. There was clearly a physical link between the flame height of the particles involved in fire and the average whole size of the matrix formed by the pile of materials. As can clearly be seen the piled material forms a matrix of random shaped and size holes all of which are as a range of angles to each other. In the initial stages of this fire test the average hole dimensions were greater that the height of the flames. Thus, the fire was able to pass through the pile unhindered. However, as the char layer started to form, expanding, the flames were prevented from penetrating the core of the pile. Thus, this fire appeared to behave like the previous fire test namely a surface fire. When in fact in the early stages the fire was a permeable fire. The initial mass loss rate was 0.67 kg/s for around 47 minutes. The initial stages of the fire consumed 45% of the mass of the fuel before the char controlled phase. During the char controlled phase thermocouples 6 and 7 recorded the highest temperatures in this experiment indicating a residue of unburnt fuel the mass loss during this phase was 0.2 kg/s.

5.1.7 Fragmentised Fluff Test 9

Figure 40: Test No 9 (table 2) Fragmentizer fluff

This test was conducted on the 18th February 2016. A propane torch was played over an area of approximately 0.5 m^2 on the upwind side of the pile in line with the test method adopted for the pile material tests. After 20 minutes the material failed to sustain a flame. Therefore, this material is considered of limited combustibility for the purposes of this test series. The flame was then applied for 52 minutes and a sustained fire was generated. However, the heat release rate was so low that the smoke lacked sufficient buoyance to dissipate and collected at ground level. The material it treated with a variety of flame retardants. The result was a strange kaleidoscope multi coloured flames ranging from bright green and yellow / brown colours to blue flames. The maximum surface temperature recorded was 580^0c although the average surface temperature was 115^0 c.

Given the lack of breathing apparatus for the test team and the proximity of public foot paths the fire test was abandoned a 120 minute for the initial application of the flame. Consequently, no thermocouple data was recovered.

Figure 41: Test No 9 (Table 2) frag fluff pile 118 minutes

It was found that the most efficient firefighting method for instant knock down of flame and smoke was the application of wet sand. Where necessary water sprays could be applied subsequently. The use of a cement pump to apply this wet sand mixture could prove an effective application method if lacking the through of a conventional fire-fighting jet.

Figure 42: Test No9 (table 2) wet sand encasement (78)

Conclusion of the surface fire series of test

MATERIAL	INITIAL VOLUME (m^3)	MASS (KG)	RELATIVE DENSITY OF THE PILE (kg/m^3)	MASS LOSS RATE (kg/s)	WIND EFFECT	Test No
Pre crushed wood	9.42	2250	238.85	0.15	S	2
Pre crushed wood	9.42	2250	238.85	0.04	L	3
Wood fines	9.42	3400	360.93	0.1	S	4
Wood fines	9.42	3400	360.93	0.01	L	4a
RDF	9.42	2699.96	286.62	0.03	L	5
Pre crushed wood over-sized	18.84	4500	238.85	0.1	S	6
SRF	9.42	3060	324.84	0.07	L	7
Shredded tyres free burning	9.42	3420	363.06	0. 67	L	8
Shredded tyres char controlled	9.24	3420	363.06	0.2	NA	8

Table 10: Table of results summary surface ignition

Note: - S represents a significant wind effect. L represents little effect from wind.

Considering all of the results and observation from this first series of test it was found that there is no evidence for a surface fire penetrating into the core of a pile of material without the involvement of the intermediate materials. Tests 1 and 8 initially progressed as permeable fire beds where the primary means of fire spread was direct flame impingement. The gaps in test 8 were sufficiently close to the limit of a permeable fuel bed for the ash production to smother this free burning stage. This was demonstrated when the fire apparently progressed in the same way as the other fire beds. However, the thermocouple data demonstrates the flames had penetrated the core of the pile in the early stages and ignited material in the core of the pile. This may account for the miss reporting of the of the causes of fire in waste pile.

It was found that the primary means of propagation into these fuel beds was form radiated heat and conduction resulting is a slow smouldering process. Wind plays a significant part in accelerating this process both in removal of the ash layer and by improving ventilation of the surface layer of the pile matrix in the early stages of the fire. However, once the char and ash layer are formed the fires are shielded from the effect of weather. This property of the char/ash layer is consistent with the experiences of the Fire Service who have reported difficulties extinguishing fires using water alone. (80) It was found that the size of the holes formed by the particles of the matrix and the mass of the individual particles had a direct bearing on how much influenced the wind had on the fires. Several of the test were conducted in heavy rain and the fire appeared to be less influenced by rain fall than wind.

The heat flux meters were of limited value. These were water cooled devises and consequently fixed in a single location at a set distance. What these devised captured was the passing flame front. The majority of the materials displayed this fire behaviour. The flame progressed over the surface of the pile with a narrow band of flame. To the fire side of this flame front the fire was suppressed by ash and char formation and progressed as a slow smouldering fire that was remarkably water resistant and hence wet weather was found to have little effect on the progression of the smouldering layer as it penetrated the pile of material. It was therefore, decided to devise a method for calculating the mass loss rate for each experiment to provide a route for further calculation for example, using mass loss to calculate Heat release rate.

$$\dot{q}_{HC} = \Delta\dot{H}_c \, m_{fuel}$$

Equation 4 Heat release rate

The ratio of the average size of the holes formed by the particle making up the matrix of the pile of material was found to be the critical factor between a permeable fuel bed or an impermeable fuel bed. However, this is in itself simplistic and the relationship between a completely impermeable fuel bed and a completely permeable fuel bed was found to be on a scale. This is described as permeable, semi permeable and impermeable fuel beds. The description of a semi permeable fuel bed is demonstrated in the next series of test, in these tests the point of ignition was moved to the core of the pile to simulate a deep seated ignition rather than a surface ignition.

Surface ignition fires can be summarised in terms of the relationship between flame height produced by the individual fragment (L^*)of a pile waste and the average porosity size ($\tilde{\varphi}_{ave}$)that those fragment form in the pile.

Where

$\tilde{\varphi}_{ave} \approx 0$ the fuel bed will be impermeable – fire behaviour will tend towards slow smouldering combustion. Deep seated ignition will be unobserved.

$\tilde{\varphi}_{ave} \leq L^*$ the fuel bed will tend to be semi – permeable. Surface fires will tend towards ash and charr controlled fires. Deep seated fire will generate convection currents that are readily detected on the surface. Deep seated fire will be relatively server where the convection currents will drive off the ash and charr resulting in fire around the peak heat release rate (fuel-controlled fire).

$\tilde{\varphi}_{ave} \geq L^*$ the fuel bed will tend to be permeable – the flames can pass through the mass of the pile producing a fuel controlled fire.

Where the critical flame height L_{crit} is maintained throughout the matrix formed when the material was piled together.

This is assuming a modified Heskestad correlation

$$L^* = -1.02 D_{eq} + 0.235 {Q^*}^{2/5}$$

Where

$$D_{eq} = D = \sqrt{4A_f/\pi}$$

$$A_f = \pi\left(r + \sqrt{H^2 + r^2}\right) \text{ equivalent radial area.}$$

Equation 5: Heskestad equation adaptation

These findings are consistent with Mc Allister and Finney 's paper (27) on the factors affecting the burning rate of a crib fire. Although they did not reduce the porosity φ to a point where their system failed.

Chapter 5 Deep Seated Fires

Having established the link between the permeability and fire spread into the heart of a pile of material in chapter 4. It was apparent that deep seated ignitions were a separate problem. Two questions needed to be answered. The most pressing question for the waste industry was how do deep seated fire behave and what measure needed to be set out in the industry guidance (5). This would affect the design of waste management sites. The second question was how these fires start. The first question seems simple enough to answer and this section sets out a range of experiments where fires were generated within the core of the waste pile. The second of these questions is more elusive.

6. Deep seated ignition test series.

The deep seated ignition fire tests series consists of the following test

- Test No. 18 Wood fines residence self-heating test
- Test No. 11 pre-crushed wood
- Test No. 12 RDF
- Test No. 15 SRF
- Test No. 16 pre-crushed wood double mass
- Test No. 19 Pre-crushed wood in a bunker
- Test No. 28 (a) & (b) RDF

6.2 Deep seated test initiation methodology

Initially a range of credible ignition sources were examined these included shorting lithium batteries. Sulfuric acid, BBQ coals, fire lighters and self-heating.

While lithium batteries did generate a considerable amount of heat the total energy release proved to be inadequate to generate a reliable self-sustaining fire particularly in RDF and Per-crush wood with a high water content. Sulfuric acid, which was used to simulate a led acid car battery leaking, did generate sufficient activation energy when 1 litre was used, and the water content actually appeared to aid this process, but the effect was dependant of the presence of a large organic material content of the target material. None of these methods were pursued due to health & safety and reliability issues. The BBQ coals were ineffective, but this was largely due to the high water content of the materials. The Barling site is sited on the River Roach estuary less than a mile from the North Sea coast and is consequently exposed to the weather and on marshy ground. The test bed was raised up to 0.25 m above the general ground level to form a relatively dry test bed. However, the materials were all stored in the open both at the suppliers and on site consequently the moisture content was a minimum of 35%.

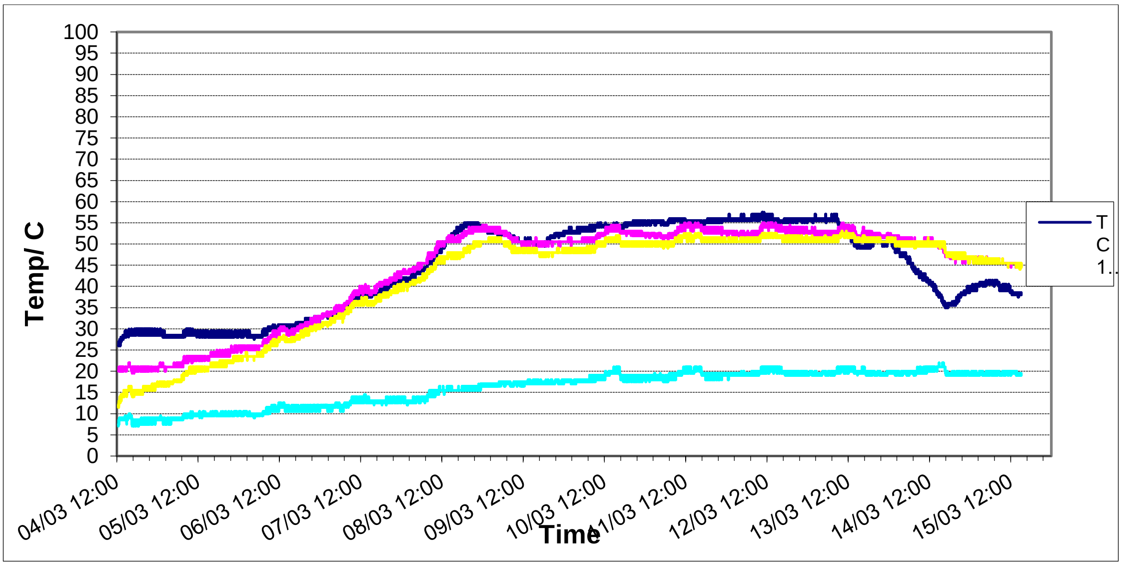
After a conversation with *Glockling J. (2015)* (81) regarding self-heating research he had conducted a self-heating tests were developed as part of this preliminary examination of deep seated ignition causation. These tests consisted of 1 wood fine piled over three k type thermocouple arranged along the centre line a 400mm intervals together with some plastic gas sample tubes located with a view to examining the gas mixtures and two piles of RDF piles in concrete bunkers

Figure 43: Test No 18 (table 2) wood fines self-heating test

Figure 44 RDF self-heating test March 2016

Figure 45: Gas sample tube and thermocouple for the RDF self-heating test

The wood fines experiment had a reduced hedgehog test rig similar to earlier test consisting of 4 k type thermocouples arranged at 20 cm intervals around the centre line from 10 cm to 90 cm. The RDF test used K type thermocouples that were inserted into the pile from the outside see figure 45. This method of inserting the thermocouples from the outside was consistent with the method employed by I. Woodward (39). This test also included three gas collection tubes arranged at 45^0 to collect samples of the gas production in an attempt to identify which if any gases contributed to self- heating ignition.



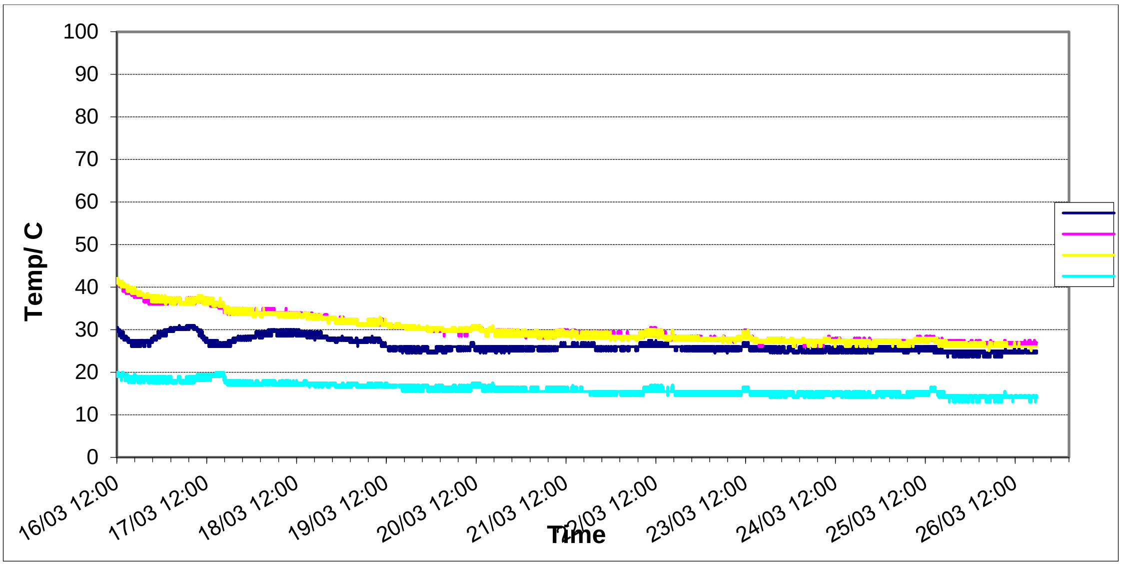


Figure 46: Test No 18 (table 2) Self heating Fires test (deep seated ignition)

The gas tests did pick up the production of some interesting candidates for auto ignition such as Acetylene, Carbon Monoxide and a number of sulphur compounds but only in trace amounts of at most a few parts per million. From and activity point of view the first two weeks showed the most activity. With periodic bursts of heating to around 30^0c to 35^0c following rainfall. Other that this the pile was reduced to compost after approximately 14 months and the test abandoned. No self-heating fire was generated.

The two RDF pile test were abandoned due to an extended period of unseasonal heavy rain that resulted in much of the test site being flooded. This resulted in the RDF producing excess leachate as a result the material had to be disposed of at a registered landfill site in accordance with the Environmental Permit. As a consequence of this flooding there was no testing on side from early March 2016 until mid-May 2016 in order to allow the water levels to subside and the test bed to dry out.

The trace gases detected were consistent with combustion, but the levels were very low. This indicates that the decomposition process of the wood fines is in effect a very slow combustion process that is controlled by the presence of water. Therefore, the key factor in preventing self-heating fire in this experiment was the high moisture content of the material. This presents a dilemma for biological self-heating as a cause of ignitions as the critical moisture content of <30% by mass is stated as being the critical factor in microbial activity, Ryckeboer et al (2003) (35). This paper stated temperature of 70 to 80 ^{0}c in compost piles that subsequently subside without causing a fire. This is due to the destruction of the microbes due to the sterilizing effect of these temperatures. It would, therefore, appear that biological self-heating is self regulating. However, there are clear cases of ignition of hay due to biological self-heating. The Postulate being explored in these tests was the notion that repeated heating would product areas of dry material within the pile that if subject to heating by biological heating by an area of wet material adjacent to it would produce a runaway combustion process that would generate a deep seated fire. It is known that introducing fresh cut Hay on to an existing dry pile is a fire hazard Fire Service Manual (31). This document states consistently that the risk factors are the cut size, moisture, content and availability of air. RFD and wood fine become quite dense as they settle excluding air. This lends weight to the argument that a pile left undisturbed is less likely to self-heat as the longer it is left the air pockets are excluded and the moisture content drops below the level that biological activity is viable. Unfortunately, 2016 was an unusually wet year and the piles never had an opportunity to dry out sufficiently to test this theory. However, it is evident that biological activity alone does not account for spontaneous ignition of combustible materials. Residence time would, therefore, appear to be a poor control measure and turning material over periodically, which is an EA requirement, will clearly increase the risk of fire by introducing air and mixing wet and dry areas within the pile. This is an area for further research.

The review of literature associated with this particular area of research revealed considerable similarities between coal seam fire behaviours and the deep seated fire that were generated and studied during this thesis.

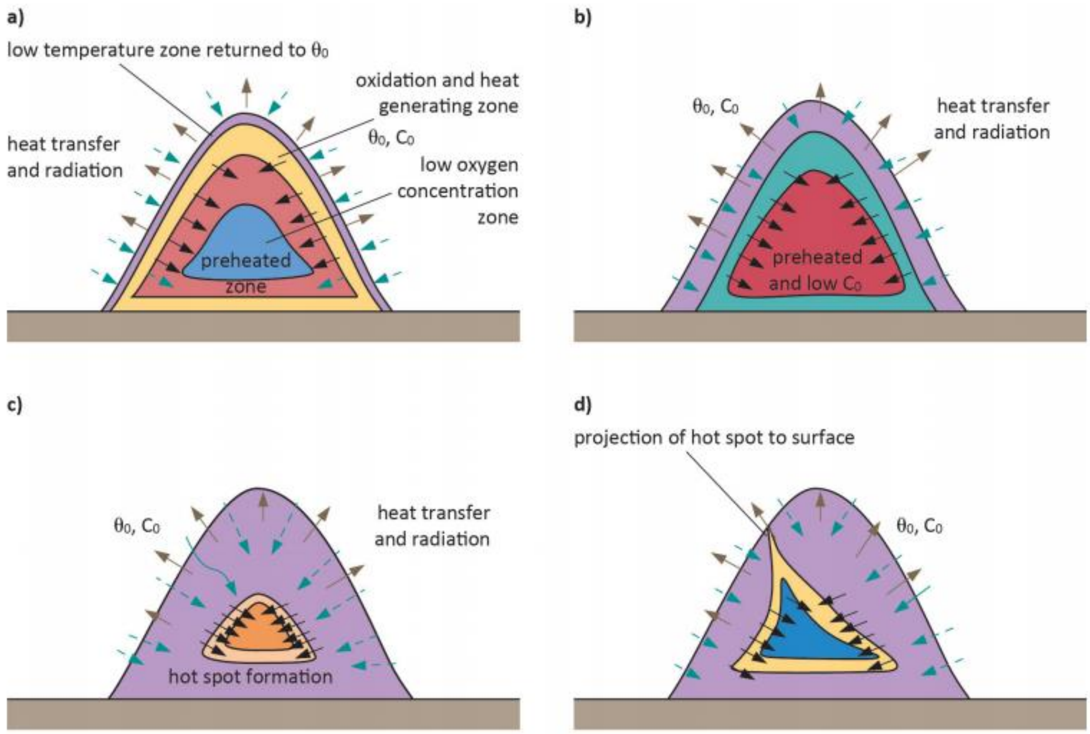


Figure 2 **Schematic showing the self-ignition process of a coal stockpile** (Sasaki and others, 2014)

Figure 47: Extract from Assessing and Managing spontaneous combustion of coal (49)

Sasahi et al (2014) (59) derived a number of mathematical models based on the known oxidation rates of specific coal types.

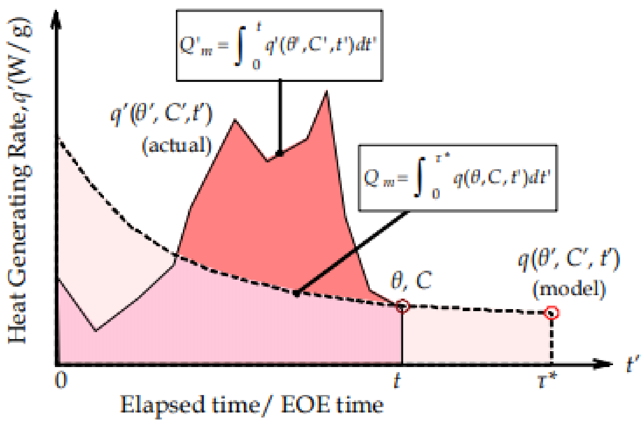


Figure 3 - Schematic definition of EOE-time of bituminous dry-coal to estimate heat generating rate by matching total heat generations (Sasaki and Sugai, 2011)

Figure 48: Extract from (59)

There are striking parallels between the fire behaviour documented in this thesis and the oxidizer driven coal fires. Both systems require an oxygen supply to initiate the fire but then progress in an anaerobic condition. With coal this is clearly the result of activating the many potential sulphur-based oxidization processes. With waste it is unclear which oxidizer is replacing the oxygen. Or for that matter if the test method itself is producing the oxidizer. The important questions for further research in this are:

- What is the oxidization regime in play with waste fires?
- Will ignition via a different ignition source produce the same result for example ignition using an incandescent heat source rather than a naked flame.

There remains a question about the mechanisms that generate sufficient activation energy. In section 8 of this paper acute activation energy is discussed. However, could a fire also be generated through an accumulative effect of repeated smaller events that alters the chemistry of the waste materials. A review of literature on the topic of self-heating is concerned with the early stages of oxidization a typical example of this is Hellerbrand et al (2006) (48). Much of this research is dependent on small samples being placed in bomb calorimeters or basket test of pre dried materials while this will certainly determine if a material is capable of self-heating it is very far from determining that they will self-ignite in a damp oxygen deficient environment. It is surprisingly difficult to generate a deep seated fire. This research has provided little in the way of answering to the question of spontaneous deep seated ignition. However, it does serve to identify the questions to be answered.

6.3 Deep seated Test Fire method 1

The majority of the tests were conducted to refine the test method. The practical problems that this test series presented took some trial and error to perfect the test method. Initially the test rig used in was removed as the rig occupied the same area that the fire was to be initiated. Therefore, to avoid congestion a new test rig consisting of three K type thermocouples arranged along the centre line and sheathed in mild steel tubes was adopted. As will be discussed in this section this proved ineffective because the thermocouples were far more exposed to the elements and failures of the equipment due to heat exposure, or water ingress was a common problem. The other issue was the lack of data points. Therefore, test 24 used a different technical approach with far more data collection points fed in from the outside of the pile. The other major issue was the difficulty in generating a self-sustaining deep seated fire. Several of the initial pre-crushed wood test were conducted with a view to perfecting an appropriate method with a view to conducting test 25 (a) & (b).
It was hoped that this would provide a reliable and realistic method for generating deep seated ignition.
While these methods are credible ignition sources, particularly after extended period of dry warm weather, they are not practical for application on test conducted in the winter months. Therefore, Petroleum based fire lighters were specified for this application.

A section of corrugated plastic 150mm diameter drainage tubing of approximately 1.8 m was set at a slight angle to the centre of the test fire. The material was piled around this to a height of 0.2 m and diameter of 3m. A 3m section of 15mm mild steel electrical conduit tubing was laid across the centre line above the intended point of ignition. A k Type thermocouple was inserted so that the data collection point was at the mid-point of the tube. This process was repeated at 0.5m and then at 1m

Figure 49: Test No 11 (table 2) shortly after ignition

The intension of the plastic drainage tube was to provide access to the petroleum-based fire lighters and to provide an air supply to ensure that the fire was self-sustaining it was anticipated from the difficult that had been experienced in the earlier tests that generating a self-sustaining fire would be a significant issue. The intension was that once the fire had taken hold the plastic tubing would fail, and the piled material would collapse sealing the fire and thereby simulating a deep seated fire.

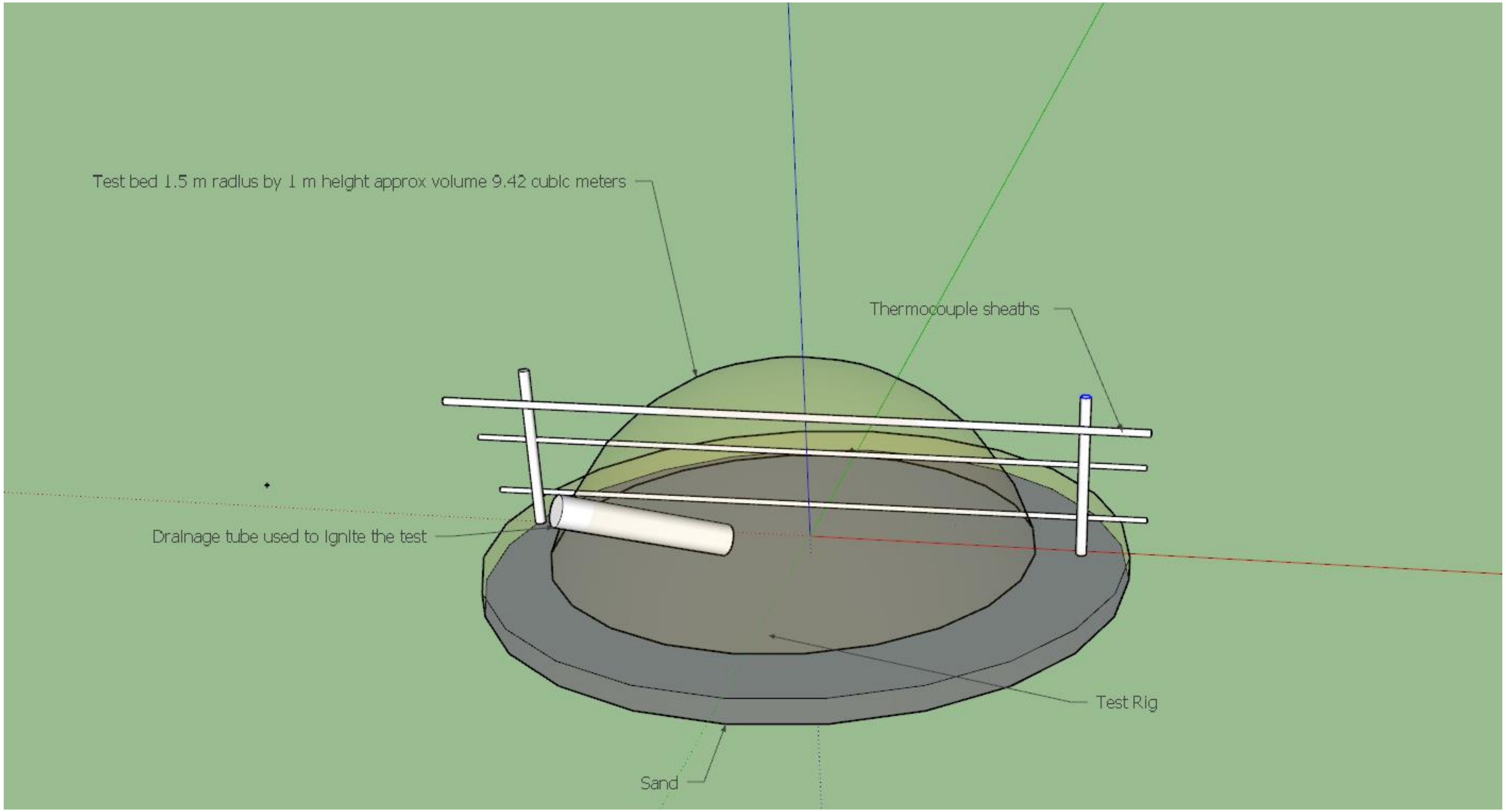


Figure 50: 3D diagram of deep seated test No 11 (table 2) Method 1

6.4 Section pre-crushed wood

This test was conducted on the 17th May 2016. The test proceeded much as planned. It was observed that smoke and heat was observed within a few second of lighting the petroleum base fire lighter. It was found that the gapes formed in the matrix of this material when piled allowed convection currents to pass through the pile.

Unfortunately, the thermocouple data was lost due to a data logged (76) failure however, periodic measurements were taken of the flame temperature once the fire had breached the surface.

WOOD BREACH		
TIME	TEMP ^{0}C	COMMENTS
08:41	579	
08:45	710	
09:00	826	
09:15	833	
09:26	841	
09:51	793	
10:15	785	
10:51	789	
11:09	779	
11:31	792	
11:44	703	
12:22	793	Embers

Table 11: Thermal image camera data table test No.11

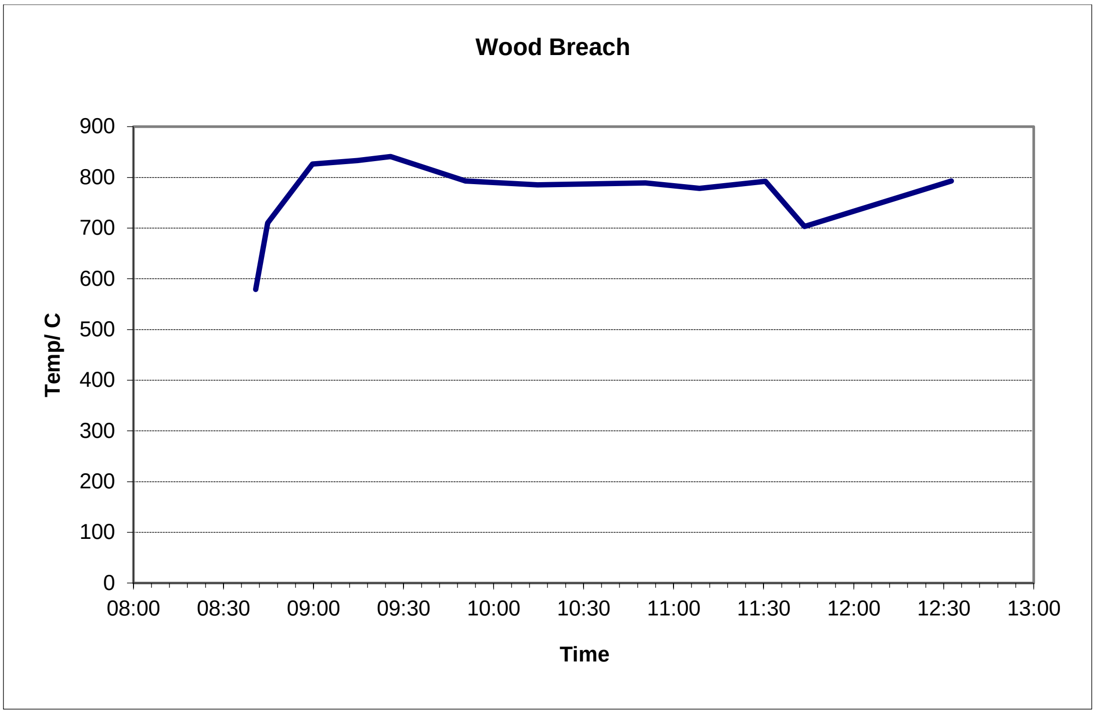


Figure 51: Test No 11 (Table 2) surface temperature Graph

It was observed that the fire which was initiated at 07:50 am had consumed the vast majority of its fuel in under 4 hours. It was also found that the fire curve was significantly different from what would be considered a conventional fire cure with an almost flat peak heat release rate.

Figure 52: Test No 11 (table 2) deep seated wood fire test lighting at 07:50 am

Figure 53: Test No 11 (table 2) shortly before the flame breached the surface 08:29 am

Figure 54: Test No 11 (table 2) fuel is almost exhausted 11:49 am

Once the fire breached the surface it was observed to be an intense free burning fire with peak flame temperatures at the maximum observed for this material in both the series 1 tests[1] and this fire test series. The duration of the peak was observed to be extended and the fire was eventually fuel controlled. This was in stark contrast to the surface ignition test where the fire quickly became ash and char controlled. Or even the permeable fuel bed that displayed the typical fire curve behaviours.

6.5 Deep seated ignition in RDF

This test was conducted on the 17th May 2016. The material proved very difficult to ignite. Even with the large boar plastic drainage tube. The flame the fire lighters formed either self-extinguished after a few seconds or burnt with a very small flame until the block of material was fully consumed. After several attempts it was decided to attempt to dry the site of the fuel bed using the propane torch. This also proved challenging due to the limited ventilation at the base of the pile. After several hours a further attempt was made to start the test with liquid BBQ lighter fuel. Unfortunately, this failed to start the fire at the core of the pile but did ignite the plastic drainage tubing which in turn generated a surface fire around the mouth of the core access hole. It was not possible to extinguish the fire for a third attempt as our only firefighting media was damp sand.

Unfortunately, the thermocouple data was lost due to the exposed thermocouple leads. However, periodic measurements were taken of the flame temperature once the fire had breached the surface.

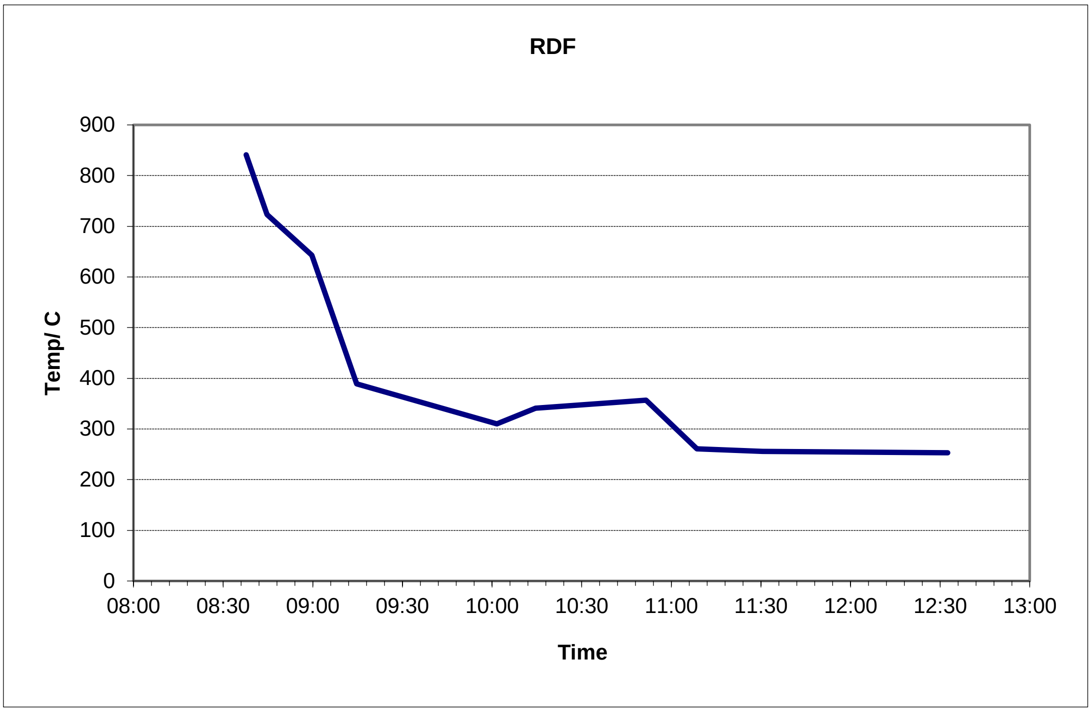


Figure 55: Test No 12 (table 2) decay curve to steady state smouldering surface fire

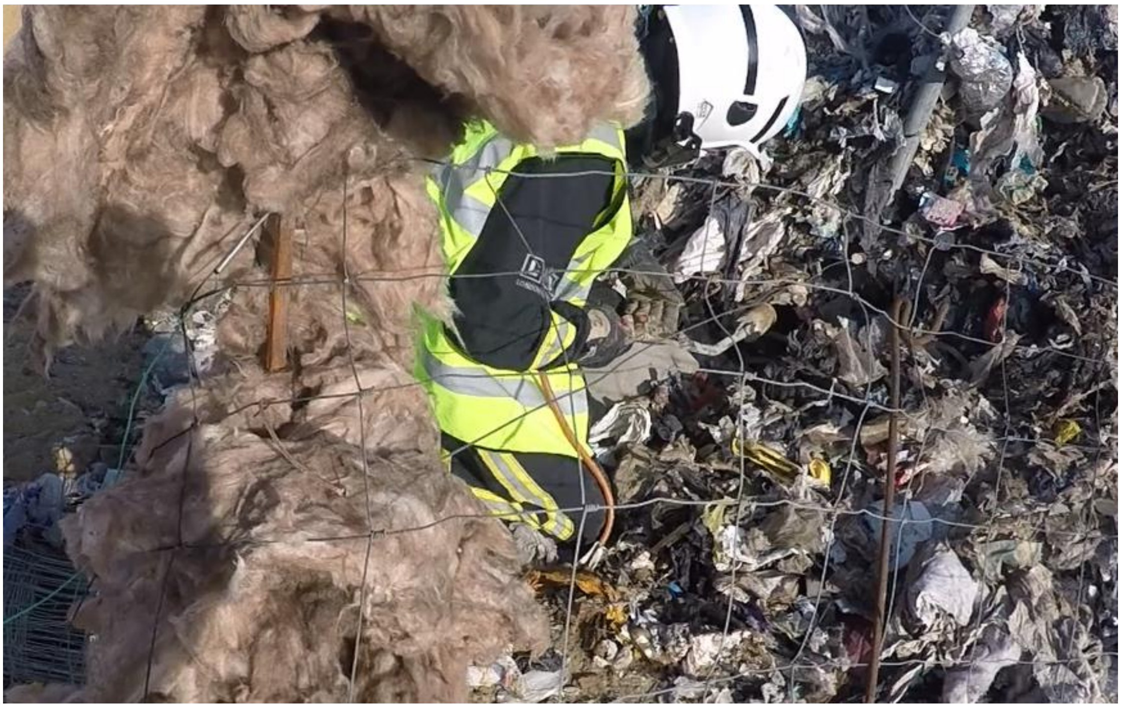


Figure 56: Test No 12 (table 2) Drying the fuel bed with a propane torch

Figure 57: Test No 12 (table 2) fire fails to take hole at the core but spread to the surface

Figure 58: Test No 12 (table2) flame front can be seen moving away from the point of origin

This test demonstrated that the activation energy required to generate a fire within a pile of material is dependent on the material properties and ventilation factors. This is consistent with known physical properties of combustion science. It was observed in the surface fire tests that RDF was more difficult to ignite than wood. It was likely that a major contributing factor was the water content within the material. RDF has layers of plastic and organic material intermingled and proved more resistant to shedding moisture to the atmosphere than wood. However, when force dried it will burn readily as this test demonstrated.

6.6 Repeat of the deep seated wood test

This test was a repeat of the fires deep seated wood test. However, the thermocouples were omitted due the rate of attrition. Therefore, surface readings were taken with a thermal image camera calibrated to 1200 ^{0}c.

The fire progressed much as before. The fire set relatively easily, and the fire curve was almost identical. The smoke breached seemingly randomly and not directly above the seat of the fire. This behaviour was observed in the earlier test. It is apparent that the heat takes the passage of least resistance. It was observed that the flames also followed this route. Once established this becomes the main "seat" of fire.

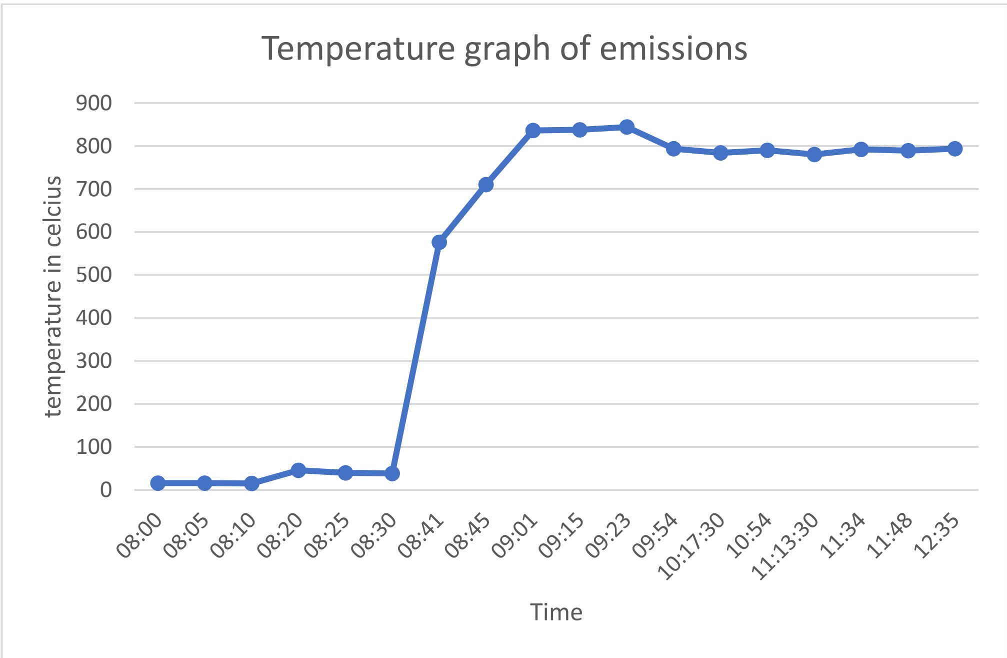


Figure 59: Test No 12 (table 2) table of temperature of the smoke and flame emissions

Figure 60: Test No 12 (table 2) still taken from a video of the initial smoke

Figure 61: test No 12 (table 2) still taken from video footage 11:24 am

It was apparent that in this Semi-permeable system there was a particular fire behaviour being displayed. The heat release rate and fuel consumption at steady state was higher with a much more dramatic growth and decay phase that was expected for piled materials.

6.7 SRF deep seated ignition.

Following the difficulties experienced attempting to initiate a deep seated fire in RDF the final deep seated fire test conducted at Barling was the SRF test. The objective of this test was to establish a method for initiating a fire in impermeable fire beds. To achieve this a 1 tonne pile of SRF was piled around a small pre-crushed initiator of approximately 20 cm diameter cone of timber with petroleum based fire lighter. Ventilation was provided by a section of steel scaffold pile at low level (this method had been used on all the fires to provide initial ventilation) with a second section of scaffold pipe at approximately 30^0 angle to allow for a cross flow.

Figure 62: Test No 15 (table 2) deep seated SRF fire test

This test was remarkable from the apparent lack of any significant fire spread the smoke emitting from the pile was a constant 40^0c with a 20% plus or minus margin for 8 am until 6 pm with no breach or apparent flame emission. At 6 pm the Essex Fire service attended to extinguish the fire. This was the only occasion that a test fire was extinguished with water. The test bed was dragged out and saturated. The materials all appeared cool and was examined with the thermal image camera to ensure there were no hot spots.

On the 23rd June 2016 the team returned to the site to clean up and hand the area back to the site operators. A small column of smoke was observed rising from the SRF pile. The site of the smoke emission was excavated, and a small area of smouldering combustion was exposed. Although it was noted that there was considerable localised heating the materials did not produce any flames once exposed to the air. Initially this was put down to this site being missed but it has become apparent that once a deep seated pyrolysis process has been generated the by-products appear to possess oxidizing properties that generate new self-heating combustion zones. This behaviour was observed in both subsequent deep seated fire tests and will be discussed later in this section.

Figure 63: Test No 15 (table 2) SRF pile showing signs of self-heating

Figure 64: Test No 15 (table 2) site of the excavation of the hot spot

Figure 65: Test No 15 (table 2) self-heating zone exposed

6.8 Summary of deep seated fires conducted at Barling.

From the data obtained above it was apparent that the composition of the pile had a direct effect on the fire behaviour. An open matrix would result is a significant fire. Pre-crush timber for example burnt more intensely if the point of ignition was deep seated that if the fire was initiated on the surface. It was also observed that where deep seated fires were achieved in impermeable fuel beds the material was subject to chemical changes that would appear to generate oxidizing by products and would bear further research. Following on from this series of experiments, it was apparent that the methods for data capture would need to be improved. The "hedgehog" test rig described in chapter 4 was abandoned as there was a clash with the thermocouples and the point of ignition that would have resulted in too much clutter in a critical zone. However, inserting the thermocouples from the surface proved unsatisfactory due to equipment failures from weather or the fire breaking out of the surface and destroying the cables.

There was an extended period of reflection and re design before these tests were repeated to confirm the results with more comprehensive data.

7. Full scale deep seated fire tests September/ October 2017

These tests were developed are part of Phase 3 Waste Industries Safety and Health real fire test program. Although these were primarily intended to prove a concept of operational firefighting protocol for waste fire see Appendix A. The Author used the opportunity to validate the findings of the smaller scale fire tests conducted at Barling at full scale.

7.1 Deep seated pre-crushed wood in a bunker

This was the last pre-crushed wood test and the first test conducted at the Fire Service College. The test was primarily programmed to establish a reliable ignition system for full scale fire test. The piled material test was to be conducted at full scale and in a series of three concrete block bunkers.

Figure 66: Concrete bunkers 5 m high and 3m by 3 m

The block wall was constructed using "Legio" blocks these are 800mm high by 800mm wide and 1600mm long. The bunkers were constructed on the edge of a disused run-way. The partition wall between the bunkers were sealed using fire rated mastic. The partition between the middle bay and the bay to be used for the pre-crushed wood was fitted with thermocouples at the surface of the wood bay 400mm (halfway through the wall) and at the surface of the inner bay. This was part of a number of a number of tests specifically aimed at establishing the fire resistant properties of the Legio blocks. Which will be discussed in section 12. These tests are not part of the central argument for this thesis but will be cover along with a number of other samples and experiments that were conducted as part of the Waste Industry Safety and Health Forum program in a later chapter.

Figure 67: Legio block bunker under construction

A section of 110mm diameter steel ducting was selected to provide a route for a propane Bunsen burn. The tube was intended to provide an air supply to establish a self-sustaining deep seated fire. A stainless steel wire basket was positioned over the Bunsen burner to prevent the Bunsen burner being smothered. The Bunsen burner was partially opened to provide a partially pre-mixed flame. The gas supply was controlled for outside on the propane bottle. The flame was to be ignited with a WIFI remotely operated detonator that ignited a 50 mm section for firework fuse. After some trial and error with small piles of wood the Bunsen burner was set to a fully defused flame and the timing of turning on the gas supply and was established.

The wood was piled up in the bunker with 4 k type thermocouple fed through the back wall and positioned 1 m from the back at 100mm above the Bunsen burner and then at 500mm intervals vertically 1 m from the back wall.

Figure 68: Test No 19 (table 2) setting up the air tube and igniter

The test failed to ignite with the Bunsen burner method. The flame was observed through the steel ducting. The flame was ignited a number of times but any fire quickly self-extinguished it was apparent that there was insufficient air supply to support combustion even with the steel ducting and the porous fuel bed.

The test was abandoned and rescheduled for October once a suitable system could be Identified.

After some debate an Oxi-propane lance was selected. This method was used to ignite the remaining deep seated fire tests.

Figure 69: Test No 19 (table 2) Bunsen burner with a wireless detonator fuse

Figure 70: Test No 19 (table 2) gaps in the wall between the bays was sealed and thermocouple indicated by the red circle

The lance could not reach the same position as the Bunsen burner and therefore, the point of ignition was slightly off set from the data collection points.

Figure 71: Test No 19 (table 2) K type thermocouple being set up

Figure 72: Test No 19 (table 2) thermocouple being positioned

Figure 73: Test No 19 (table 2) test before ignition

Figure 74: Test No 19 (table 2) October with modified ignition system

Figure 75: Test No 19 (table 2) smoke emission just before the flame breached the surface

The fire progressed much as the earlier tests and the intense flame cone followed the same route that the smoke had taken.

Figure 76: Test No 19 (table 2) test at 14:43pm

The central flame emanating from the core ignites the surface generating a surface fire. This was observed in all the earlier deep seated pre-crushed wood test. Clearly this behaviour was not dependant on scale.

Figure 77: Test No 19 (table 2) at 18:50

Had this been a surface fire it would have become ash and char control the system. At this point it was apparent that the ash is either being driven off or drawn into the fuel bed with a fresh air supply and is entrained into the flame cone. In figure 76 it was observed that the surface of the fire bed is reminiscent of a blacksmiths furnace with air forced into it be a set of bellows. Examination for the thermocouple data within the piled material demonstrated the passage of the combustion zone from the point of origin through the material. It was apparent that once the fuel was consumed the fire curve decays and then reached a point approximating steady state. This was the residual char and ash that was being heated by the passage of air.

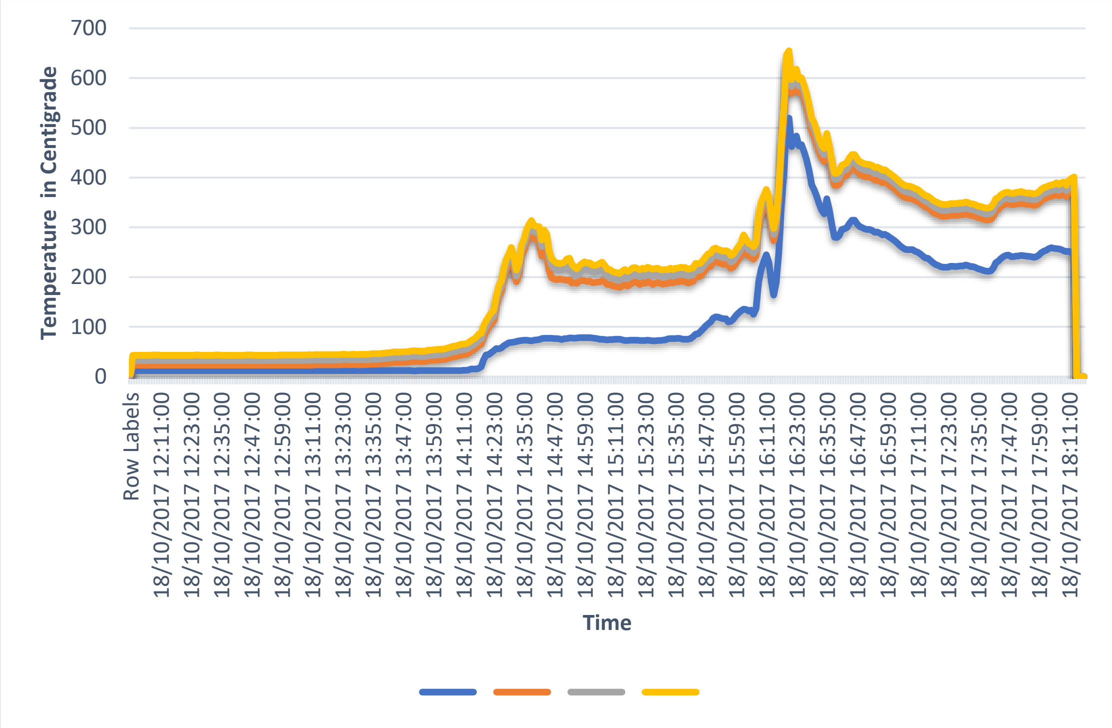


Figure 78: Test No 19 (table 2) thermocouple data through a central vertical line taken through the middle

This fire behaviour is typical of semi-permeable fuel beds of piled material. Impermeable and semi-permeable share a similar behaviour when subject to an ignition at the surface of the fuel bed. But if the point of ignition is deep seated a semi-permeable fuel bed will generate and intense fire that has a steady state heat release rate which is at the peak for that material and the fire will be fuel controlled.

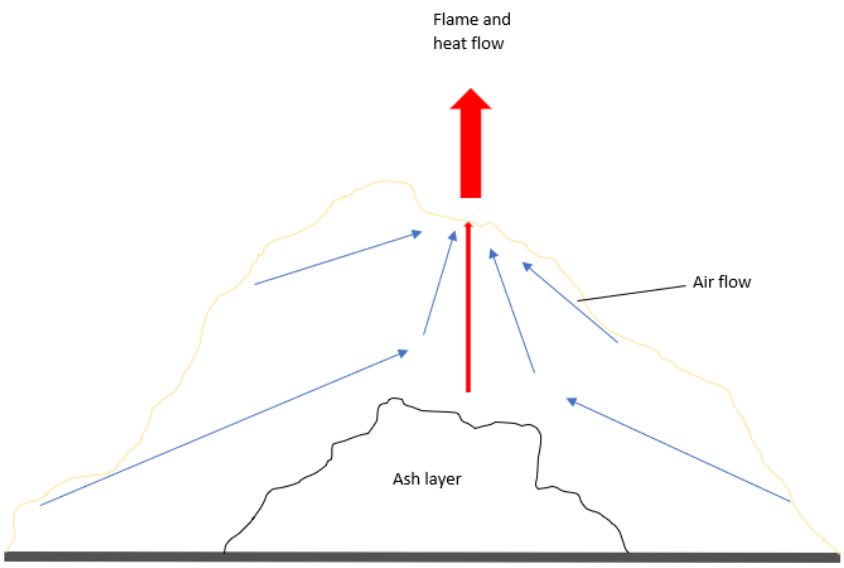


Figure 79: theoretical model for semi-permeable deep seated fires

7.2 Section 3.2.25 (a) & (b) RDF

7.2.1 Deep seated test method 2.

Following the pre-crushed timber test described in section 7.2.5 above. The test method was refined. A diamond core 115 mm wide was drilled in the rear wall. The height of the hole varied slightly between the middle bay and the right hand bay. Legio block are 800mm x 800mm x 1600mm and weight 2320Kg.

Figure 80: test 25 a & b (table 2) rear wall

The middle bay hole was drilled at 100mm hole centre from the floor. The right bay hole caused the block to crack so the hole was not taken all the way through the block. A second hole was drilled though the block at 500mm hole centre.

The test rig was constructed on a second world war bomber air base runway. The original design was for a four bay bunker 5 m high, but this was reduced to 3 bays at 4 m high after reviewing a structural engineer report on the runway construction. However, the surface of the runway did show signs of failure. Fortunately, after two weeks this settled, and the tests were allowed to proceed. It was apparent that the bottom line of blocks was under strain. Therefore, to avoid the possibility of the block failing the decision was made to drill the hole further up the block. A smaller hole was drilled towards the top of the pile. All the Freeland Scientific (82) thermocouple strings were fed in through this hole on the basis that they were likely to survived for longer in this location as they had a maximum design range of 110^{0}c. An array of K type thermocouples was threaded through the gaps in the wall which was not sealed. All thermocouple data was collected on data loggers and transferred to computer files (83).

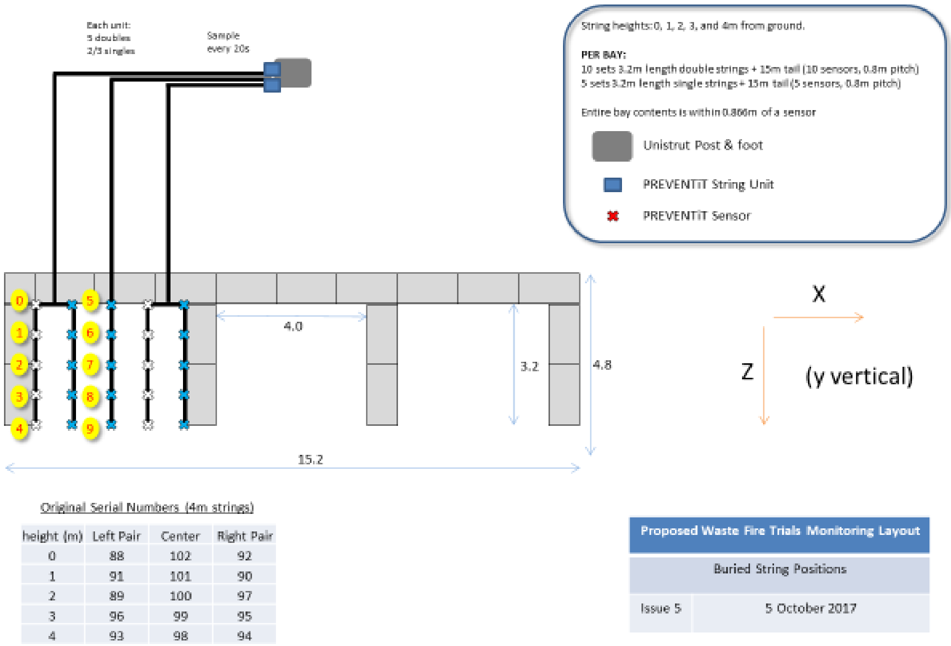


Figure 81: Freeland Scientific thermocouple string location diagram (83)

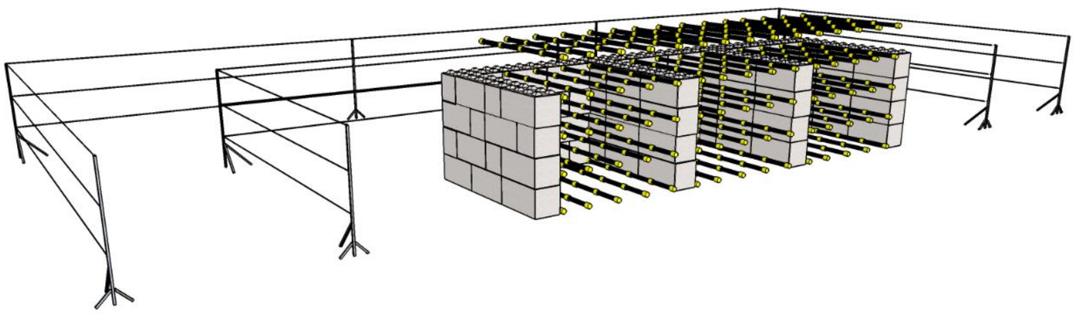


Figure 82: 3D image of the thermocouple strings (83)

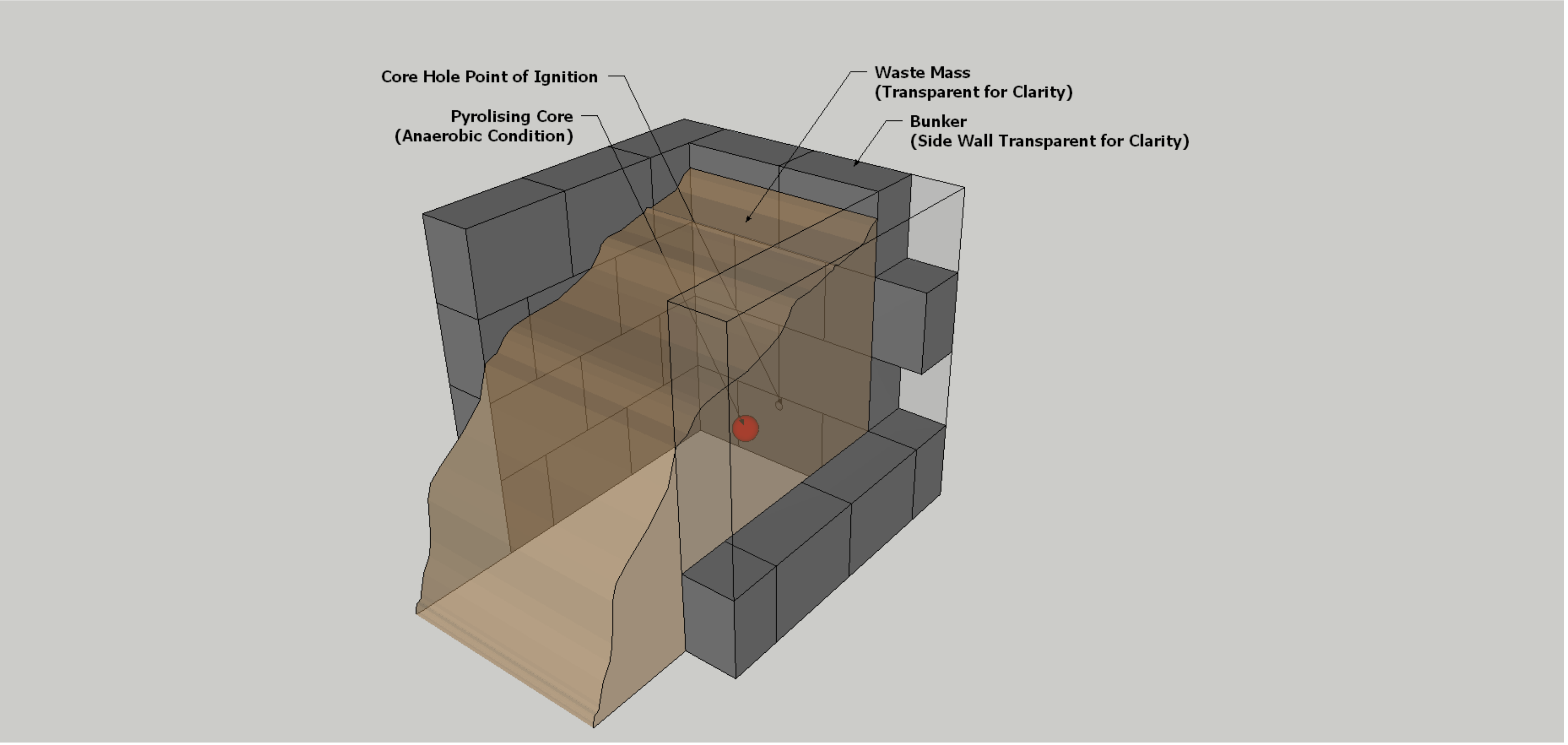
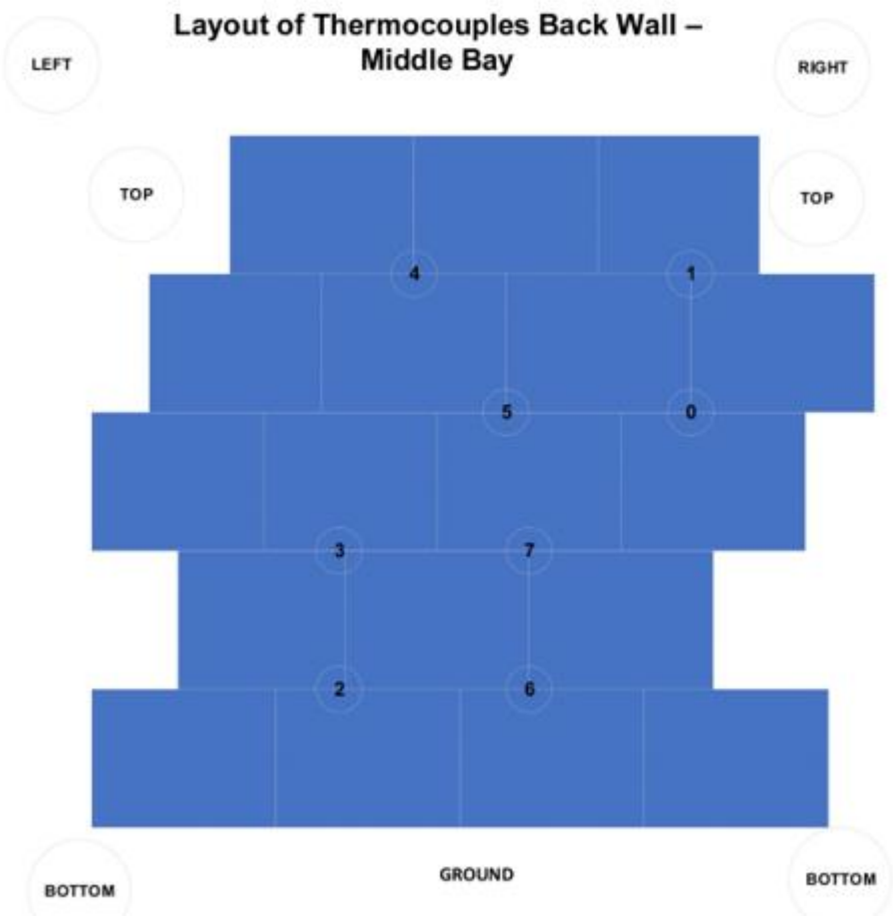
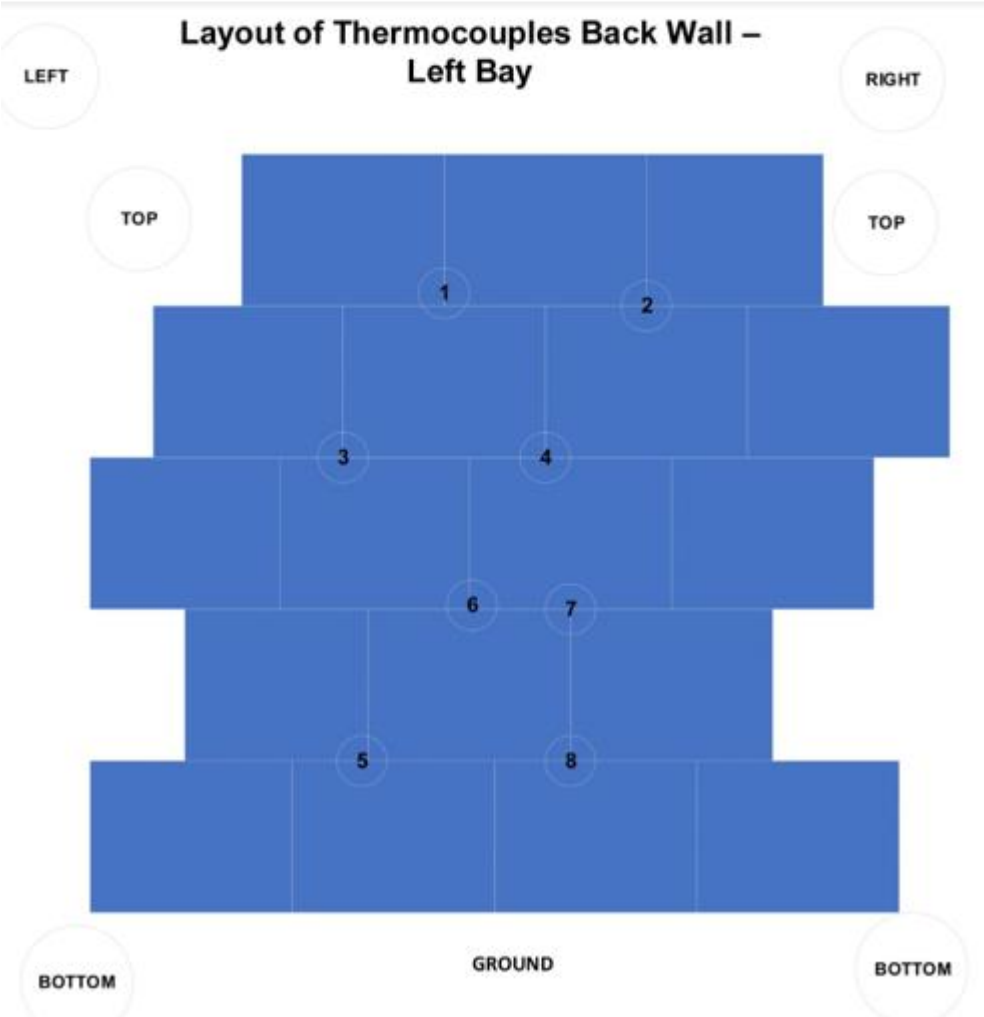


Figure 83: Test 28 (table 2) schematic diagram of test method used on test 25 a & b (drawing by Craig Plested)



Channel	X distance (m)	Y distance (m)	Z distance (m)
0	1.6	2.4	0.2
1	4.0	2.4	0.2
2	2.4	0.8	1.2
3	2.4	1.6	1.2
4	3.2	3.2	0.2
5	2.4	2.4	1.2
6	1.6	0.8	0.2
7	1.6	1.6	0.2

Figure 84: Test No 28b K-type thermocouple locations middle bay (83)



Channel	X distance (m)	Y distance (m)	Z distance (m)
1	2.8	3.2	0.2
2	1.2	3.2	0.2
3	2.4	2.4	1.2
4	1.6	2.4	0.2
5	2.8	0.8	1.2
6	2.4	1.6	0.2
7	1.6	1.6	1.2
8	2	0.8	0.2

Figure 85: Test No 28a K-type thermocouple locations Left Bay (83)

Figure 86: Test No 28(table 2) Setting up the igniter tube for deep seated RDF pile fire

A steel section of tubing was inserted into the wall to a point 500mm from the rear wall. Due to the difficulty in setting the earlier RDF and SRF fires at Barling (phase 2 tests). A small pile of pre-shredded timber was built as a pilot fire for the larger test.

Figure 87: Test No 28 (table 2) Setting a timber pilot fire bed for the RDF fire

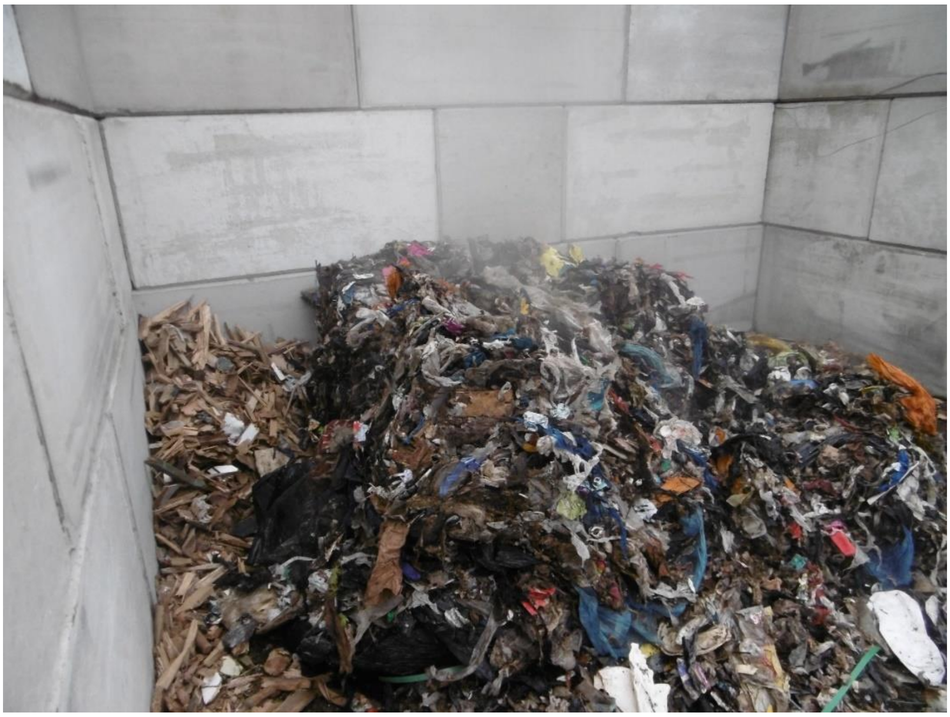


Figure 88: Test No 28 (table 2) layering RDF on the pilot pile

The RDF was plied on to this in layers and the "Preventit" (82) thermocouple strings and K Type thermocouples were positioned as described earlier in this section.

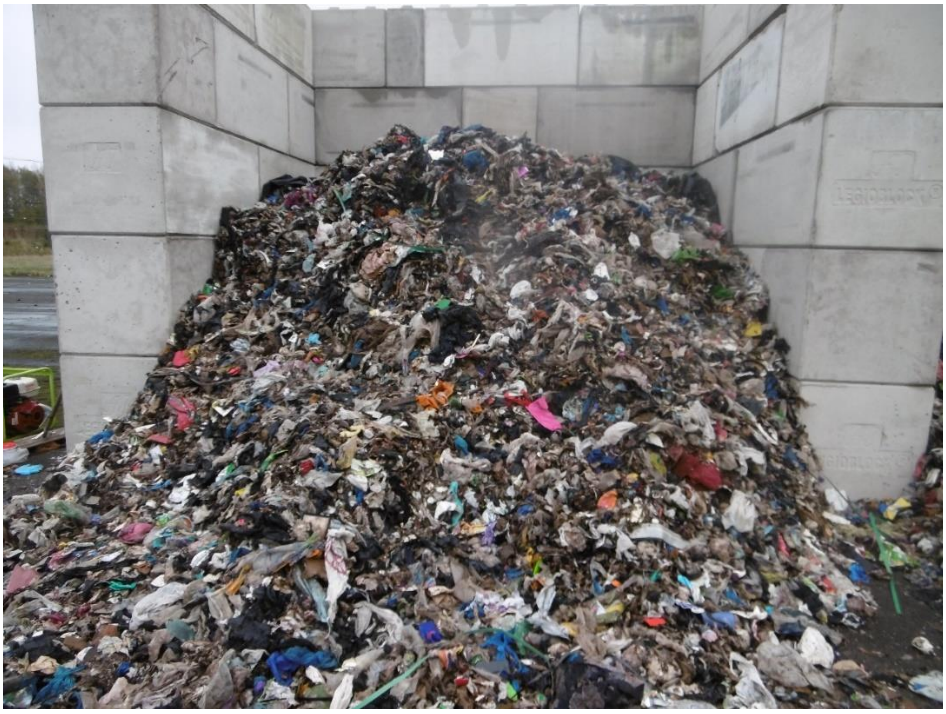


Figure 89: Test No 28b (table 2) deep seated RDF test fire ready to ignite

Figure 90: Oxi-propane lance supplied by Freeland Scientific Ltd (83)

The oxi-propane lance picture in figure 113 above was selected as the ignition method following the deep seated wood test detailed in section 7.2.5.

Figure 91: Pre-setting the flame prior to lighting the test fires

The flame was pre-set to ensure a stable flame and then it was inserted into the rear of the test pile through the steel pipe.

Figure 92: Test No 28a (table 2) middle bay being ignite by Peter Martin

The surfer plots (84) were supplied by the technical support team Preventit thermocouple string data (82). The K type and thermal image data was interpreted by the author base on the data supplied (83). The initial readings taken prior to the commencement of the test reveal how much biological activity was naturally occurring in RDF. Temperature of up to 80^0c were observed. However, these temperatures quickly receded. Observation of the mass prior to the start of the test and the results of test 3.2.18 indicate that basket testing was not a reliable indicator or self-heating fires. From these large scales test it was found that one of the critical factors was the water (moisture) content of the material. For a pile to generate a fire due to self-heating the water content must be reduced significantly for the initial condition. However, without a significant water content the biological action is suppressed. To Ignite these test fires the oxi-propane lance had to be left in place for 20 minutes. A considerable amount of steam was observed to be driven off before the material would sustain pyrolysis process. That said there are clearly examples of biologically driven self-heating fires (4)(6). The subject of self-heating is addressed in the literature review and section 6 to this thesis, repeated test conducted during this test series only served to define the lack of understanding in these areas and can be summarised as a knowledge gap between biological action taking the plie to 80^0c and known chemical oxidizing reactions that require a temperature of 150^0c to 400^0c to activate.

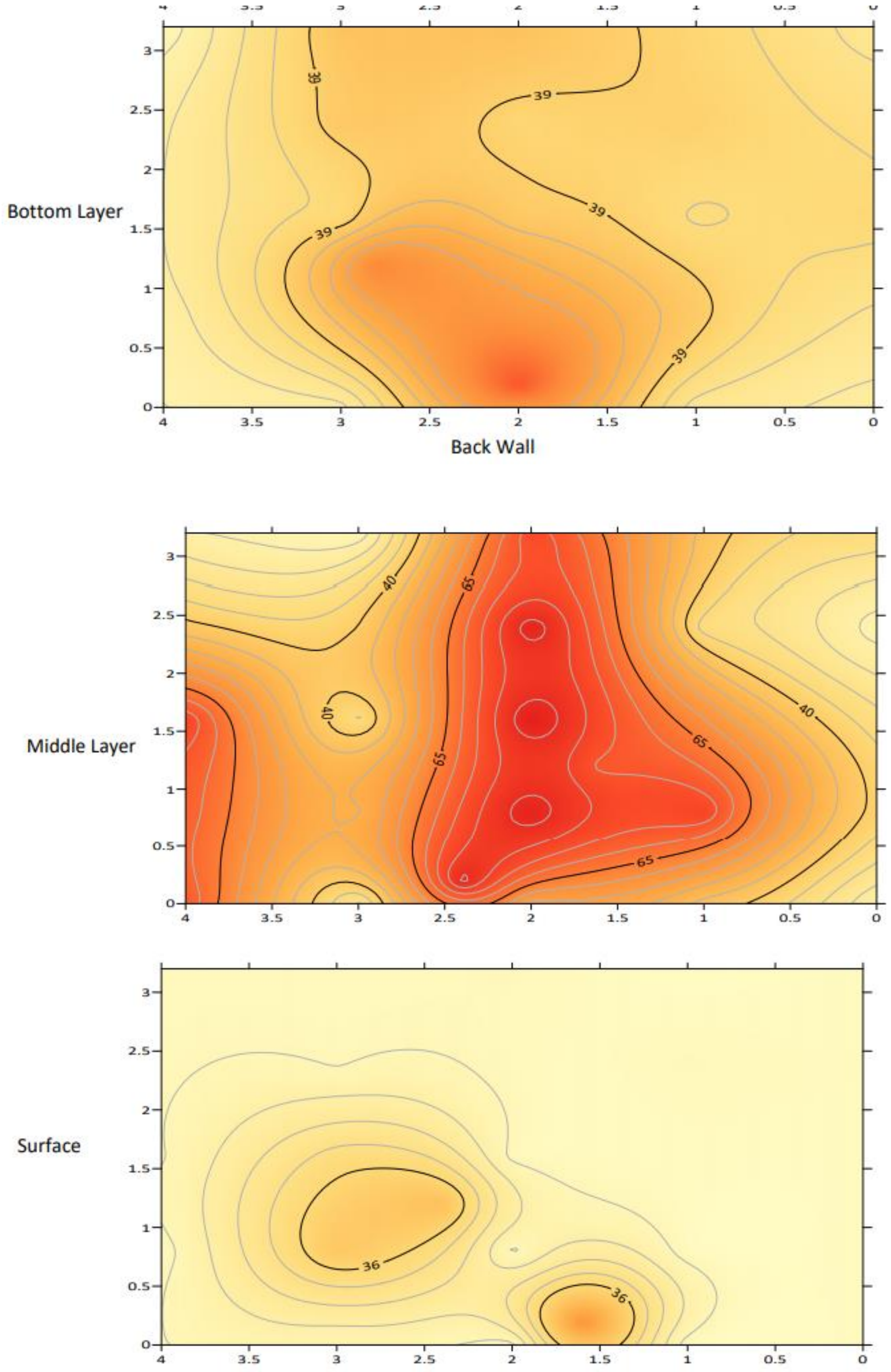


Figure 93: Test 28b (table 2) Pre fire test data (84)

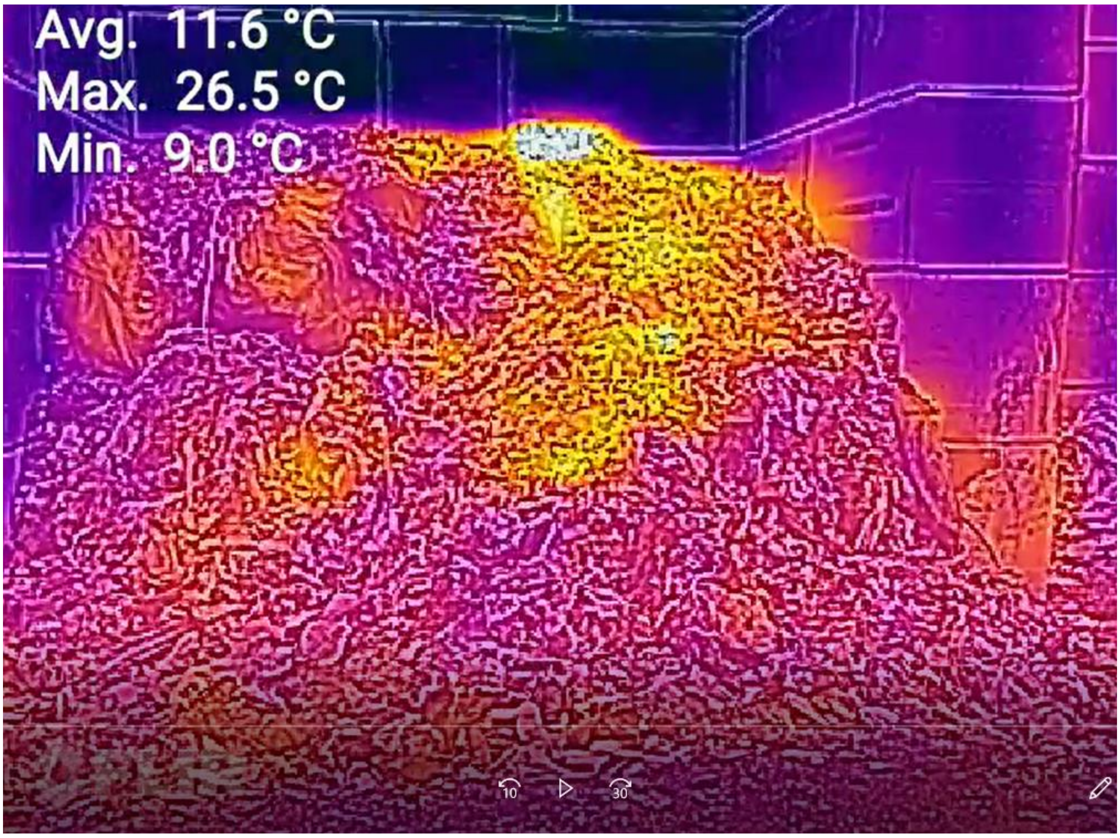


Figure 94: Test 28b (table 2) thermal image camera (77) photo pre fire test

The surfer plots for the left bay have been provided at three intervals. The surfer plot program has limitations which are revealed when the K type thermocouple data was plotted on the surfer plots alongside the string data (82) see table 12 and figures 94,95 & 96. The surfer plot program assumes a linear heat transfer rate and therefore, connects common temperature reading and represents these as thermal boundaries. However, waste materials such as RDF are biologically very active and the hot spots cannot, therefore, be assumed to be related to pyritization processes.

Thermocouple No.	Colour on the plan	Temperature ^{0}c
1	Pink	15.3
2	green	15.1
4	purple	60.2
6	black	86.1
8	blue	96.1

Table 12: K type thermocouple data Test 28b (Table 2)

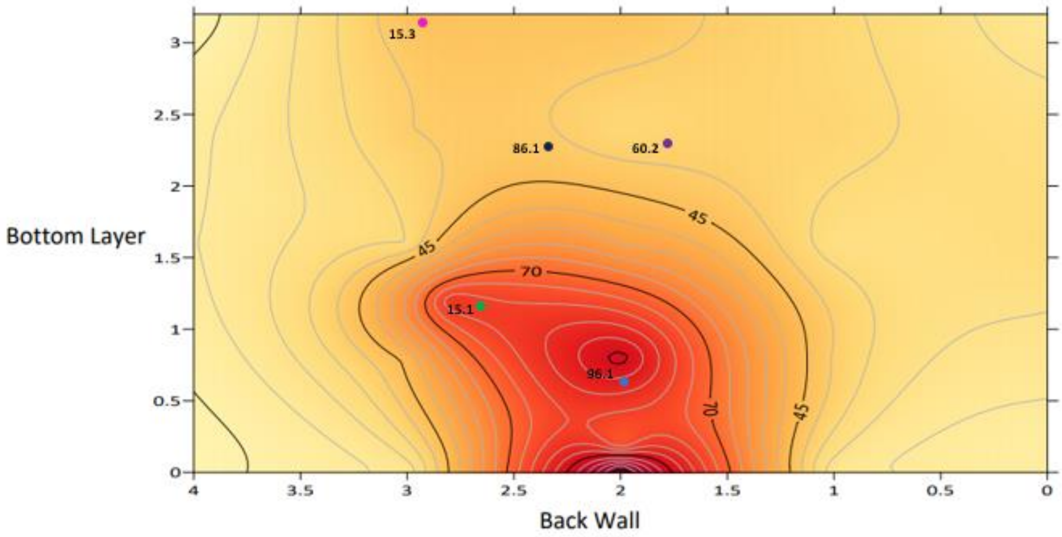


Figure 95: Test No 28b (Table 2) surfer plot of left hand side bay with K type data overlay 14:30

The most reliable indicator of the fire was thermocouple 8 which was adjacent to and slightly (150mm approx.) below the ignition point.

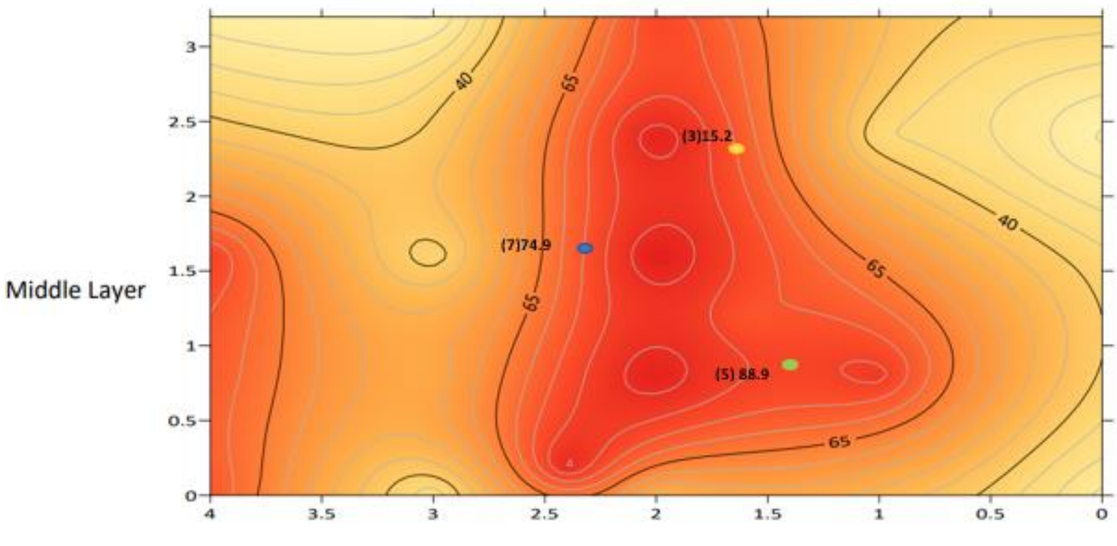


Figure 96: Test No 28b (Table 2) surfer plot left hand side bay with K type data overlay middle section 14:30

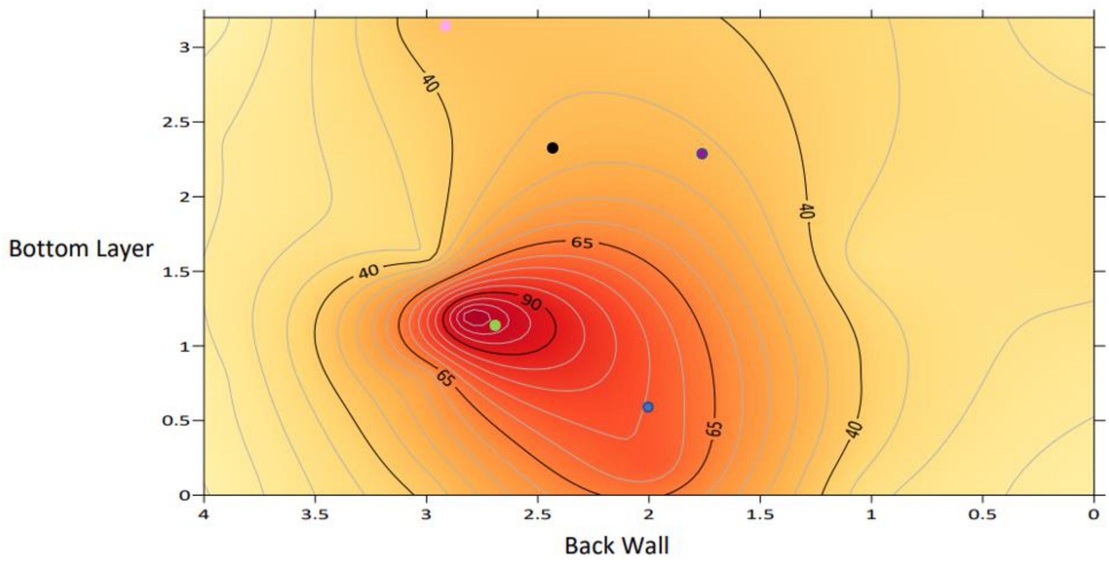


Figure 97: Test No 28b (Table 2) Left hand bottom surfer plot 17:30 with k type overlay

Thermocouple No.	Colour on the plan	Temperature ^{0}c
1	Pink	15.69
2	green	19.2
4	purple	19.39
6	black	43.59
8	blue	100.69

Table 13: Test 28b (table 2) bottom surfer plot table 17:30

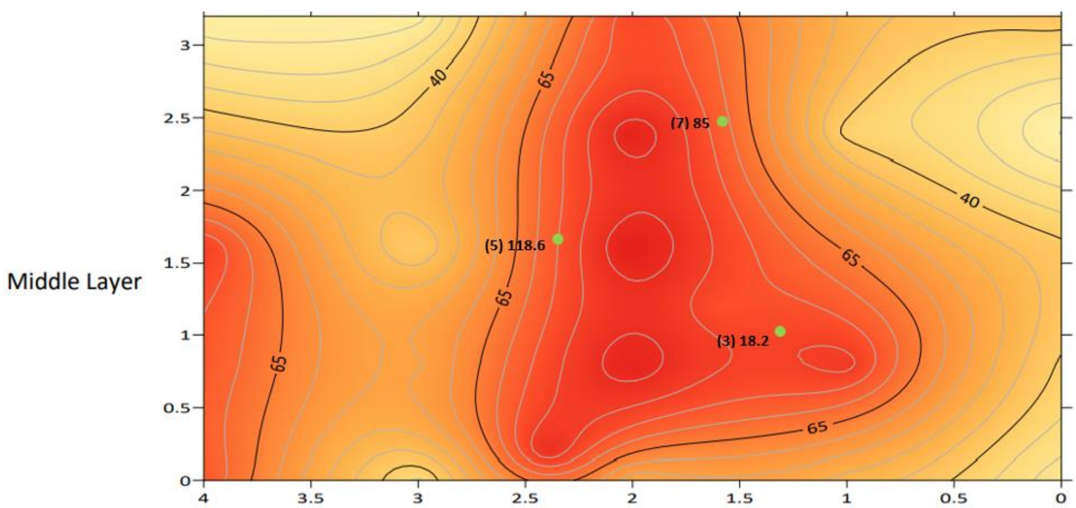


Figure 98: Test 28b (table 2) surfer plots taken at 17:30 with k type over lay

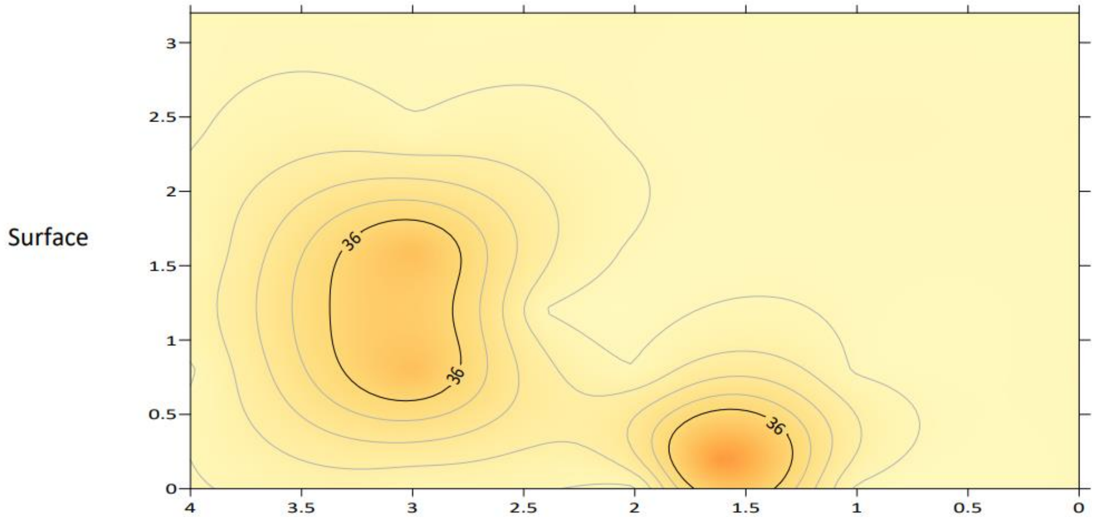


Figure 99: Test 28b (table 2) surfer plot left hand bay 17:30

Unfortunately, this examination of the surfer plots demonstrates that, this modelling software was unreliable for this application. It was, therefore, necessary to examine the raw data and build up a picture of the pyrolysis process manually. This arrangement of the data can be found in Appendix B. For illustrative purposes the data has been plotted using OriginPro software (85) as this software seemed less susceptible to this problem. As this illustrates general trends. Once it was accepted that the software like the earlier software averaged the profiles and therefore, introduced errors it can be observed that it is useful for demonstrating general trends

7.2.2 Left hand bay analysis of data

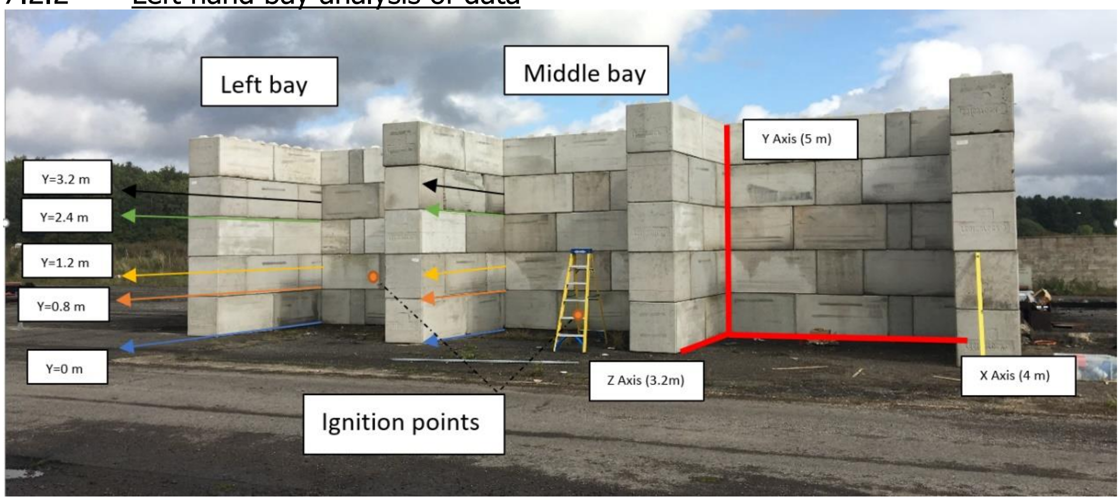


Figure 100 : Bay layouts

All the following data slices are configured as detailed in figure 83. The slices heights are expressed as the initial heights when originally set up. The bays were set up one week prior to the tests and as a result there was some settlement of the pile. The raw data was presented with the Y access representing height due to the volume of data configured in this way all the data was presented using the axis as detained in figure 99 above. . The data in Appendix B for the left-hand bay has been synchronised and expressed in seconds from the common point at which the data collection started. A period of approximately 24 hours has been analysed although data was collected for around 48 hours. The oxi-propane lance was inserted to light the fire at around 1000 s. It was clearly evident that the waste material exhibited areas of biological self-heating. The pile in reality consisted of two piles. Firstly, the timber with a moisture content of less than 20% see Figure 110. This was used as a pilot for the larger RDF piled on top of it. The RDF had an average moisture content closer to 35% but this was randomly distributed through the pile. From earlier testing the previous year it was evident that generating a self-sustaining fire in this material presented significant challenges.

Test 28 b temperature slices through the pile at 500 seconds (prior to ignition) figures 100, 101 and 102 should be viewed together

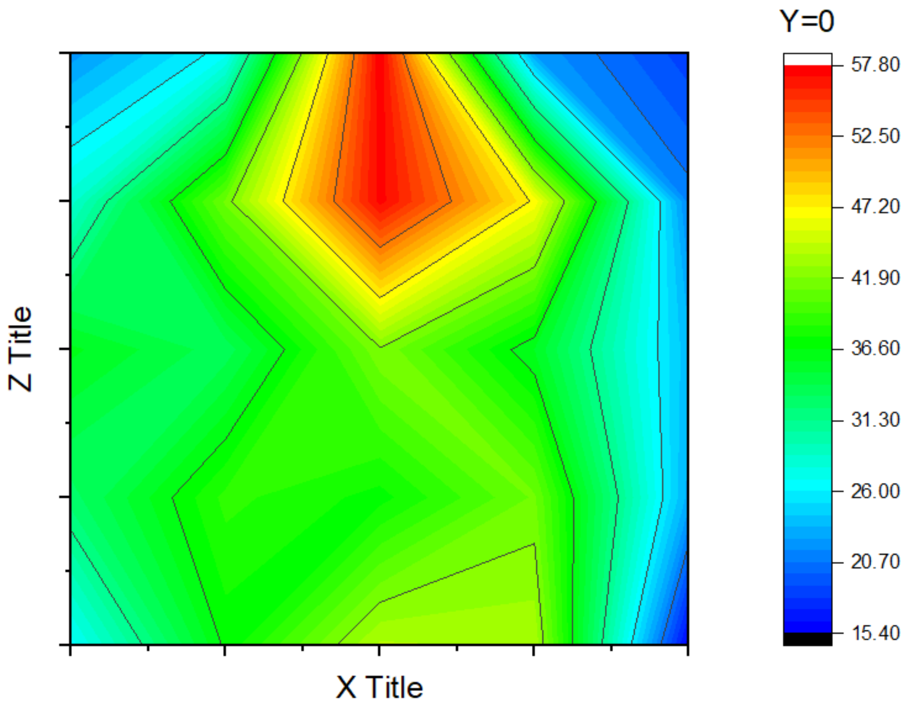


Figure 101: Test 28b (table 2) at Y= 0 at 500 seconds

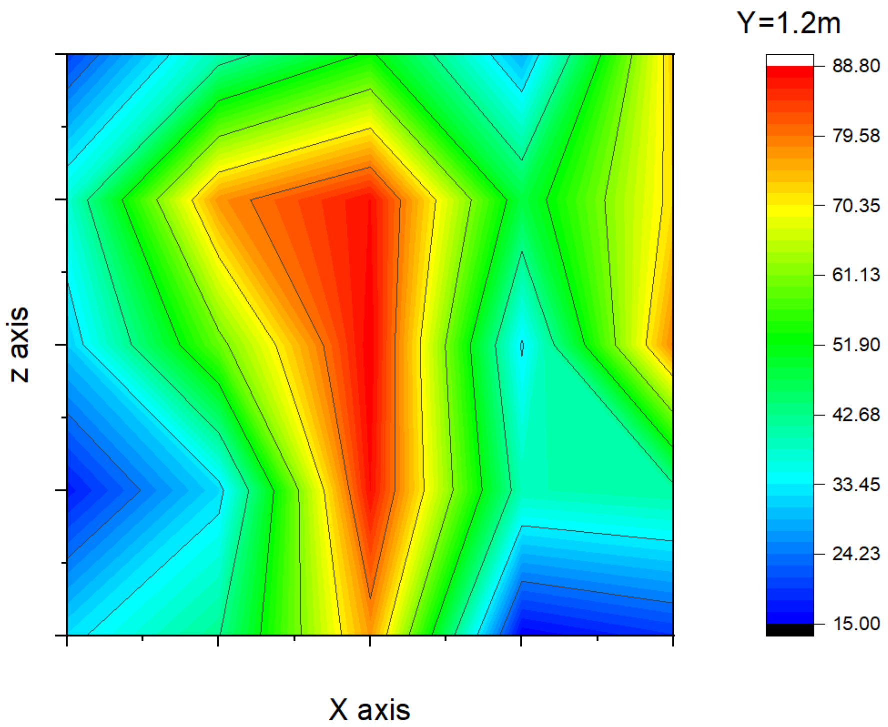


Figure 102: Test 28b (table 2) at 1.2 m at 500 seconds

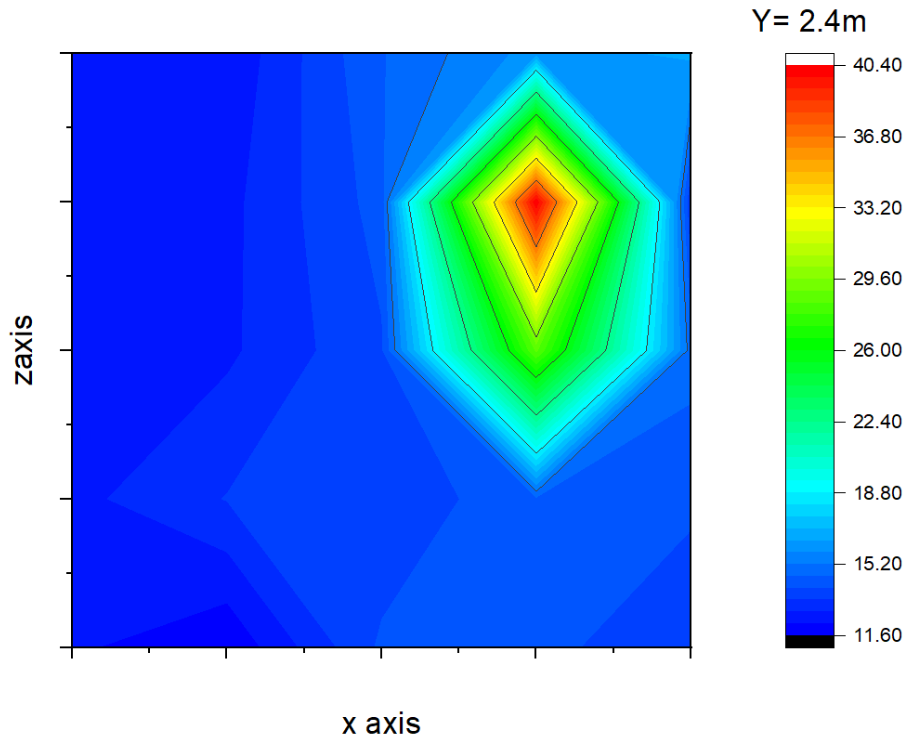


Figure 103: Test 28b (Table 2) Left hand Bay at 2.4 m at 500s

It can be seen from these slices that the biology of the material had generated significant temperatures. It was observed that the highest temperatures were generated in the wettest zones, and this accounts for the constant emissions of steam from the pile. This is typical of an RDF pile.

At 980 seconds as the pile was being ignited the temperature profile was largely unchanged with some minor increase in temperature at 2.4 m (approximately 0.8 m from the surface). At Y=0 it was apparent that the wood element was cooling slightly at this point, although not significantly.

Test 28 b temperature slices through the pile at 980 seconds figures 103, 104 and 105 should be viewed together.

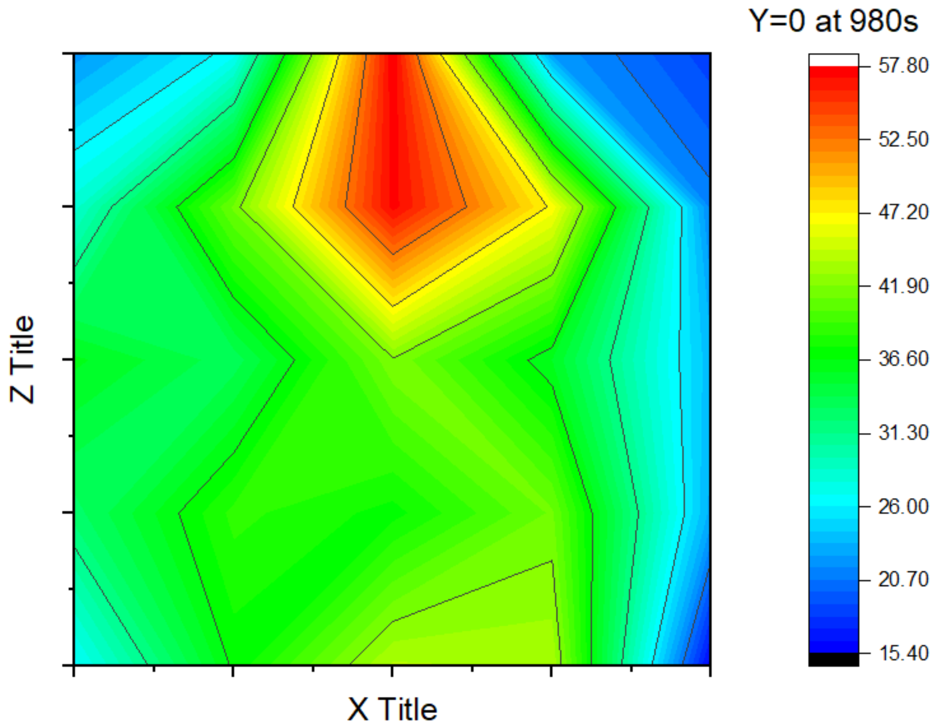


Figure 104: Test 28b (table 2) left bay at Y=0 at 980 s

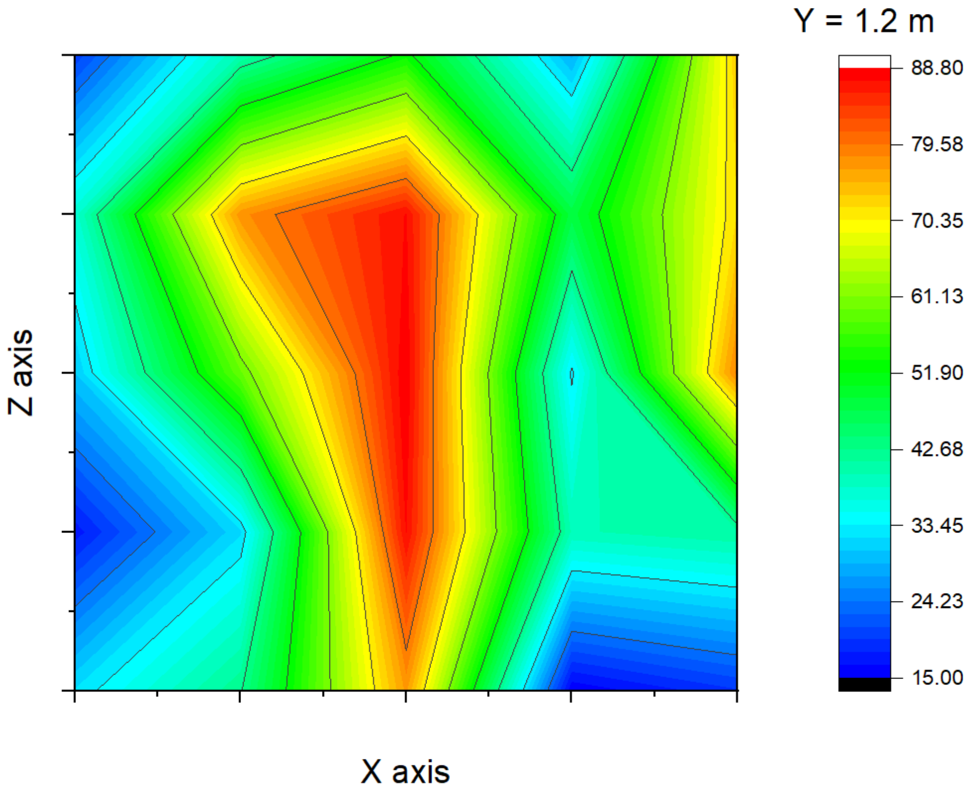


Figure 105: Test 28b (Table 2) at 1.2m at 980 s

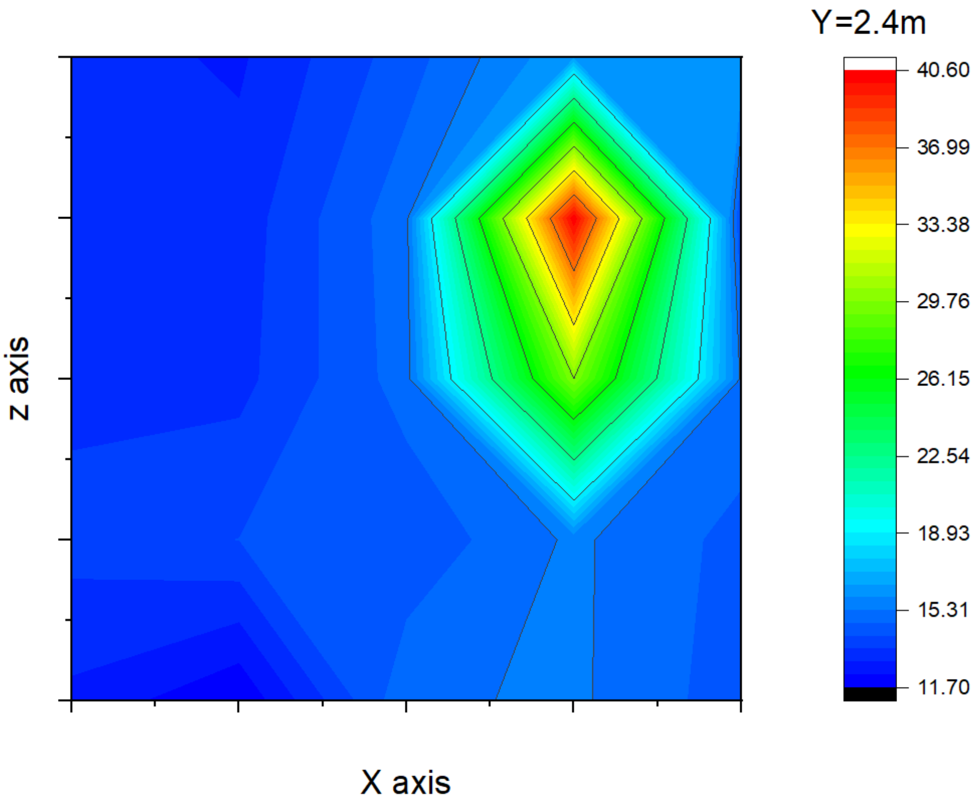


Figure 106: Test 28b (Table 2) at 2.4 m at 980 s

Test 28 b temperature slices through the pile at 11100 seconds figures 106, 107 and 108 should be viewed together.

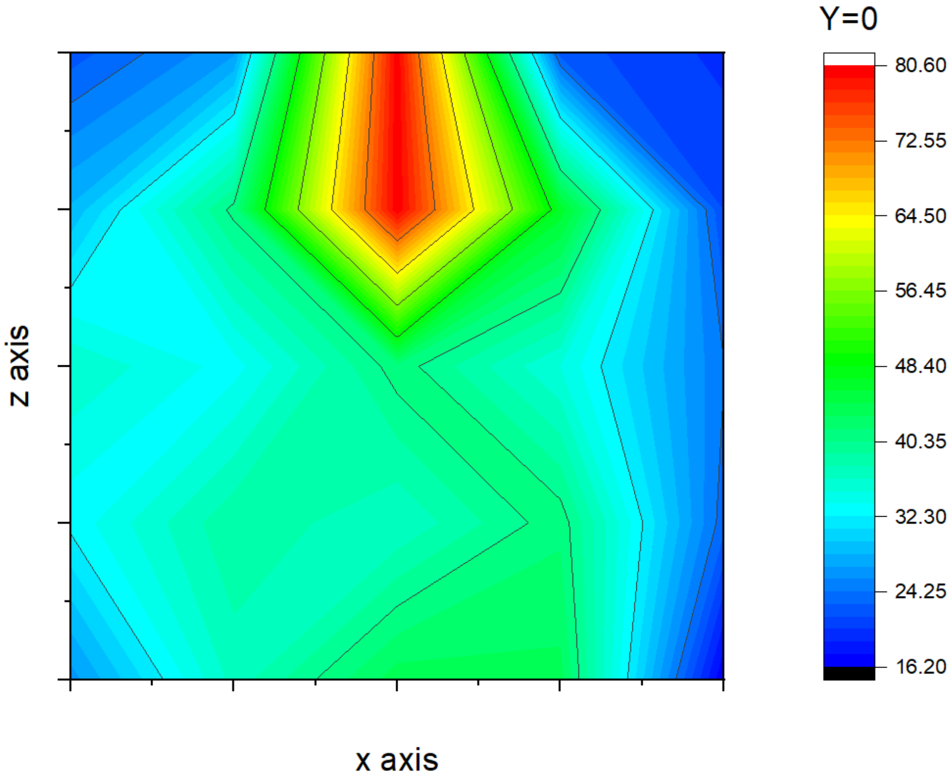


Figure 107: Test No 28b (table 2) a Y=0m at 11100 s

The lance was applied for 20 minutes and by this point the "fire" was self-sustaining. Unsurprisingly 200mm below the point of ignition the temperature rise in the timber was recorded. Although no apparent pattern of heating was obvious at 1.2 m some 0.9 m above the point of ignition.

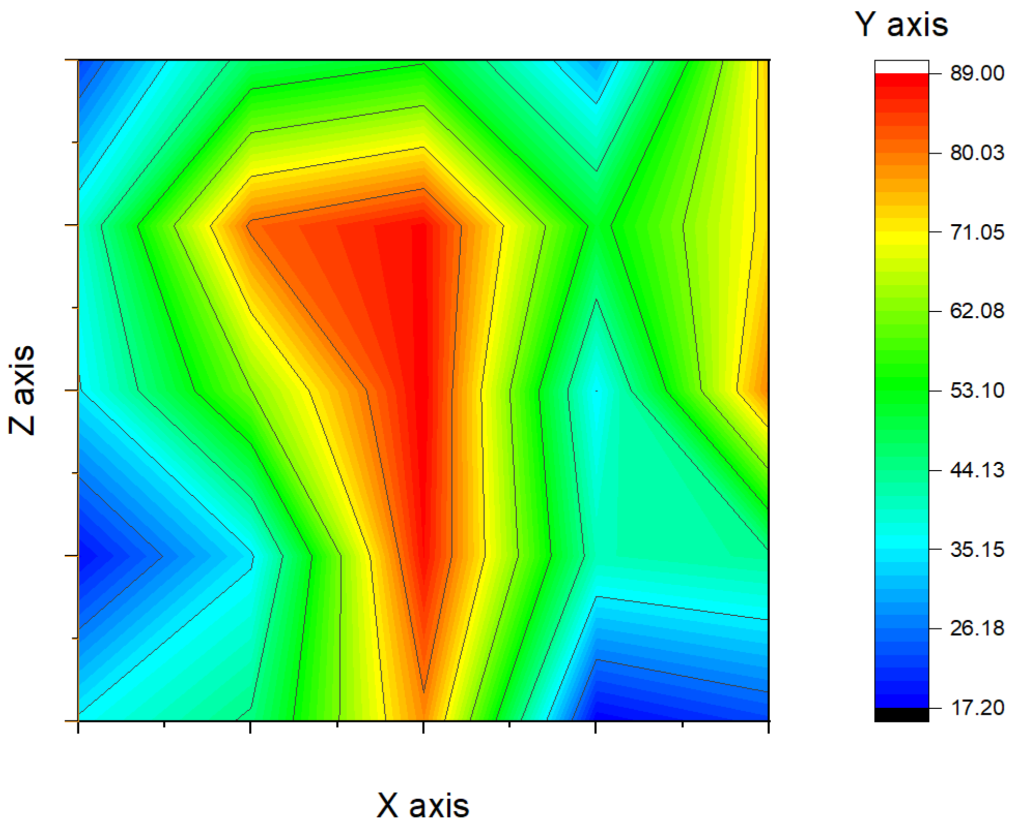


Figure 108: Test No 28b (table 2) at 1.2 m at 11100 s

Some continued heating was apparent at 2.4 m. This, however, continues a trend that started prior to the start of the test was most likely the result of biological self-heating

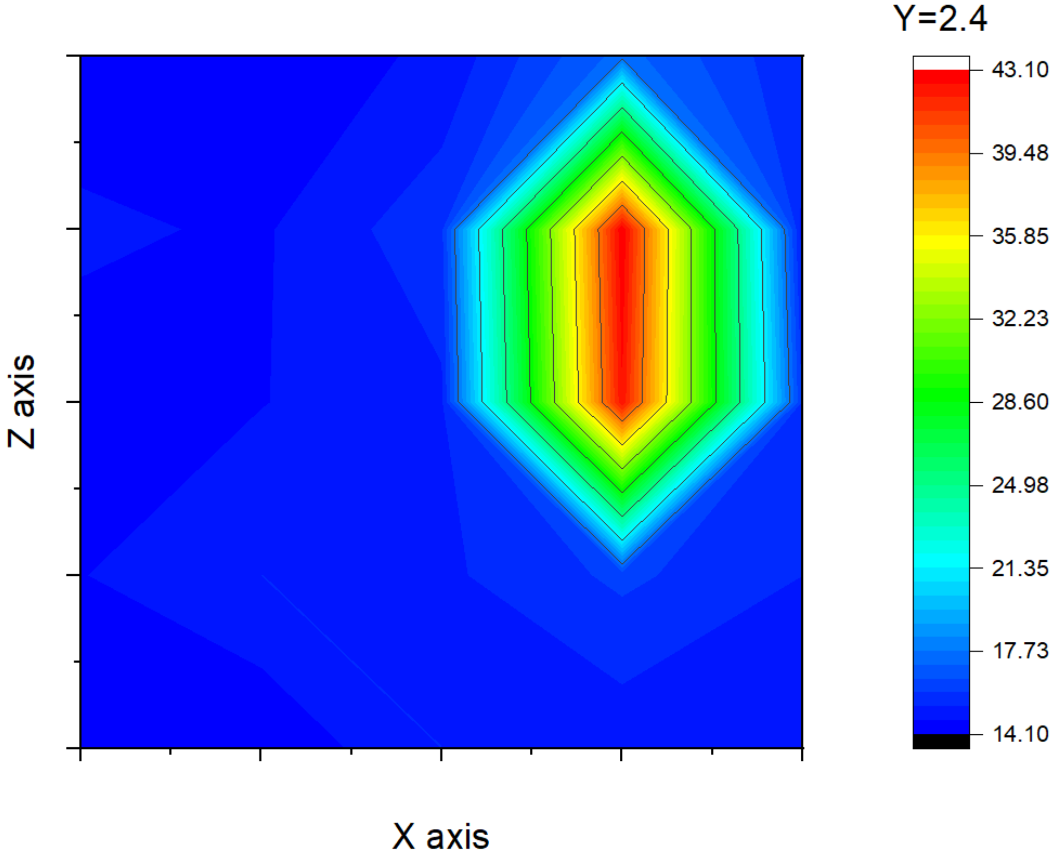


Figure 109: Test No 28b (table 2) at 2.4 m at 11100 s

Test 28 b temperature slices through the pile at 14400 seconds figures 109, 110 and 111 should be viewed together.

At Y=0 It was very apparent that the pyrolysis process was progressing through the timber in all directions. Which it to be expected it was noted however, that the was a clear boundary at the point at which the two materials meet. As stated earlier the moisture content was very different between the two materials and this can be seen to significantly hinder the progression of the pyrolysis front into the RDF. At this point in time there was no apparent impact on the temperature profile at either 1.2 m or 2.4 m slices.

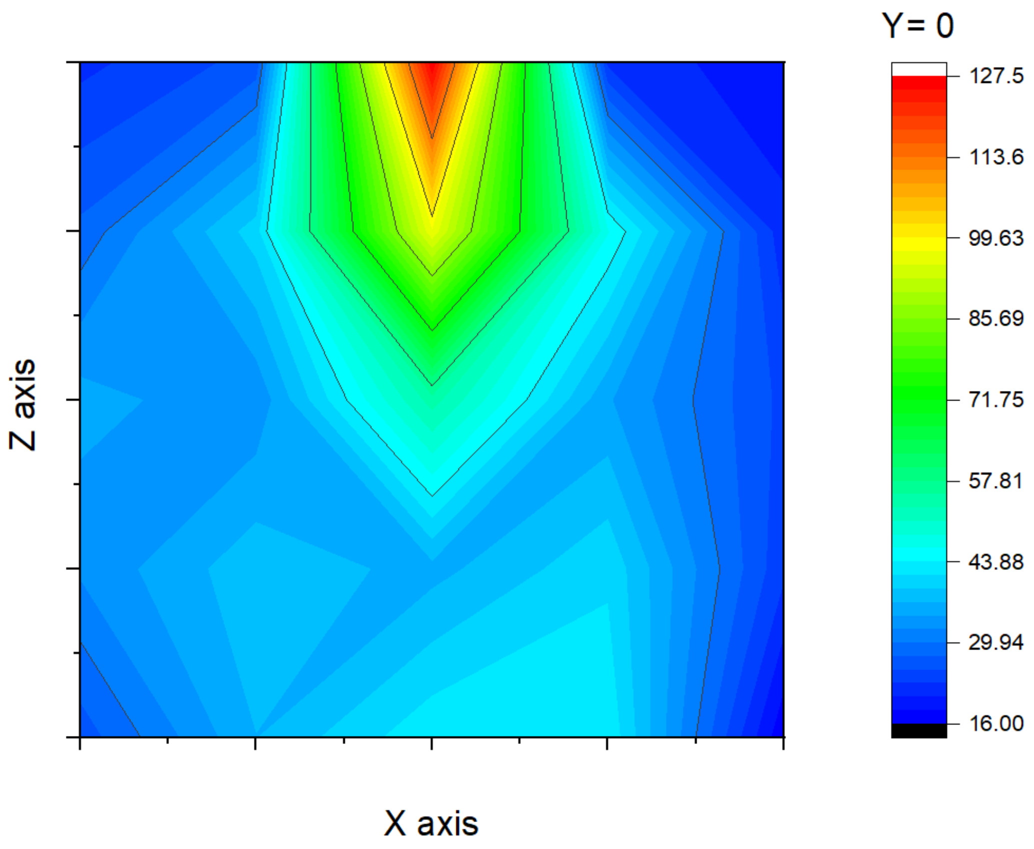


Figure 110: Test No 28b (table 2) at Y-0 at 14400s

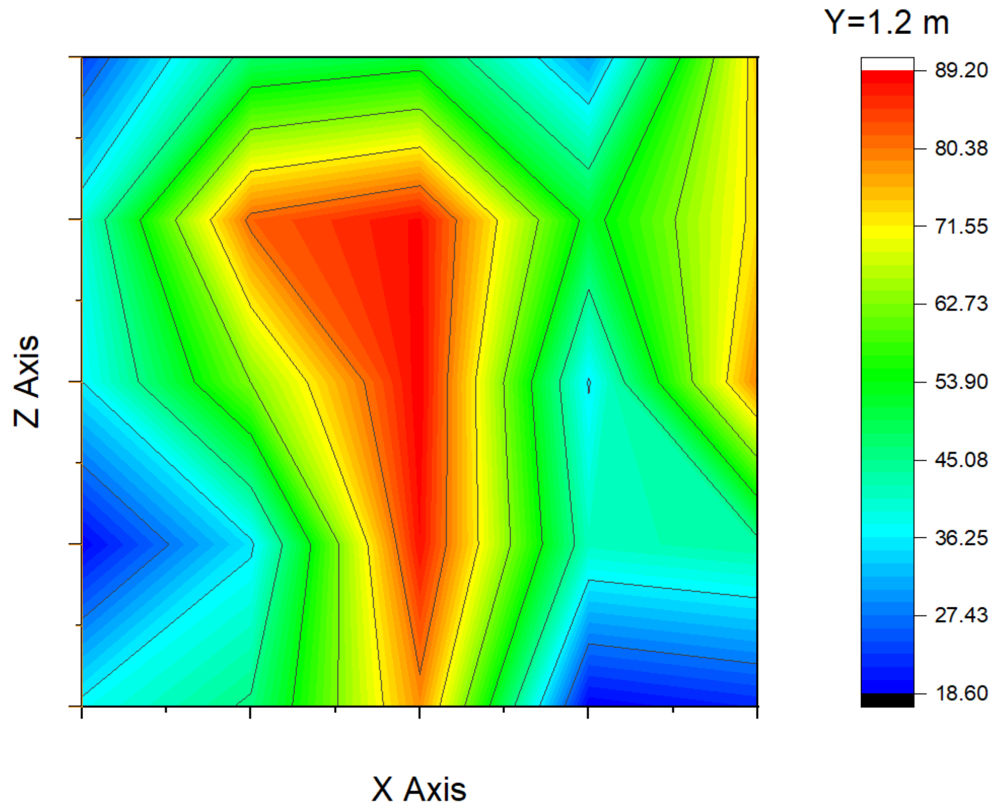


Figure 111: Test No 28b (table 2) at 12.m at 14400s

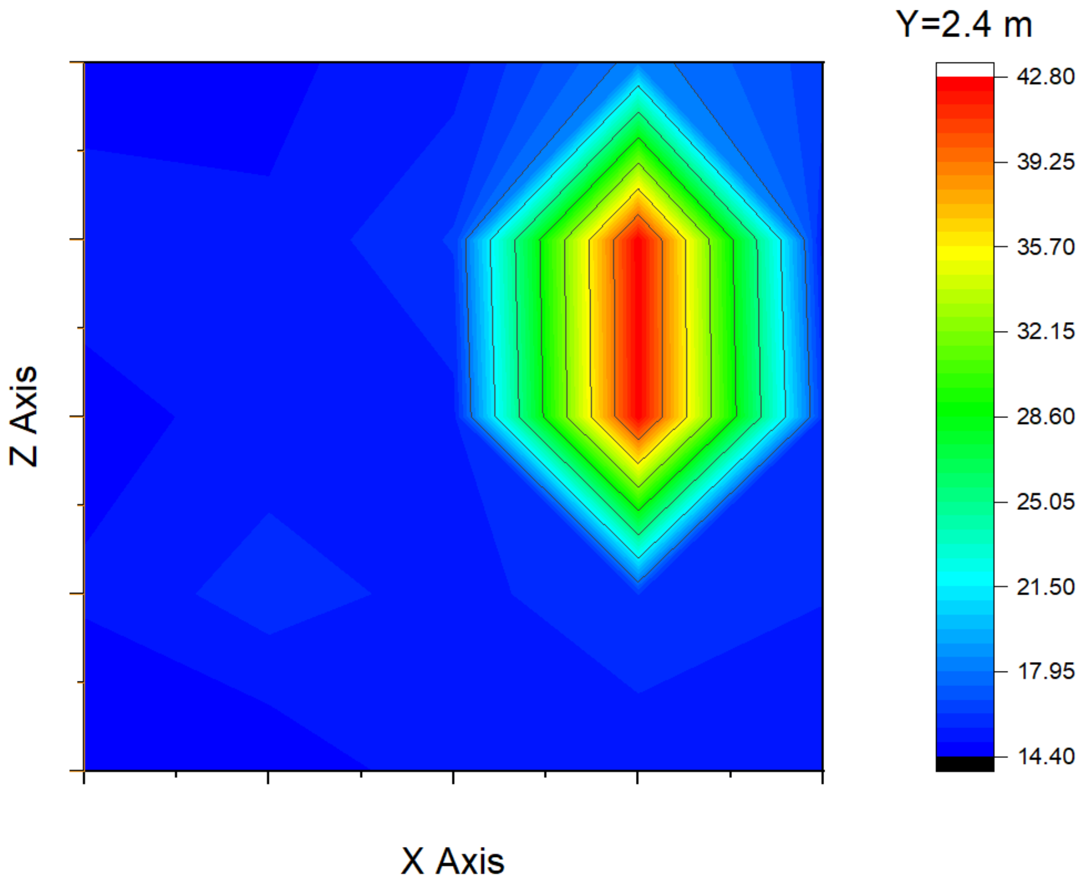


Figure 112: Test No 28b (table 2) at 2.4m at 14400s

Test 28 b temperature slices through the pile at 14760 seconds figures 112, 113 and 114 should be viewed together.

This was the last point at which that purely OriginPro plots (85) will be examined. Beyond this point the pyrolysis front begins to disable the thermocouple strings. The software (85) did not produce good quality plots without this data. From this point the individual thermocouple readings from the remaining strings and the K type thermo-couple readings will be represented in the same way. At 14760 (1 hour 20 minutes from the introduction of the flame), it was apparent that the progress of the pyrolysis front was extremely slow.

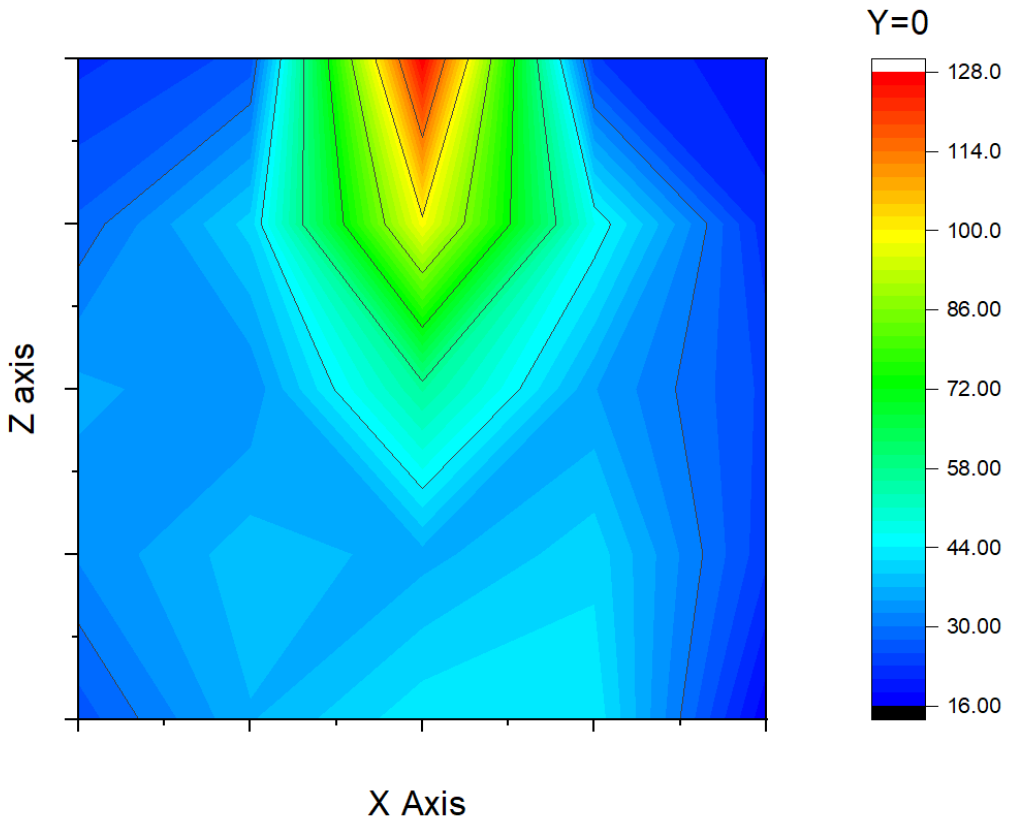


Figure 113: Test No 28b (table 2) at Y=0 at 14760s

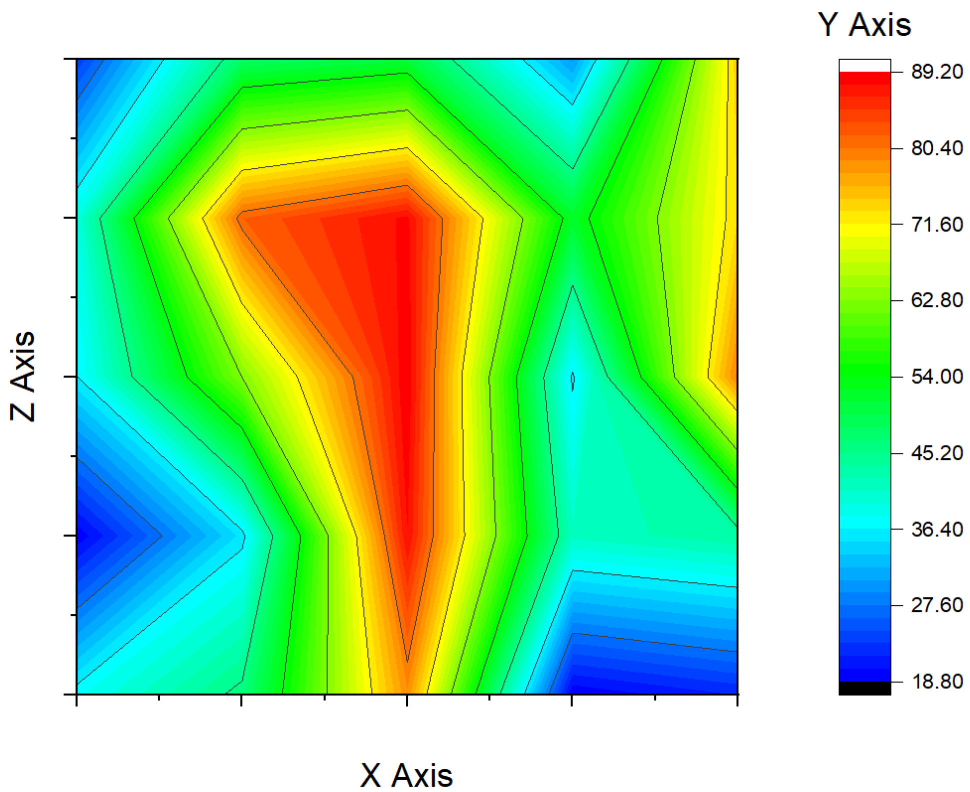


Figure 114: Test No 28b (table2) at 1.2 m at 14760s

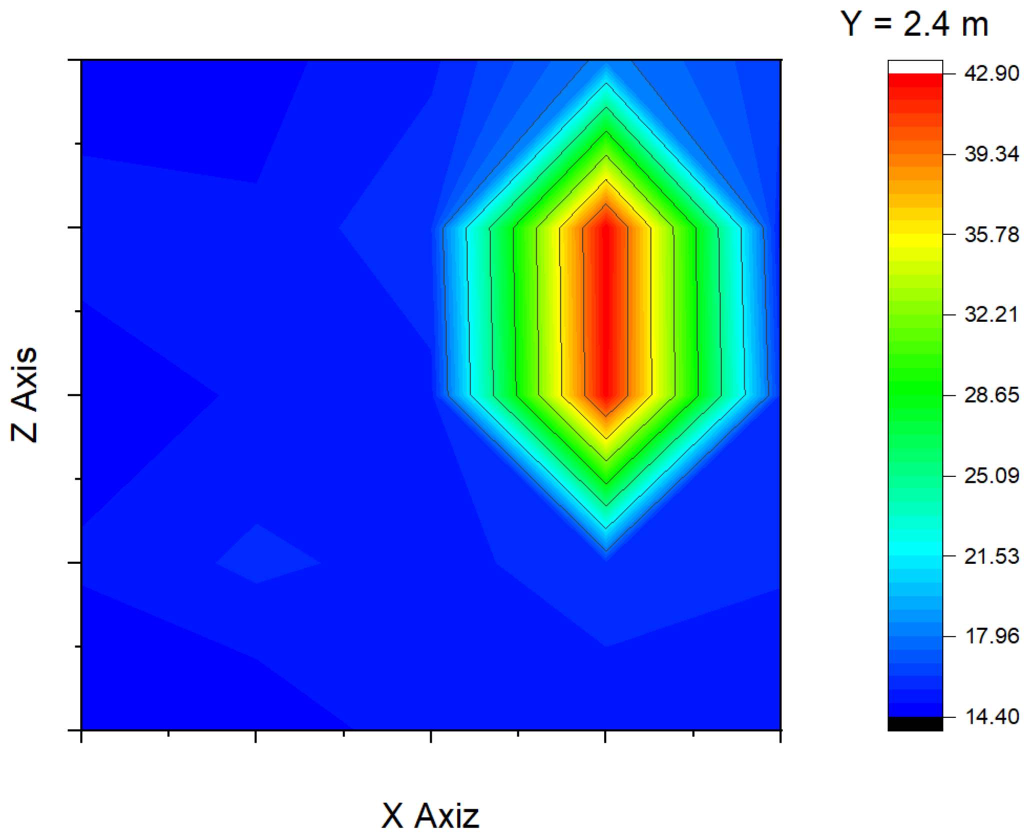


Figure 115 Test No 28b (table 2) at 2.4 m at 14760 s

Test 28 b temperature slices through the pile at 30000 seconds figures 115, 116,117,118 and 119 should be viewed together.

By 30000 seconds the K Type thermocouple at 0.8m plain some 0.5 m above the point of ignition was showing a consistent level of heating which can only be associated with the progression of the pyrolysis front. This thermocouple was located within the layer of RDF above the wood material and indicates significant eating of the RDF for the first time. Just over 5 and half hours after the start of the test. It was clear that at this point the water have been driven out of this material. Some lateral heating was observed at Y=0. The slices at 1.2m, 2.4m and for the first time surface readings at 3.2m are all apparently unaffected in terms of temperature profile at this point.

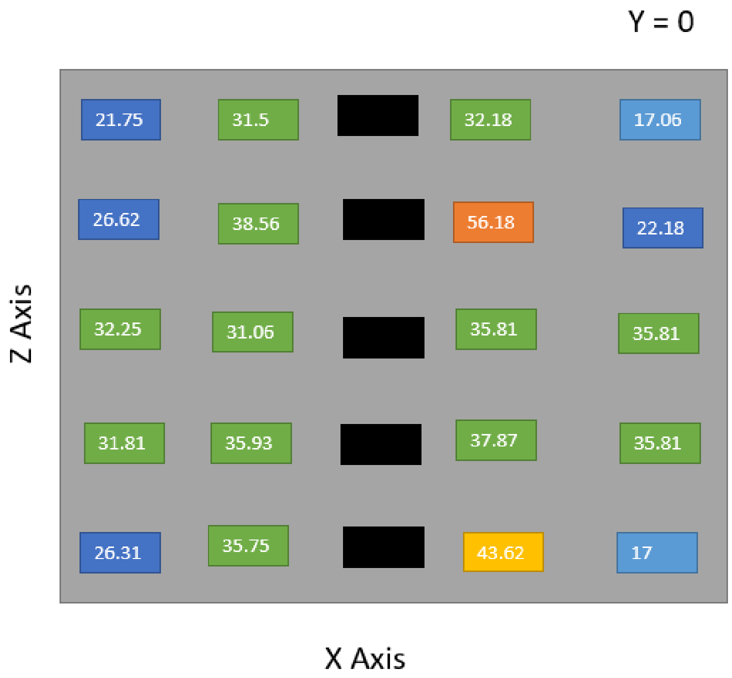


Figure 116: Test No 28b (table 2) Y=0 at 30000s

At this point the middle string of thermocouples has failed. Given the earlier reading it is unlikely that all these thermocouples have exceeded 130^0c, therefore, the most likely explanation is that the developing fire has burnt through the cable feeding this string close to the main core of the fire approximately 500mm above this level.

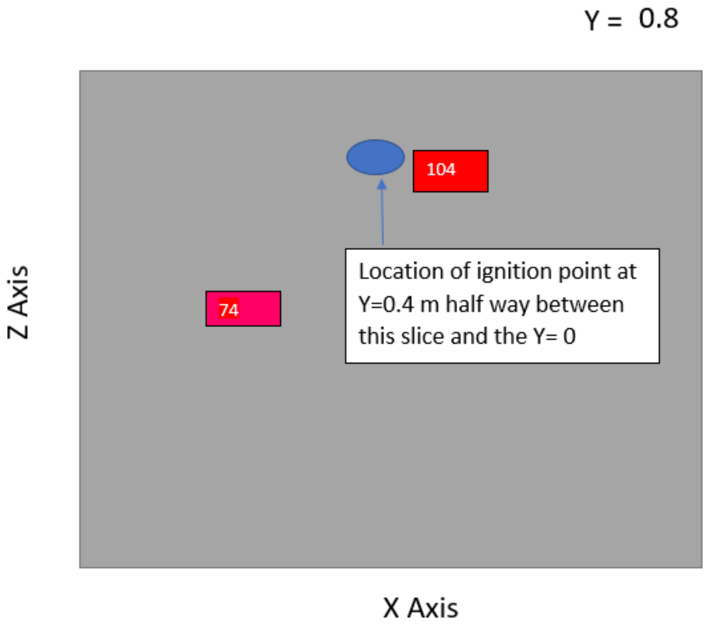


Figure 117: Test No 28b (table 2) at 0.8 m at 30000 s

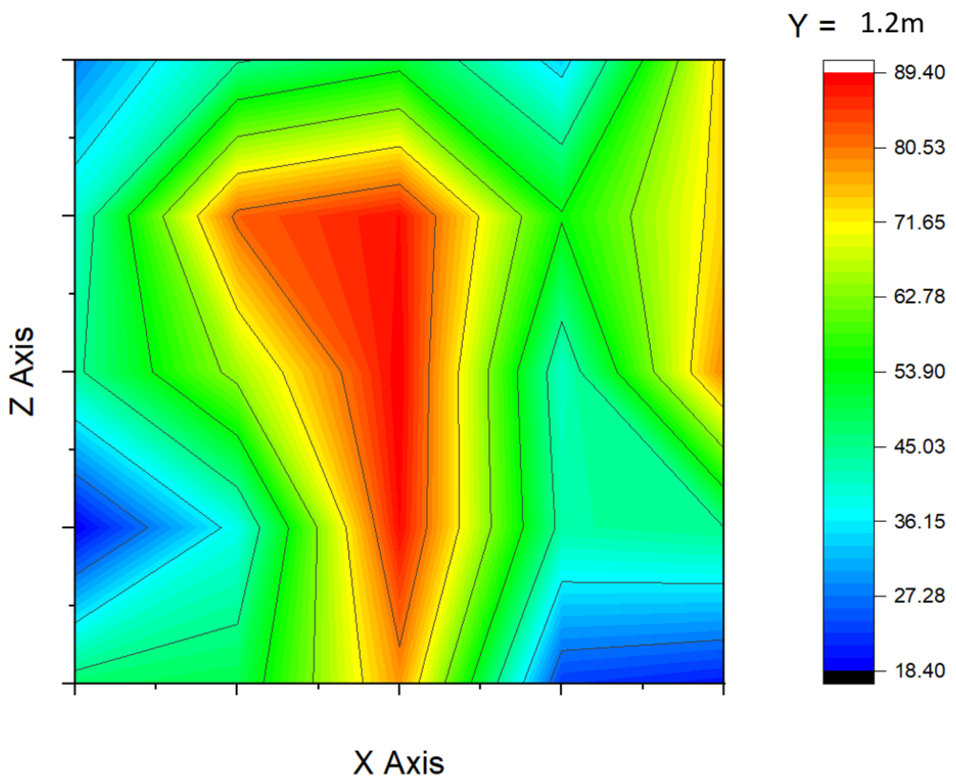


Figure 118: Test No 28b (table 2) at 1.2 m at 30000s

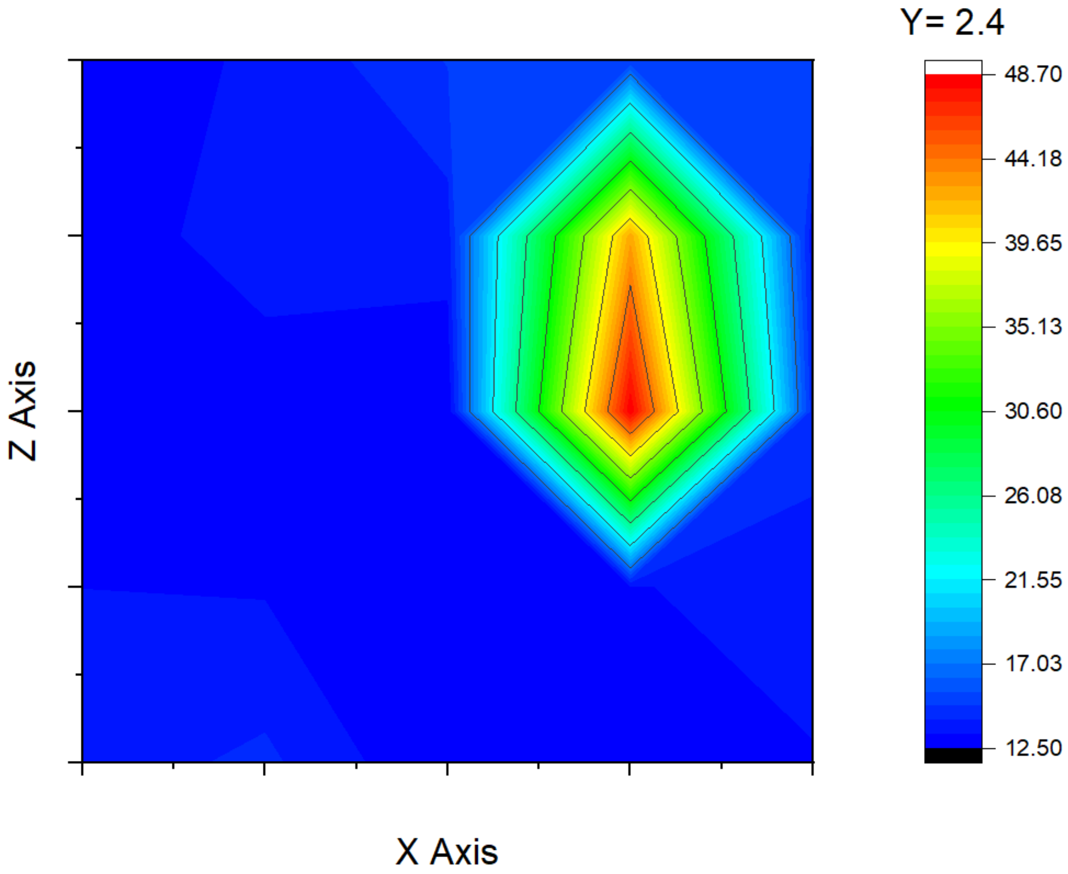


Figure 119: Test No 28b (table 2) at 2.4m at 30000s

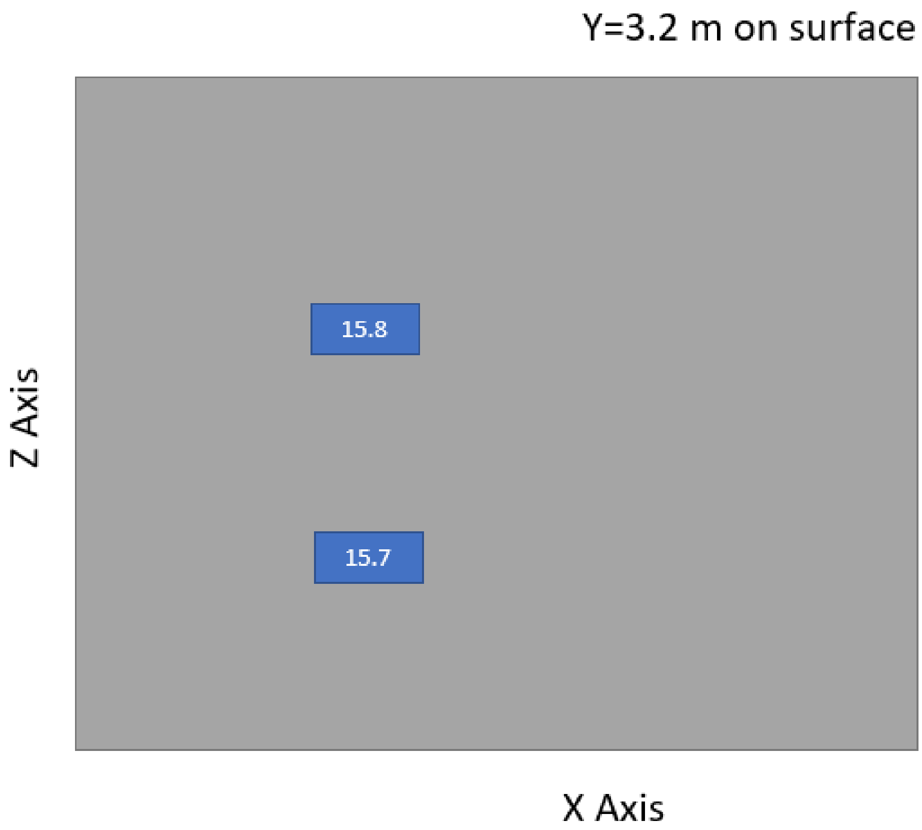


Figure 120: Test No 28b (table 2) at 3.2m at 30000s

Test 28 b temperature slices through the pile at 54000 seconds figures 120, 121,122,123 and 124 should be viewed together.

At time = 54000 seconds it can clearly be seen that the passage of the pyrolysis front was moving towards the rear far right corner of the left bay. It was interesting to note that this follows the line of the most significant self-heating events within the pile. It is logical therefore, that the passage of the pyrolysis front takes the passage of least resistance through the pile linking up areas of heating that has the effect or firstly reducing the moisture content in the local area and preheating that zone. It was apparent therefore, that the significant factor regarding the spread of fire because of heating has two critical elements if the fuel is disregarded firstly the activation energy present and secondly the moisture content.

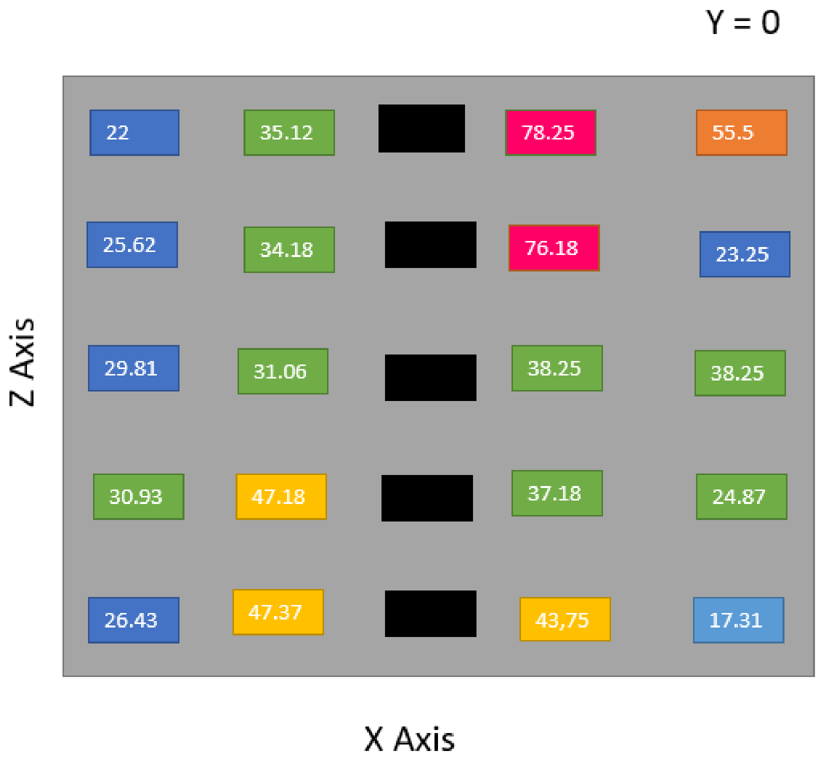


Figure 121: Test No 28b (table 2) at Y=0 at 54000 s

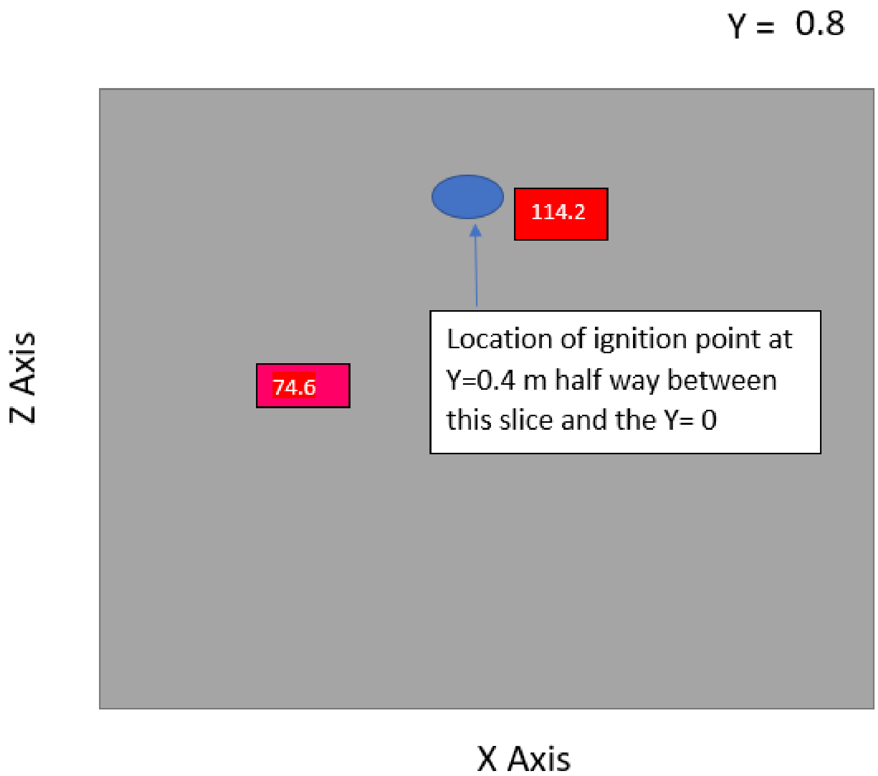


Figure 122: Test No 28b (table 2) at 0.8 at 54000s

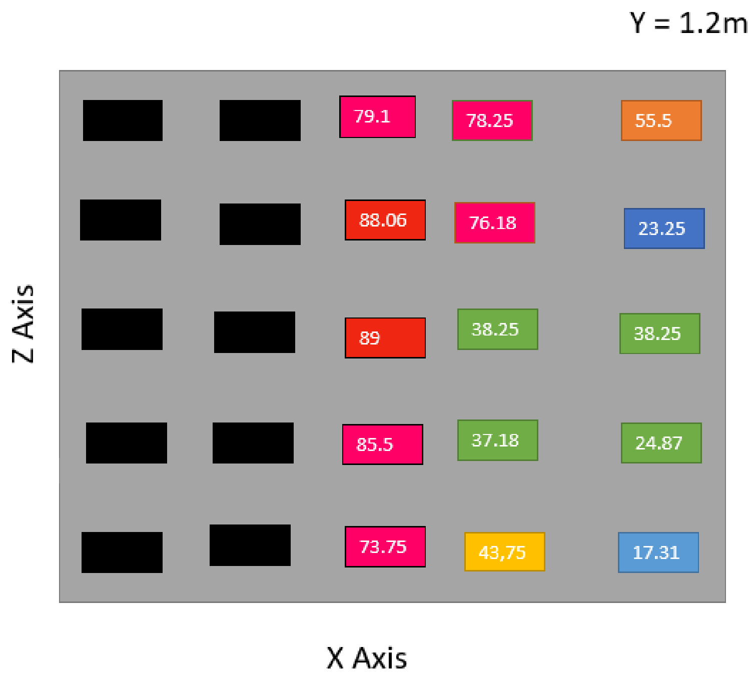


Figure 123: Test No 28b (table 2) at 1.2 m at 54000s

At 54000 seconds into the test a second string has failed. This is consistent with the spread of the fire within the wood pilot pile driving the fire growth. Although the cables were positioned through the RDF as this was expected to burn at a slower rate than the wood it would appear that the fire is developing to the left of the pile as seen from the front of the bay. This is the opposite side to the hot spot observed on the surface which appears to strengthen the argument that the heating on the right of the pile as observed from the front of the bay is independent of the developing fire and due to biological activity.

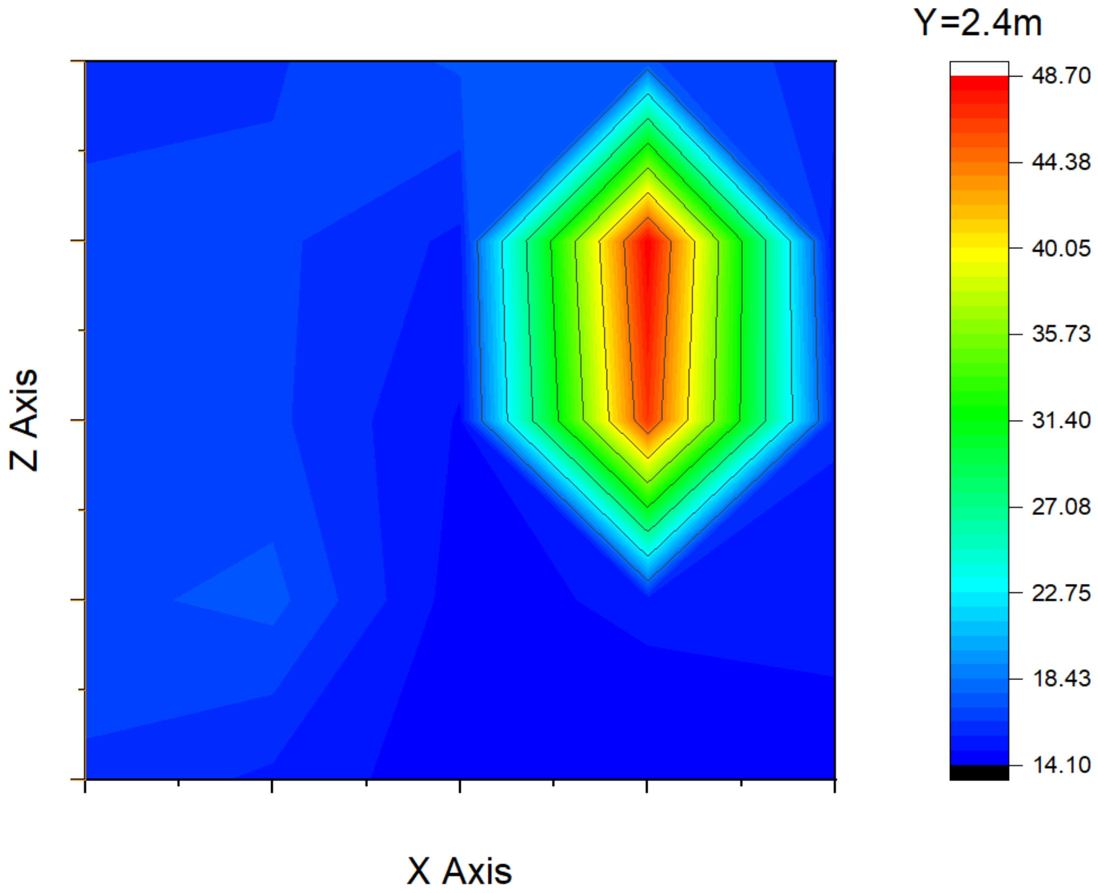


Figure 124: Test No 28b (table 2) at 2.4m at 54000s

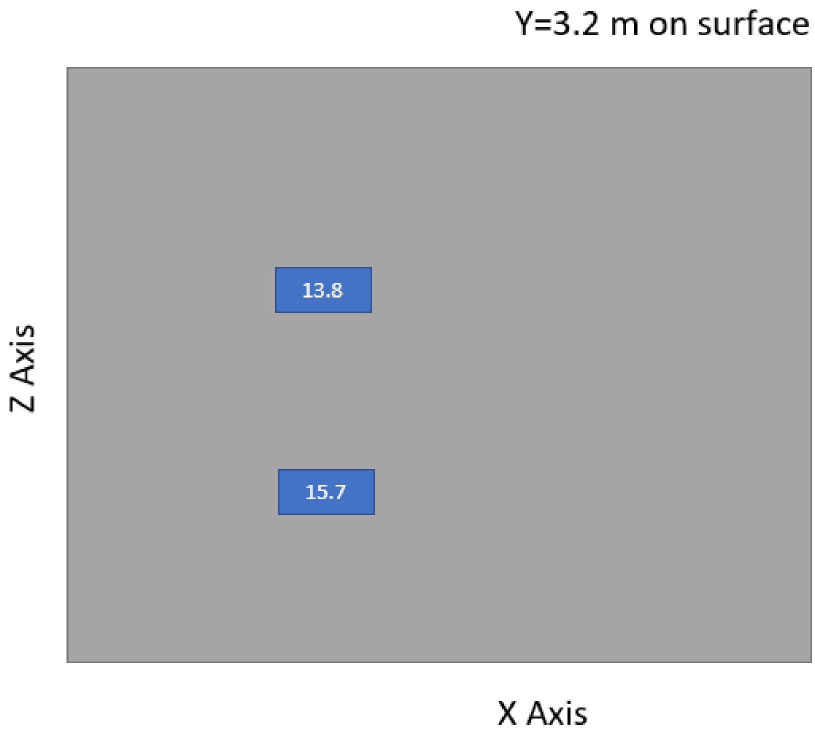
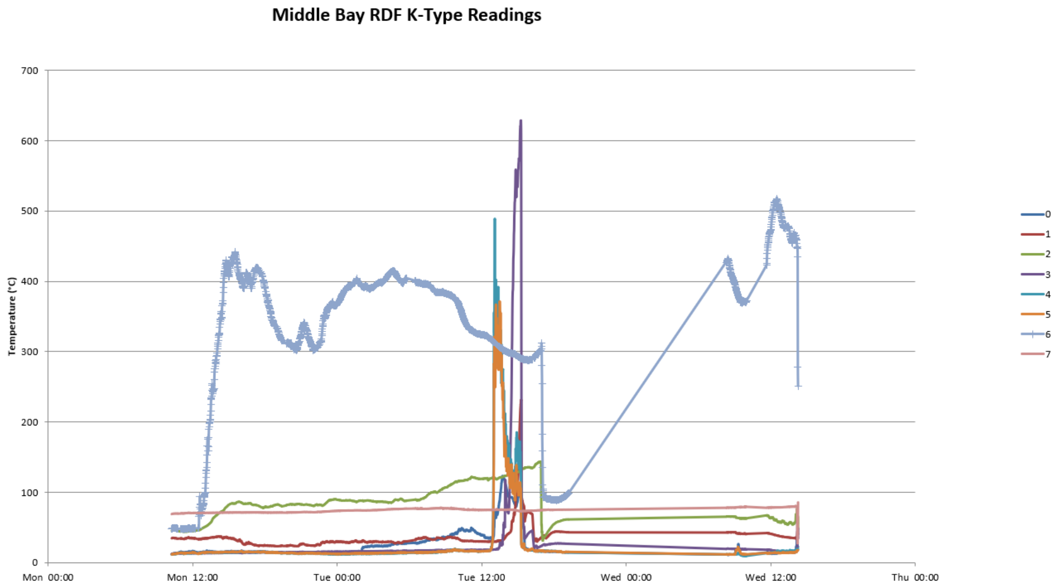


Figure 125: Test No 28b (table 2) at 3.2m at 54000s

Analysis of the middle bay.



Channel	X distance (m)	Y distance (m)	Z distance (m)
0	1.6	2.4	0.2
1	4.0	2.4	0.2
2	2.4	0.8	1.2
3	2.4	1.6	1.2
4	3.2	3.2	0.2
5	2.4	2.4	1.2
6	1.6	0.8	0.2
7	1.6	1.6	0.2

Figure 126: Test No 28a (table 2) middle bay k Type graph

The preventit data (82) was almost identical to that of the left bay. In this test there was sufficient data logging capacity to capture the k type data. This provides graphical data in the vertical plain and the full-time frame for the experiment. By good fortune K type N0. 6 was in the pyrolysis zone and provides temperature data. The pyrolysis zone spread through the wood over and slow but steady temperature rise was observed through the wood. Again, the wet RDF appeared to present a barrier to the spread of the pyrolysis front. The temperature profile of thermocouple No.2 directly above thermocouple 6 shown a steady rise in temperature. Extrapolating the thermocouple data from these two experiments it was estimated that it would have taken 144 hours for the pyrolysis front to breach the surface.

As this series of tests was also developed to provide test fires for the NFCC (80) fire tests it was decided at this point to take measures to accelerate the pyrolysis process.

Initially pure oxygen was introduced via the lance into the fire core through the pilot hole.

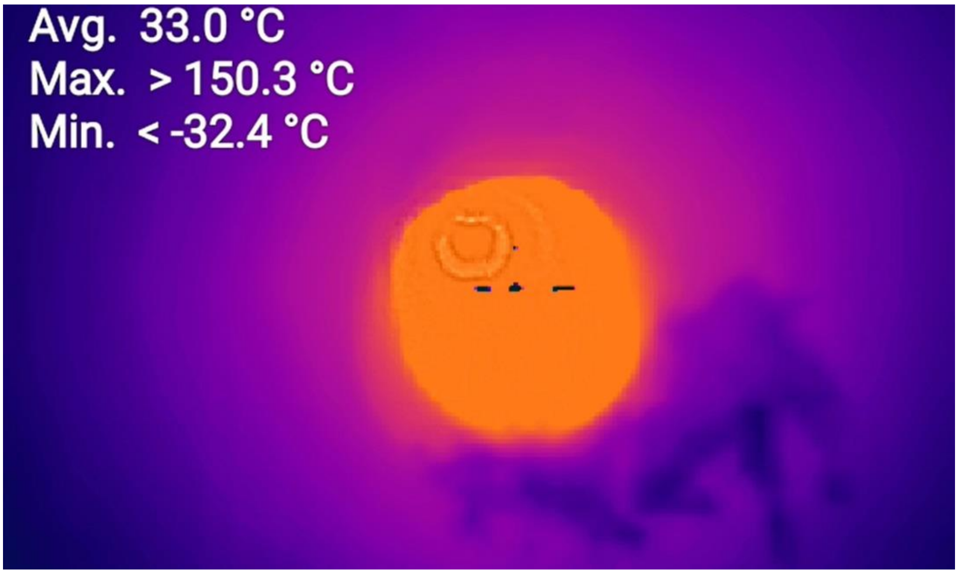


Figure 127: Test No 28a (table 2) thermal image camera image (77) of the pyrolysis zone

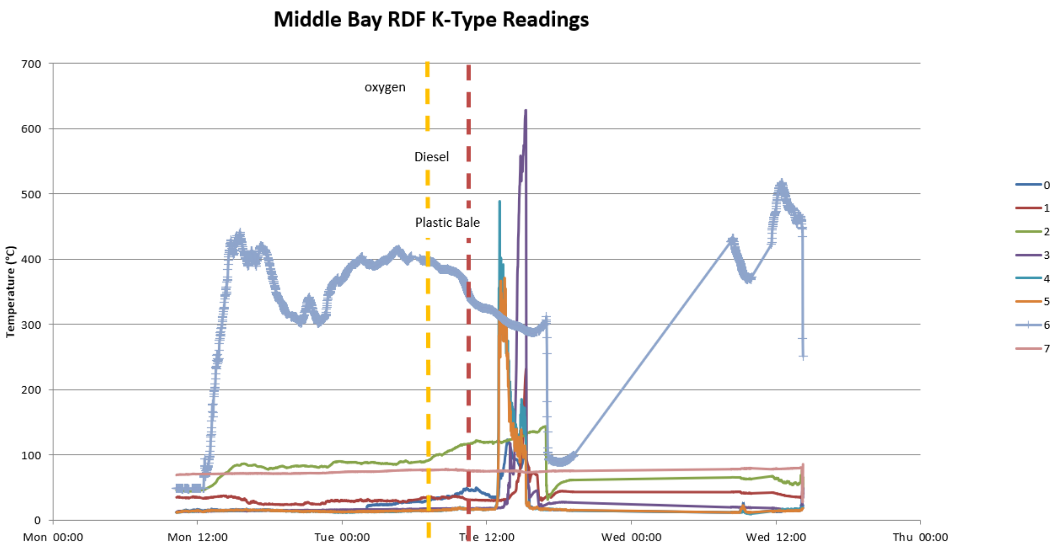


Figure 128: Test No 28a (table2) K type thermal data graph with attempt at acceleration indicated on the graph

The introduction of oxygen was attempted twice but had no obvious effect other than the brief ignition of dust around the hole on the outside of the wall. No change in temperature was recorded by the thermocouples and no change of colour of the core was observed.

C= Centigrade
F= Farenheit

color	approximate temperature		
	°F	°C	K
faint red	930	500	770
blood red	1075	580	855
dark cherry	1175	635	910
medium cherry	1275	0690	0965
cherry	1375	0745	1020
bright cherry	1450	0790	1060
salmon	1550	0845	1115
dark orange	1630	0890	1160
orange	1725	0940	1215
lemon	1830	1000	1270
light yellow	1975	1080	1355
white	2200	1205	1480

Figure 129: Steel temperature chart (86)

Although crude this commercially available temperature chart was used to provide some indication of temperature where the temperature exceeded our thermal image camera operating range of 150^{0}c. This chart was obtained from Hearth.co.uk. The core of the test was observed to maintain a constant dark cherry colour.

Figure 130: Test No 28a (table 2) diesel accelerant being applied

Diesel was poured around the rear of the pile with the hope that this would filter down to the core and accelerate the pyrolysis process. However, once again this had no apparent effect of the core.

Figure 131: Test No 28a (Table 2) plastic bale ignited

Figure 132: Test No 28a (table 2) Plastic Bay initiates a surface fire on RDF

Finally, a plastic bale was placed on the pile and ignited this generated a surface fire which was clearly picked up by the k Type thermocouples close to the surface of the material. It was clearly apparent from the thermocouple data that this had no impact on the progress of the deep seated core. The graph in effect describes two separate fire events. Once the fire crews had extinguished the surface fire using water with a 0.3% surfactant mix, I was apparent that this mixture had failed to impact the deep seated core. Therefore, in order to comply the Fire Service College Health and safety guidelines of extinguishing unaccompanied fires overnight a firefighting jet with the surfactant mix was applied through the pilot hole of each of the test fires. The effectiveness of this process was observed using the thermocouple data. To the surprise of the experiment team, it was noted that both cores had returned to their previous temperatures overnight. The precise curve was not captured as the data logger battery had run down. It, therefore, became essential to utilise the Fire Service excavation technique known as the "Muddy Puddle tactic" to full extinguish the fire. The Fire-fighting tactics developed and tested at the Fire Service College are discuss in Appendix F. Some discussion of the results is necessary at this point. There are apparently, some quite sharp temperature changes throughout the material. Current research, based on small scale basket tests (87), would suggest that many of the temperatures observed should have caused a runaway self-heating event see Appendix D . However, the data collected in these series of test directly contradict these findings. Which was unlikely given the breadth of testing as research undertaken, in developing systems for using these materials as sources of fuel. To a degree this could be explained as an issue of scale, but this was also unsatisfactory as an explanation. Temperature is after all a measure of energy at a local scale the size of the body is irrelevant as the material has an equivalent quantum of energy whether it is the size of pea or a beach ball the potential for the material to ignite due to temperature is the same. The main flaw in the test methodologies is that basket tests are designed to determine if a material is capable of self-heating and the sample are prepared is such a way at to facilitate that heating process. Namely the samples are pre dried. What was evident from the experiments conducted at Morton in the Marsh is the impact of water on the process. Extremely high temperatures were recorded in the materials many reaching temperature around the boiling point of water. These temperatures were also observed to cool sometime surprisingly quickly. It was observed however, that temperatures above 100^0c were not recovered. Clearly a temperature of over 100^0c is an indication that the material in that zone has had the water driven off.

The second law of thermodynamics – The entropy of an isolated system not in equilibrium will tend to increase over time, approaching a maximum value at equilibrium. We know that this is true of chemical and physical systems. If we consider some materials to act like a large wet sponge in which a small area deep within its mass is heated by bacteria the water in this area is turned to steam. The steam cannot escape entirely but does displace the moisture around it. However, in reaching the boiling point of water the bacteria are killed and stop the heating process this area is now at a lower moisture and pressure than the sponge around it. In this way the moisture content of any material behaves according to the laws of thermodynamics and seeps back into the dry area until the whole system reaches equilibrium. This would account for the observation of temperature around 90^0c that subsequently cooled. However, the system as a whole has lost a small quantity of moisture. Because the moisture content of the system, acts as a break for pyrolysis the material can display much higher temperatures than would be indicated by basket testing. In this way basket testing of small samples of material is not a reliable indication of self-ignition of large pile as it does not consider the moisture content or behaviour of moisture as a suppressant in pile materials. The "fire" that was generated in these tests proved to be impervious to oxygen this will be discuss in depth later in this thesis. The precise chemical processes involved was not identified and will need further research to understand fully. However, sufficient activation energy was imparted in a localized area to generate a self-sustained "pyrolysis" process. Therefore, there must be a critical temperature (energy transfer) at which the retarding effects of water are overcome. To quantify the results, it is necessary to consider the test in terms of an energy transfer problem.

Taking the basic enthalpy of change equation

$$q = m \times c \times \partial T$$

Where:

q is the enthalpy or change in internal energy ($kg.m.s^{-2}.k^{-1}$)

m is the mass (kg)

c is the specific heat capacity of water

∂T is the temperature change

Equation 6: enthalpy of change equation

Then this can be explained as

$$\partial T_{crit} = \frac{q_{crit}}{m \times (c + \partial u_{vapw})}$$

∂T_{crit} = critical temperature of the material

q_{crit} = critical quanta of energy in the system

∂u_{vapw} = enthalpy of vaporization of water.

Equation 7: critical enthalpy equation

Taking this equation and applying this to an approximation of the RDF material in these experiments this equation is further modified

Where c is the composite of the specific heat of the materials making up the pile

$$C = m \times (c_1 \times \partial T_{crit} \times f_{mass}) + m \times (c_2 \times \partial T_{crit} \times f_{mass}) \dots \dots \dots n$$

Equation 8: equation describing the activation energy requirement for deep seated ignition

Where f_{mass} = the fraction of the mass made up by this specific material

Using this formula to calculate the energy required to ignite 1 kg of a plastic/paper/water (26%/39%/35% by mass) mix and taking the specific heat of water as 4.18 kj/kg, plastic as 1.67kj/kg, paper representing the remaining material 1.32 kj/kg and the critical temperature of 423 k and the water content by mass as 35% obtained from empirical observations by (26) The critical quanta was calculated to be 7.687x 10^{5} kg.m.s^{-2} .k^{-1} and the specific heat required to reach the ignition temperature was 1817.21 kj/kg . for convenience this is equivalent to 1.817 MW/kg. If we assume the ambient temperature within the pile at the point of ignition was 20^{0}c and taking the ignition point as 150^{0}c the energy require to ignite the test bed was 1.106 MW/kg. The significant factor in reaching the activation energy is the specific heat of vaporization of water which accounted for 791 kj/kg in both calculations. Therefore, there are two self-heating regimes an acute ignition such as the method used to start these test fires. In normal storage condition the activation energy is significant and would only be caused by high energy contamination such as a power cell or significant chemical reaction, the second is a dry fuel bed if we consider the scenario above in the absence of water the activation energy required would be 187.2 kJ/kg (assuming 40% plastic and 60% paper). These calculations clearly demonstrate the effect of water in self heating regimes. The presence of water in the mass of material will prevent self combustion. This was apparent from the self-heating wood fines test No18. Wood fine has a bad reputation within the industry for spontaneous combustion. The fact that this pile had repeated biological self-heating events but did not develop into a fire is undoubtably due to the unusually wet year that the test was conducted over. The longest period that the site did not experience significant rain fall was 10 days. As a result, the pile water content increased over time thus increasing biological event but failing to dry sufficiently to progress to a self-heating fire.

7.3 Summary

There is a clear relationship between the type of fire and the permeability of the fuel bed. In a similar way to surface fires the less resistance to air penetrating the pile the more intense the resulting fire will be. But equally with this type of fuel bed early fire detection such as video heat and smoke are far more effective with both system detecting the pilot light before the fire had caught in the large scale wood test. Impermeable fuel beds are a far more intractable problem to solve. While the second set of fire experiment confirmed the results of the initial fire tests at Barling. The data is still too course to detect the root like fire spread hinted at by the excavation of the SRF fire test 15 figure 64. The results of these experiments hint at an examination of variation in mass being a better measure of fire behaviour within a pile of material. It was observed that the area of heating drives moisture away from the point of heating and the zone that was heated produced a ball of dust and ash. Further research in this area could explore the possibility of using other technologies such as those used for archaeological studies of ground conditions.

Chapter 6 Bales Fire Tests

This chapter explores the initial fire tests conducted on stacked bales as originally scoped in work package 2. It was anticipated that the fire would be more intense than that generated in WP1 (30). This is clearly due to the flame front being stretched up the vertical surface of the fuel bed (63), (65). The original test design assumption was for a peak flame temperature at or just over the published data for a turbulent flame for that material. For safety this output was doubled and the siting of equipment was based on this figure. The FPA fire test on high bay warehouse carton (60) has also been reviewed. However, the resulting fires were more intense than expected as the interplay between adjacent flame fronts generated a vortex which produced a fire behaviour more reminiscent of an exposed chemical reactor. Similar results were obtained by Jim Glockling (69) some years earlier but not published as the research was restricted due to a nondisclosure agreement with his client.

8. Baled Fire Tests

8.1 RDF Bales

The first experiment using stacked RDF bales involved two stacks of three bales set against a concrete retaining wall. This was a preliminary test and the wall was used to provide structural support to the bales as the stability of bales under fire conditions was not understood at this point. All the fire tests were conducted on a bed of uncompacted sand so that if a bale fell it would tend to dig into the sand rather than roll or bounce.

Figure 133 Test No 10 (table2) setting up RDF Bale test

The experiment was started at the corner of a bale closest to the wall. The Flame was applied for 20 minutes. The bales were reasonably wet having been stored outside the previous week and had been exposed to two days rain. However, the bales were wrapped in a plastic film. The fire progressed as expected and consistent with the rate of fire growth described by work package 1 (7).

Figure 134 Test No 10 (table2) bale Fire developing with flame impingement on second vertical bale

Figure 135: Test No 10 (table 2) RDF Bale Fire affecting third bale

Figure 136: Test No 10 (table 2) surface fire now spreading to second stack

The fire development continued and it was noted that the ash and char layers fell away from the vertical surfaces constantly exposing virgin fuel. In this way the fire progressed more efficiently than have been observed in the laboratory tests conducted by the FPA in work package 1 (7). The fire was observed to intensify in the gap between the two stacks of bales. This was apparently due to the interplay between the two flames, the fluid dynamics around the gap and exchange of radiated heat in this zone.

Figure 137: Test No 10 (table 2) area of intense flame is observed to generate in the gaps between the stacks.

Figure 138: Test No 10 (table 2) RDF fire Vortex

The fire in the gap between the stacks formed a very distinct vortex and this zone generated considerably more heat output as a result. The peak temperature in the vortex taken with a thermal image camera was 918^{0}c the temperature immediately adjacent to this zone was 748^{0}c and this tapered off towards the middle of the left stack to 253^0c. The very high temperature was maintained in the vortex zone. In previous test such high temperatures for RDF were only reached momentarily at the peak for the fire curve and the fire quickly entered the decay phase (see section 5).

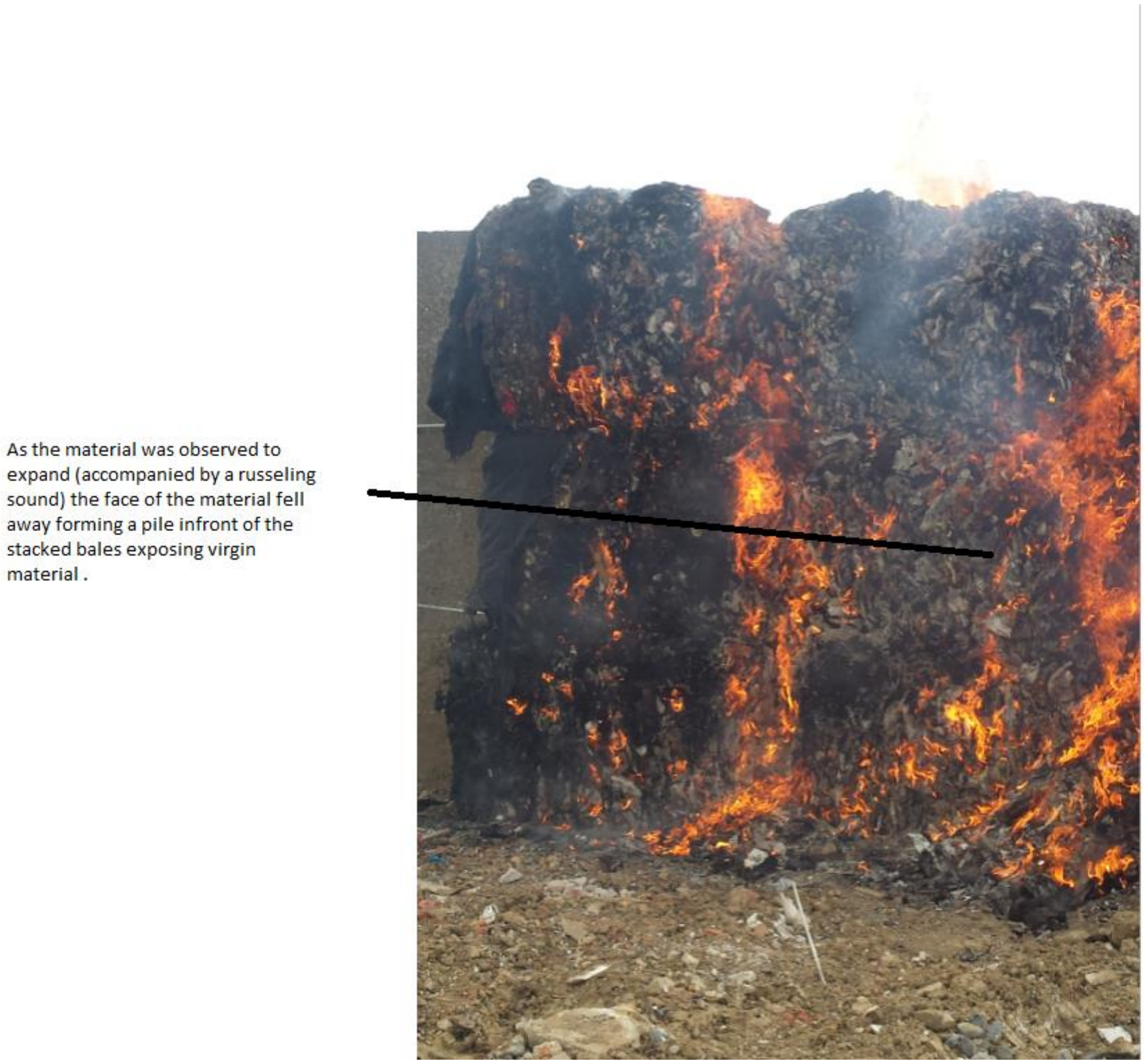


Figure 139: Test No 10 (table 2) RDF Stack degradation.

As the fire progressed it was observed that periodically reasonably large sections of the face of the stack would fall away. This was preceded by a gently rustling sound. In doing so the material formed a pile in front of the stack and occasionally both exposed surfaces of the RDF were formed of virgin fuel. The surface fire was observed to quickly spread across this expose fuel. On a larger scale this could account for the miss conception of a deep seated fire being the cause of a fire at waste sites and could partially account for some miss reporting.

Figure 140: Pinsent photograph of a glassier calving.

It was also noted that ash and material falling between the gap between the two stacks interrupted the fire vortex. Which had to reform. Eventually this process of calving broke down the system that generated the fire vortex.

8.2 HDPE Bale test

The HDPE bale test was conducted on the 17th May 2016. The temperature at the commencement of the test was 19^0c and the wind was dead calm with occasional breeze of 1 knot. At the request of the WISH board the potential for a Chinese lantern to ignite this fire was to be explored. A Chinese lantern was allegedly the cause of the fire at the Jayplas recycling centre in Birmingham in 2016. This material had previously been tests during Work package 1 (7) and had proved difficult to generate a self-sustain fire. The bales when tested on their own will generate a surface fire. This will quickly become a char-controlled fire.

Figure 141: Test No 13 (table 2) HDPE bale fire ignition

Therefore, the fire was initiated with a single block of petroleum firelighter placed in the gap between the stacks with a view to optimising the fluid dynamic effect observed in the RDF test.

Figure 142: Test No 13 (table 2) HDPE fire takes hold

The fire quickly took hold and developed up the gap between the two stacks. The fire growth was quicker than expected as was the heat release rate. The test had been designed around the assumption of fire growth and heat release rate based on the laboratory tests (30).

Figure 143: Test No 13 (table 2) HDPE test vortex forming

A number of K type thermocouples had been placed in the gap at three point and one midway between the gaps mounted in the approximate mid-point on the surface of a bale. None of the thermocouples survived the test recording max temperature of 1198^{0}c, 1158^{0}c, and 1163^{0}c before failure within 3 minutes of the start of the test. The thermocouples were covered in 6m of 3mm stainless steel sheath. This melted and no trace of the thermocouples were observed after the test. The heat flux meters placed 4 m from the stack were quickly withdrawn. Three GoPro cameras placed 10 m from the fire were damaged beyond repair due to the fisheye lenses focusing the heat onto the processers. The fire was measure using a thermal image camera calibrated to 1200^{0}c this recorded surface temperatures of 1300^{0}c although this was obviously un-reliable as this temperature was outside of the instrument's calibration.

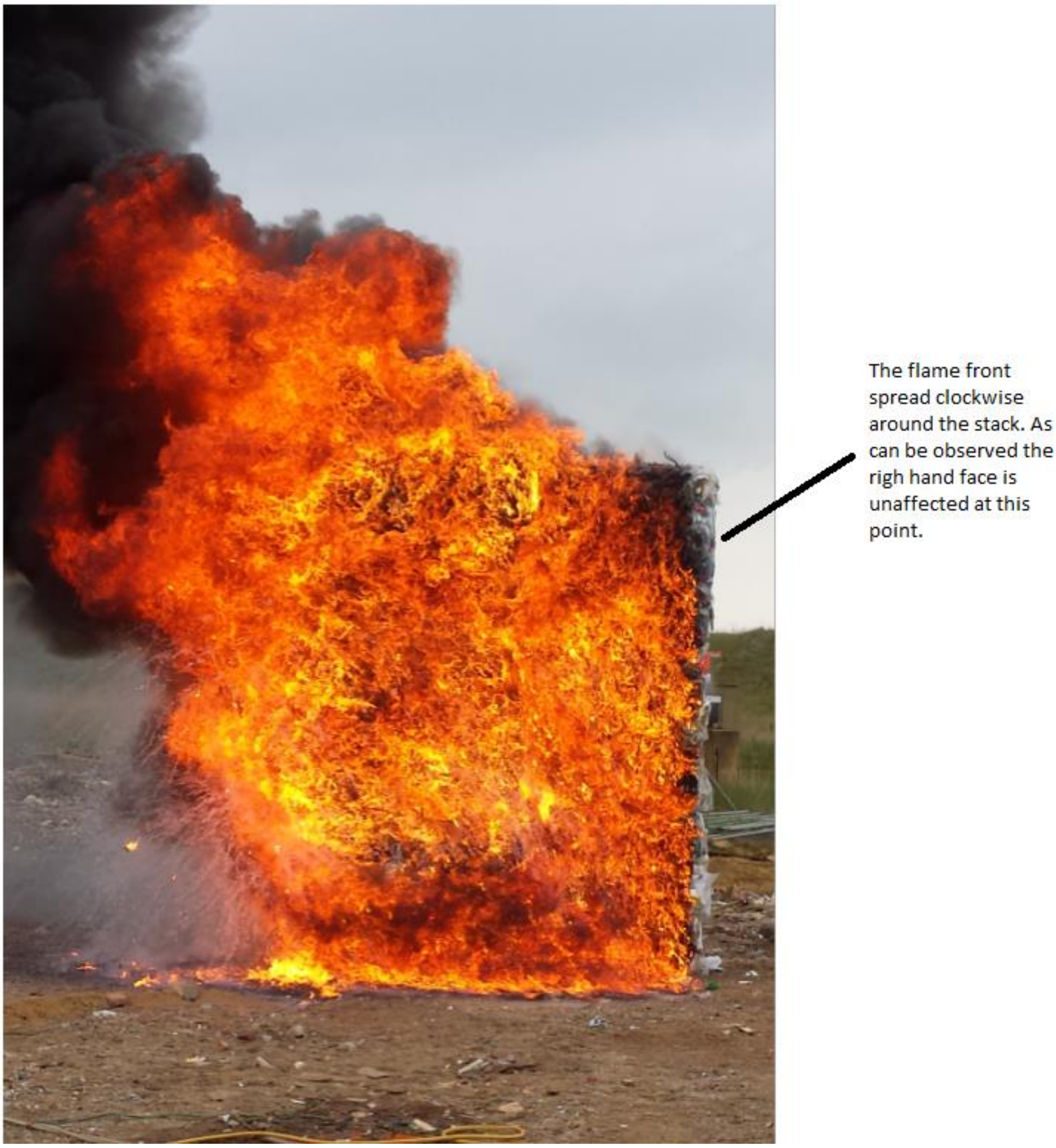


Figure 144 Test No 13 (table 2) HDPE clockwise fire spread

The fire was observed to spread clockwise around the stacks and full involvement of the whole surface area of the test occurred in 4 minutes of the ignition of the firelighter. As the fire heat release rate had clearly exceeded the scope of available instruments. Only observations were made from this point.

It was observed that the fire was generating a steady air flow towards the fire. Smoke at ground level was rotating around the base of the fire in a clockwise direction. The combined vortex and smoke column had a clear general rotation in a clockwise direction and tended to lean in the direction of the general wind direction although this was hard to measure given that the fire was drawing air from all directions. This change of wind direction and velocity was picked up by the site weather station although due to an instrument error this data was not recorded.

Figure 145: Test No 13 (table 2) HDPE lone Bale

Approximately 3 minutes into the fire the stack on the southern right corner became unstable and the top bale fell off the stack. It landed approximately 3 m form the main fire. The surface that was facing away from the main fire quickly reverted to a char-controlled fire with only the surface facing the main fire flaming readily. It was interesting to note that the main stack completely used up all the available fuel and did not calve or drop any material around its base rather the plastic was vaporised and any char turned into ash and transported away in the smoke column. After 4 and half hours the main fire burn out leaving only a small pile of ash where the lone bale self-extinguished and having approximately 70% of it mass intact. It was clearly apparent that the geometry of the stack arrangement significantly influences the resulting fire. In effect the stacks arranged in vertical columns allows the fluid dynamic flow to generate vortices. The flame velocity and pressure in these zones clearly increases the efficiency of the combustion process to a point that the material involved burns at the peak heat release rate possible for that given material.

Figure 146: Test No 13 (table 2) HDPE fire vortex and smoke column

8.3 Comparisons of large scale field trials with WISH Waste Fire Phase 1 results

The phase 1(23) tests were commissioned by WISH in 2014. These tests were conducted primarily on 1 tonne bales of the range of material use for the Phase 2 experiments which are the subject of this thesis. The phase 1 laboratory tests (23) were intended to provide peak temperature data on which to base the specifications for the phase 2 test series. The second objective of these test was to attempt to eliminate as many material types as possible from the large scale test series due to environmental considerations. On this basis paper, card, textiles, screened wood and LDPE were eliminated as the results were consistent with other materials in terms of heat release rates etc, Smoke emissions were not analgised after Pollington due to funding see appendix A. Paper/card, textiles and screen wood were represented with pre-crushed timber. Plastics were represented by HDPE.

8.4 Discussion of the results

As can be seen from the series of graphs that follow the temperatures achieved in the phase 2 tests were considerably higher that the laboratory tests. To a degree this was expected as allowance had been made for flame acceleration over a higher surface. However, as will be discussed the temperature achieved in the baled test were significantly in excess of anything that was anticipated. Therefore, an undiscovered mechanism must be in play.

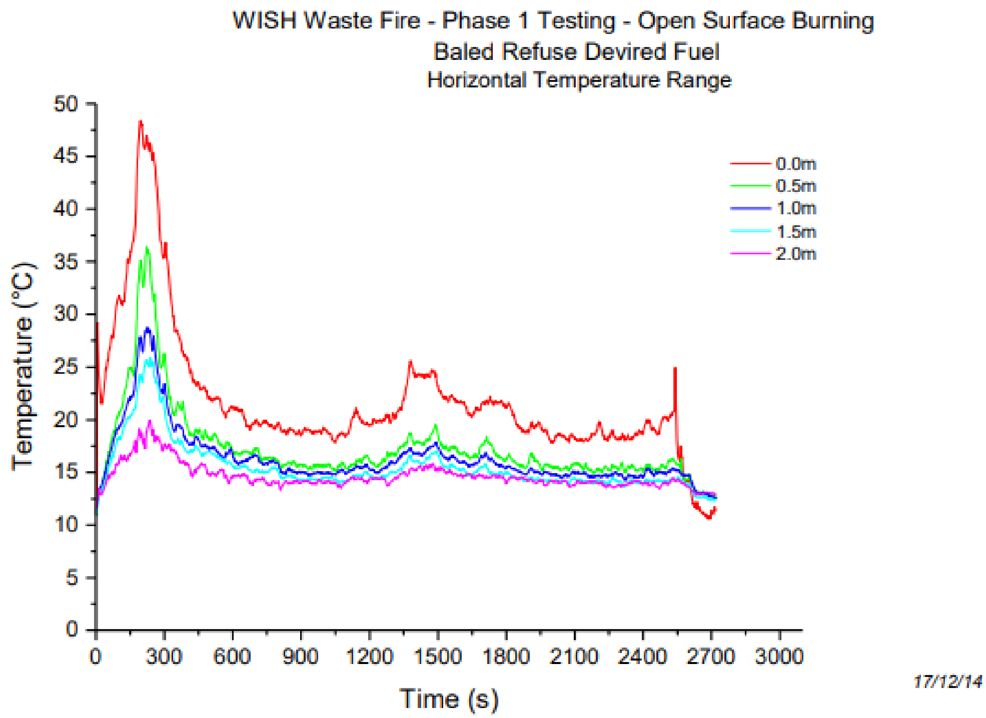


Figure 147: RDF Laboratory test results (30)

SRF is derived from RDF. The main difference being that SRF is refined to remove the majority of chlorinating plastics to reduce the production of dioxins when burnt. SRF is then shredded mixed and dried to provide a homogenised fuel with a consistent burn characteristic for energy production. Therefore, in theory RDF is capable of producing a heat output very similar to SRF. However, RDF is considered the lowest grade fuel in the European marketplace and waste management companies have to pay for its removal. In the UK it is either sent to land fill or to power plants that have extensive and complex environmental scrubbers to cope the emissions. Consequently, RDF has very little pre-treatment and poor storage compared to other recycled materials. RDF generally has a very high water content this accounts for the difficulty in setting light to the material, its propensity for biological self-heating and the low surface temperature recorded in the laboratory test and the piled material test detailed in this thesis. It is, therefore, surprising that the RDF bale test recorded temperatures over 900^{0}c in the vortex.

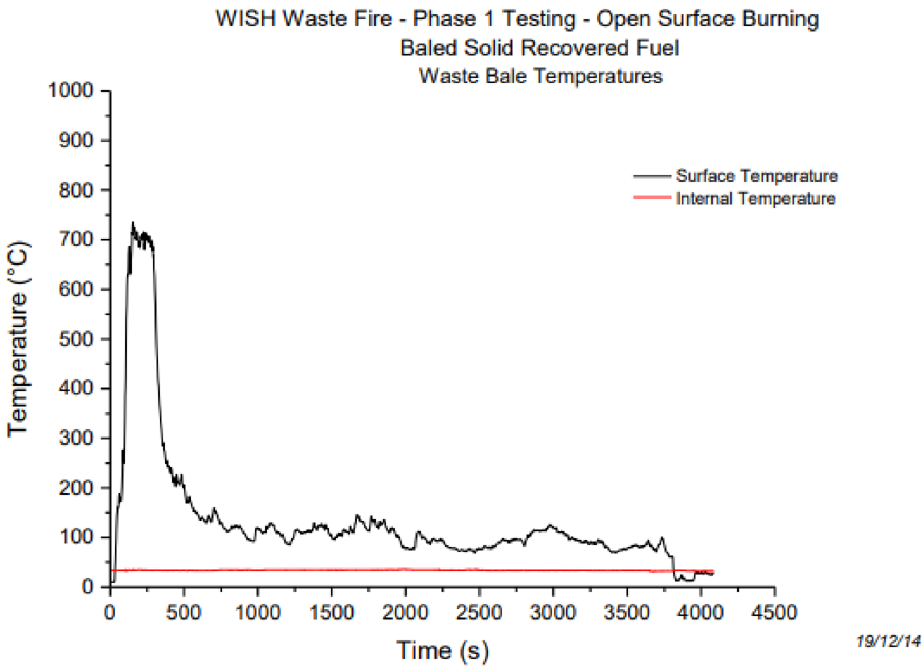


Figure 148: SRF laboratory results (30)

It is interesting to note that the wet RDF bales achieved temperatures closer to the SRF temperatures. This indicates that the vortex was generating sufficient energy release rates to vaporise the water content and burn exposed fuel.

The temperatures achieved in the HDPE fire test were completely unexpected based on the laboratory tests. Charring which had been such a factor in the laboratory was apparently absents. The flame temperatures were approaching the heat release rates of Diesel or Kerosene (67). Thus, having identified a new phenomenon some parameters need to be established.

1. Is the heat release rate a function of the vortex or vice versa?
2. Are the fluid dynamic flows created by the random surfaces of the bales generating the rotation as the convention currents rise or does the Coriolis effect have sufficient influence to generate this rotation?
3. It was observed that the system broke down temporarily when the base of the column was disrupted how critical is the relationship between the horizontal and vertical interface. Could this be used to develop fire suppression systems see appendix F.
4. What influence does the material have on this fire behaviour?

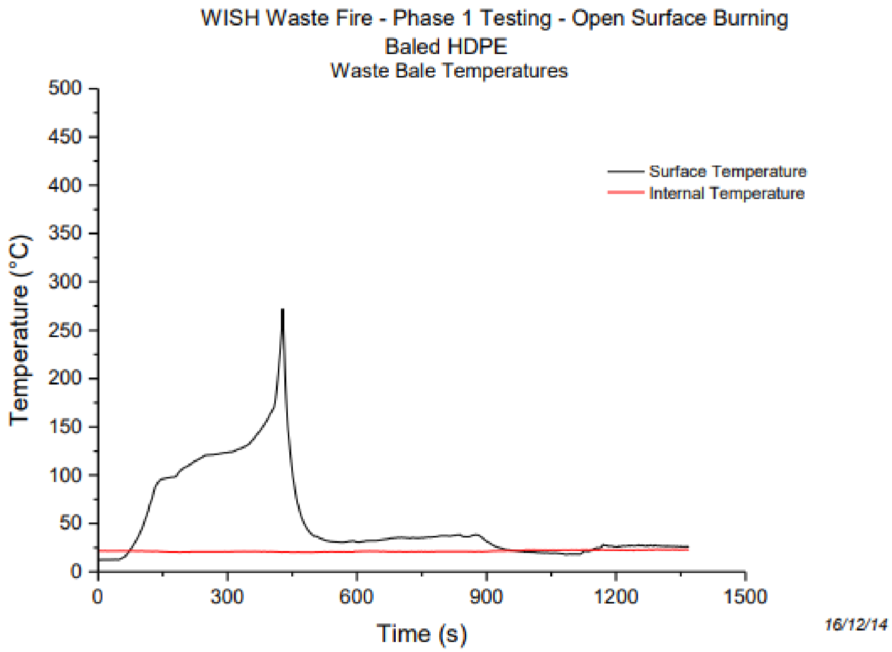


Figure 149: HDPE laboratory result (30)

8.5 Vortex Theory

The SRF test was adapted to establish if the column height was a critical factor in the development of the vortex. This was based on the relatively lack lustre fire generated by a single bale test. The SRF bales were arranged in a brick lay pattern so that the arrangement of the bales interrupted the vertical column. This did however, present the fire with a horizontal gap. Thus, effectively laying the vertical column on its side. The test stack repeated the 3m high test.

The fire was initiated with a fire lighter in common with the HDPE test. The initial fire growth was similar to the HDPE test. However, once the fire reached the bale at second layer it developed along the gap horizontally to the left. It should be noted that the SRF although wrapped in a cellophane type material had been stored outside so displayed a similar moisture content to the RDF used in the earlier test. The fire spread to the gap between two bales to the left of the point of ignition via burning material dropping into the gap. The initial stages of the fire quickly developed. It was noted the fire only took hold in the gaps as the surface fires and horizontal fire quickly went out. This established that the height of the column and the orientation of the column are essential elements in the generation of the fire vortex behaviour.

Column height is a critical factor and the column must be in the vertical plain. This by implication indicates that the flame velocity and convection flows are critical. As seen earlier the column formed by the brick wall and the flame front did not form a vortex fire. So, the critical factors identified thus far are summarised

- Minimum of two adjacent flame fronts
- Vertical column greater than 1 m height

Figure 150: Test No 17 (table 2) SRF Brick lay test

This information informed the second edition of the WISH Guidance 28 and was critically reviewed by the Building Research Establishment on behalf of the Environment Agency. In particular their observation" *In addition, scientific papers studying thermal decomposition of plastics shows that only polymers which decompose via end chain scission can achieve such high combustion temperatures. The majority of plastics do not thermally decompose via random chain scission, and therefore would be highly unlikely to combust at such high temperatures.*" See appendix G a private correspondence. Therefore, for the firefighting tests Work package 3, see appendix F, low grade plastics were selected this comprised polyethylene single use plastic bags and a range of thermoset plastics used for food packaging and generally considered uneconomic to recycle. The material supplied had a high level of contamination ranging from food wastepaper and metal bottle tops and various cans this was estimated to comprise approximately 15% of the material by weight. Consequently, the material displayed a higher than expected moisture content. The first test was piloted with a small pile of timber to overcome the contamination and the anticipated difficulty in igniting the material. However, this precaution was unnecessary as the fire quickly established a vortex fire the fire growth pattern was consistent with the previously observed fire behaviour. The use of timber to pilot the test was omitted in the subsequent baled plastics test.

Figure 151: Test No 20 Low Grade plastic bale test

The fire vortex quickly established itself. The rate of combustion was surprising. It was anticipated that this plastic would either melt and then vaporise while other plastic types would behave like other were expected to burn slowly producing significant charring which was expected to retard the rate of burning. However, as the fire progressed no melting or droplet production was observed. The transition from solid plastic to flame was observed to be almost instantaneous in the fire vortex zone.

Figure 152: Test No 20 (table 2) Low Grade plastic fire vortex has formed

Figure 153: Test No 20n (table 2) Fire spread in a clockwise direction

Figure 154: Test No 20 (table 2) Low grade plastic in the process of being extinguished with water see appendix F

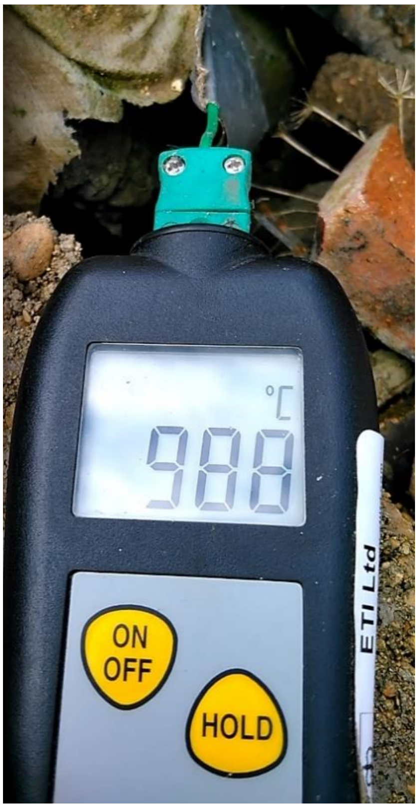


Figure 155: Test No 22 (table 2) Flame Temperature taken with a K Type thermocouple

The temperature was taken at a point at the midpoint in the column on the right side of the stack from behind cover some 6m from the fuel be, however, the measurement had to be abandoned as the condition became untenable. As there was insufficient budget to directly measure the flame temperatures. To achieve this the temperature was recorded at a range of remote point and the surface temperature extrapolated.

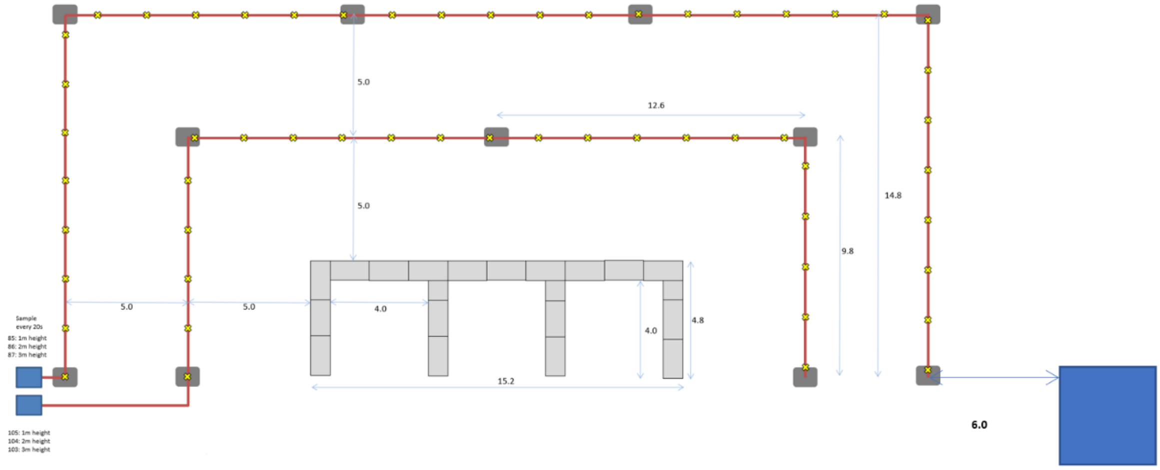


Figure 156: Site lay out showing low grade plastic test 20 (table 2) in relation to the thermocouple arrays

Table 1. Calibration errors of spectrometer and CCD camera.

Blackbody Furnace		Spectrometer				CCD Camera			
T (K)	*ε*	*T* (K)	Error(%)	*ε*	Error(%)	*T*(K)	Error(%)	*ε*	Error(%)
1143	1.0	1116.1	2.35	1.05	4.71	1144.6	0.14	0.97	2.53
1173	1.0	1140.4	2.78	1.05	5.43	1162.9	0.87	1.05	5.25
1203	1.0	1178.3	2.05	1.04	4.33	1209.1	0.51	0.96	3.94
1233	1.0	1219.2	1.12	1.03	2.78	1246.4	1.08	0.96	4.03
1263	1.0	1281.2	1.44	0.97	2.57	1279.7	1.31	0.93	6.72
1293	1.0	1308.1	1.17	0.98	2.24	1307	1.07	0.95	5.06
1323	1.0	1335.3	0.93	0.98	2.02	1339.1	1.22	0.96	3.67
1353	1.0	1362.3	0.69	0.99	1.14	1364.3	0.84	0.97	3.18
1383	1.0	1390.0	0.50	0.99	1.02	1386.7	0.26	0.98	1.93
1413	1.0	1425.2	0.86	0.98	1.93	1410.2	0.21	1.02	1.72

Figure 157**: table 1 taken from *Emissivity Characteristics of Hydrocarbon flame and temperature measurement by colour (86)**

So, assuming the flame temperature is in the region of 1261 k this table provides four possible values for the emissivity of the flame. Taking the average of the valued the value of 0.97 is derived and was used in this calculation.

To calculate the surface temperature of the fire it is necessary to know the specific heat capacity of the thermocouples. It was found that the specific heat capacity is in the range of 1.05 J/g at 20^0 c to 1.52 J/g at 100^0 c. Four heat capacity findings were plotted on a simple linear graph to obtain a gradient from which to calculate the specific heat capacity at any given temperature this was found to be 0.006 J/g increase for each degree Celsius increase. It is likely that the real relationship will be an exponential graph but given the relatively limited temperature range this relationship is considered acceptable.

$$\partial T * 0.006 + c_{orig} = c_{\partial T}$$

Equation 9 Specific Heat Capacity equation.

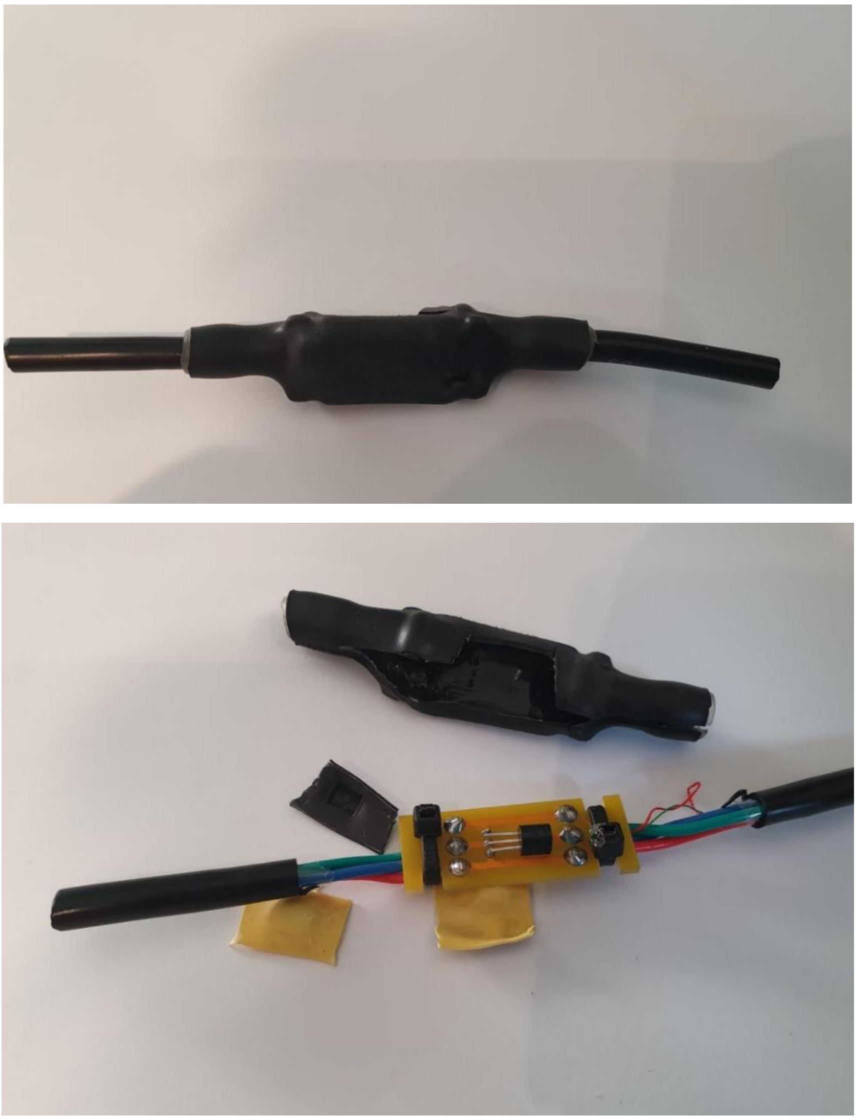


Figure 158: Preventit (82) thermocouple dissected.

$$q = cm\Delta T$$

$$\therefore q = \dot{q}T \text{ where T=1 s}$$

$$\dot{q} = {}^{q}/_{T}$$

Equation 10: Specific heat Capacity

$$\frac{Q}{t} = \sigma \varepsilon A T^4$$

Equation 11: Stefan Boltzmann Law of Radiation

$$q = c_{\partial T} m \Delta T$$

Equation 12: amended specific heat capacity equation

$$\dot{q} = \frac{\sigma(T_F^4 - T_C^4)}{\frac{1-\varepsilon_{fire}}{A_{fire}\varepsilon_{fire}} + \frac{1}{A_{fire}F} + \frac{1-\ \varepsilon_{TC}}{A_{TC}\ \varepsilon_{TC}}}$$

$$\frac{q}{t}\ (\frac{1-\varepsilon_{fire}}{A_{fire}\varepsilon_{fire}} + \frac{1}{A_{fire}F} + \frac{1-\ \varepsilon_{TC}}{A_{TC}\ \varepsilon_{TC}}) = \sigma T_{Fire}^4 - \sigma T_{Tc}^4$$

$$\sqrt[4]{\left(\frac{q}{T}\ \frac{1-\varepsilon_{fire}}{A_{fire}\varepsilon_{fire}} + \frac{1}{A_{fire}F} + \frac{1-\ \varepsilon_{TC}}{A_{TC}\ \varepsilon_{TC}} + \sigma T_{TC}^4\right)\frac{1}{\sigma}} = T_{fire}$$

Equation 13:surface fire temperature calculation rearranging view factors

$$\sqrt[4]{\left(\frac{\partial T * 0.006 + c_{orig} m \Delta T}{T}\ \frac{1-\varepsilon_{fire}}{A_{fire}\varepsilon_{fire}} + \frac{1}{A_{fire}F} + \frac{1-\ \varepsilon_{TC}}{A_{TC}\ \varepsilon_{TC}} + \sigma T_{TC}^4\right)\frac{1}{\sigma}} = T_{fire}$$

Equation 14: Combining equation 6 and 10 provides the method for calculating the flame temperature of the fire.

The 6 closest thermocouples were analysed using a standard view factor from the SFPE (64). It was found that 2 thermocouples had failed after reaching 138^0c and so this data was disregarded. The average surface temperature was found to be in the region of 1000^0c fluctuating at "steady state" between 970^0c and 1011^0 c. this was consistent with the direct measurement.

Figure 159: Test No 21 (table 2) Low grade plastic fire with anti-clockwise rotation vortex

During the second firefighter test see section 11 one of the bales dislodged slightly this caused the vortex on the right to change the direction of rotation to anti clockwise direction this had the effect of widening the fire cone into two contra rotating vortices rather the single cone observed in the other test.

This establishes the principal that in the absence of a physical barrier then the Coriolis effect will influence the direction of rotation of the vortex, but it is subordinate to deflection by physical object that influence the direction of rotation.

CFD modelling using FDS demonstrates the fluid flows that generate the vortices. This also shows that the boundary conditions at the base of the column are critical in generating the flows that influence rotation in the convection currents and individual flames. The interaction of two flames with sufficient velocity and rotational motion cause the flames to interact in a vortex that intern generates the vortex fire column.

9. Fire Dynamic Simulator Model (FDS)

The geometry of the bales was modelled in FDS (88) using a 10 mm mess in the vortex zone this was stepped up to 10 cm across the model. The stacked had a 5 cm gap between them and the stack were 1m^2 area and 3m hight. The stock Polyethylene model was used (89). The object of this modelling was to determine if the model generated the fire vortex behaviour and therefore, a natural phenomenon associated this any column between combustible material, or a function or the interaction of the uneven surface of the waste bales. The simulation was run for 5 minutes as this time period matched the empirical data from ignition to full involvement.

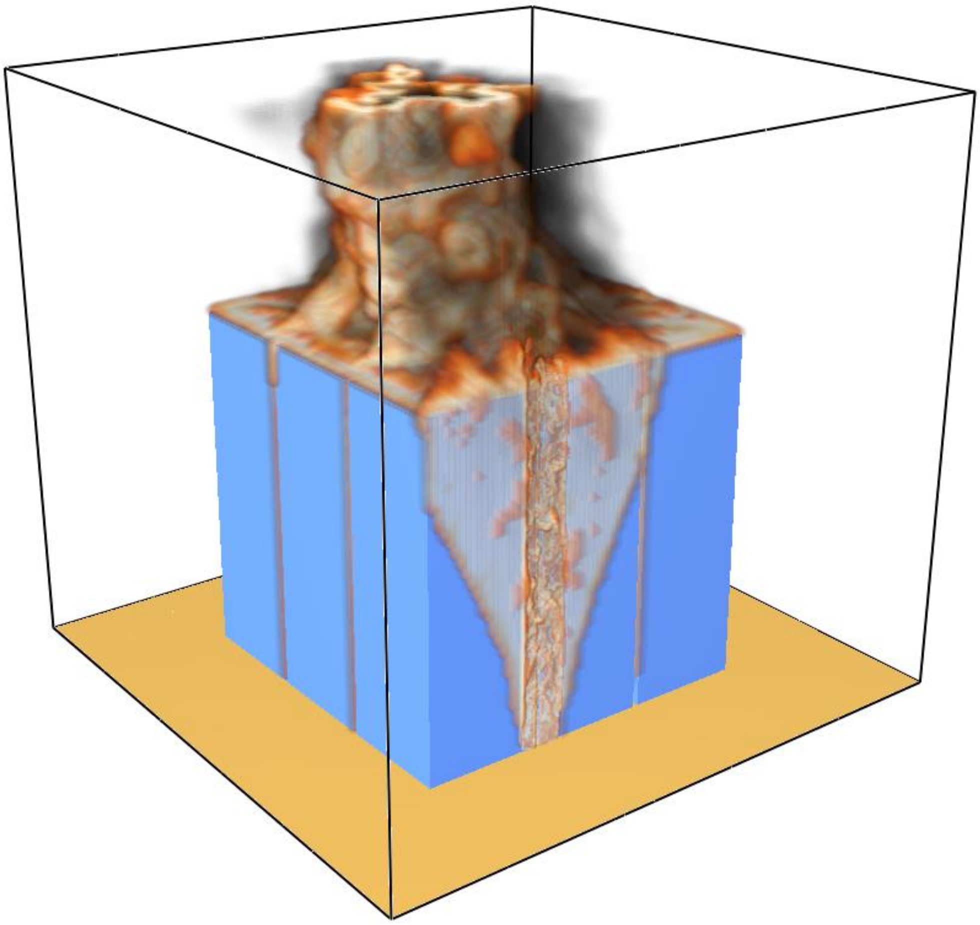


Figure 160: Smoke view image of the FDS fire Model.

The model generated a very similar fluid dynamic flow and a peak heat release rate of 10.4 MW. The model provided a good correlation with the empirical data. Therefore, this is a general theory for tall columns of combustible material placed in close proximity of each other.

6. Numerical simulations of whirling flames

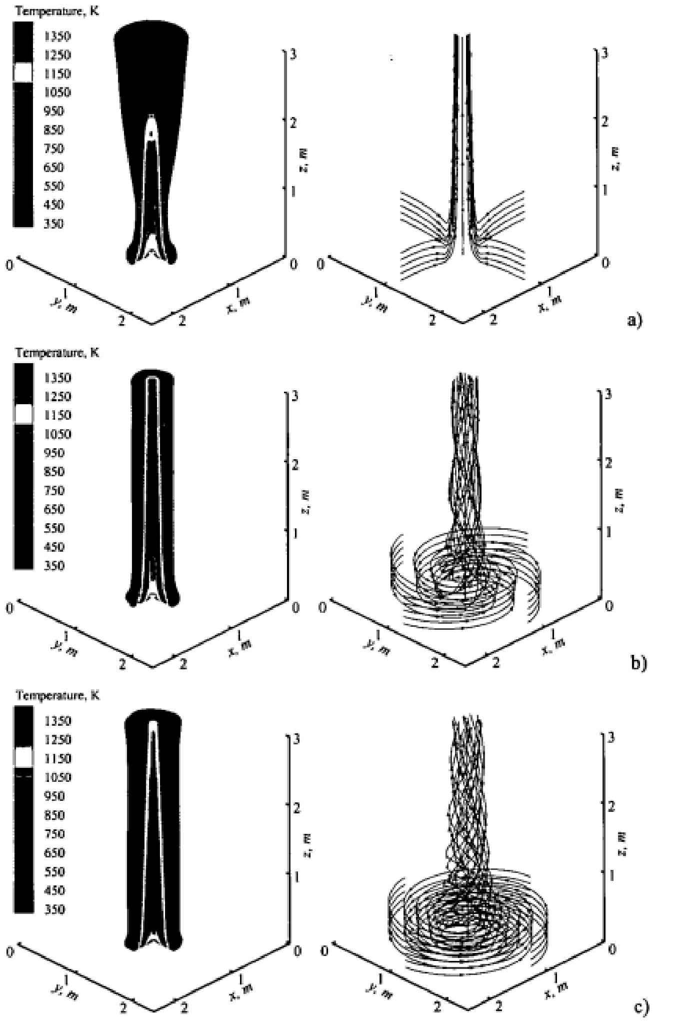


Fig. 6.1. Steady state mean temperature fields and mean-flow streamlines in a 516 kW flame: a) Γ_0 = 0 m²/s; b) Γ_0 = 1.45 m²/s; c) Γ_0 = 4.35 m²/s.

96

Figure 161: Extract from James A. Marsden 2005 (68)

Comparing the empirical images of the vortex formation and the velocity data from the CFD model it is apparent that:

$$u(x) = -\frac{\tau^0}{2\pi}\frac{y-y_0}{(x-x_0)^2+(y-y_0)^2}, y = 0, y_{max}$$

Equation 15: whirling flame equation 6.1 (68)

$$v(y) = -\frac{\tau^0}{2\pi} \frac{x - x_0}{(x - x_0)^2 + (y - y_0)^2}, x = 0, x_{max}$$

Equation 16: whirling flame equation 6.1 (30)

These describe a steady state fire with imposed rotational flows a circular pool fire fuel source. Clearly the fuel bed will generate a buoyant flame condition and therefore, Heskestad' s equation (65) seems to be the logical starting point. However, this research has limitation with regard to its applicability to this study most notably the flows generated in these studies imposed the rotational motion by placing physical deflectors to induce the initial motion. It is clear from the numerous tests conducted during this research project that the rotational motion in induced by the interaction of two vertically and parallel presented fuel beds.

$$L_f = 0.235\, Q^{*2/5} - 1.02D$$

Equation 17: Heskestad equation (64)

As was observed on each occasion the fire that generated the vortex was a fire at the base of the column. Heskestad mathematical model describes this well. However, this initial fire does not generate the fire vortex. But does generate two simulations fires on the vertical face of each stack this initial fire spread can be described by equation 10

$$\rho V \Delta H = q^*$$

Equation 18: William's equation 1977 (Drysdale, 2011)

Empirically it was observed that the critical column high to generate the vortex was approximately 2m although there is evidence that this is material dependent. For example, RDF generated the fire vortex at a column hight of 2.3m, where HDPE was just under the 2m range. At the critical column height CH_{crit} the combination of the pool fire with the addition of the two vertical flames reached a critical flame velocity FL_{crit} . At this point the vortex motion is imposed by the disparity in the ventilation factors.

In the CFD model we start to see a more complex picture of two zones of rotational flow either side of the vertical column that will be filled eventually with the fire vortex the slice below is taken a 1.5 m height. The flow velocities of the air in the gap behind the column has a slightly higher average velocity than the air entrained from the front of the fire. In a fire burning against a vertical surface, we would expect to see the flame being stretched up the vertical surface. Indeed, this is precisely what is initially observed. However, when the flame detaches from the fuel bed the rotational flow is entrained into the flames the two rotational flows cause the flame to rotate around each other which in turn increases the flame velocity general pressure and the fire vortex is formed. In effect the two vortices act like the deflector plates often used to induct fire vortices in experiments (68). While it is clear from experimentation that the is a critical column Height CH_{crt} > 1 for all the waste materials tested. It is reasonable to also conclude some other criteria. A minimum of two interacting flame fronts. This can reasonably be concluded from these experiments. It is strongly suspected that flame height and flame velocity are also critical factors. The fires were all started by an initial horizontal fire generating two adjacent flame fronts. Even the brick laid SRF fire the second column was self-generated when melting material pooled in the gap between the two baled that form the characteristic column. The problem is what effect does the interplay between the three fuel beds have on the initial fire development how much of the vertical plan fuel bed influences this fire behaviour.

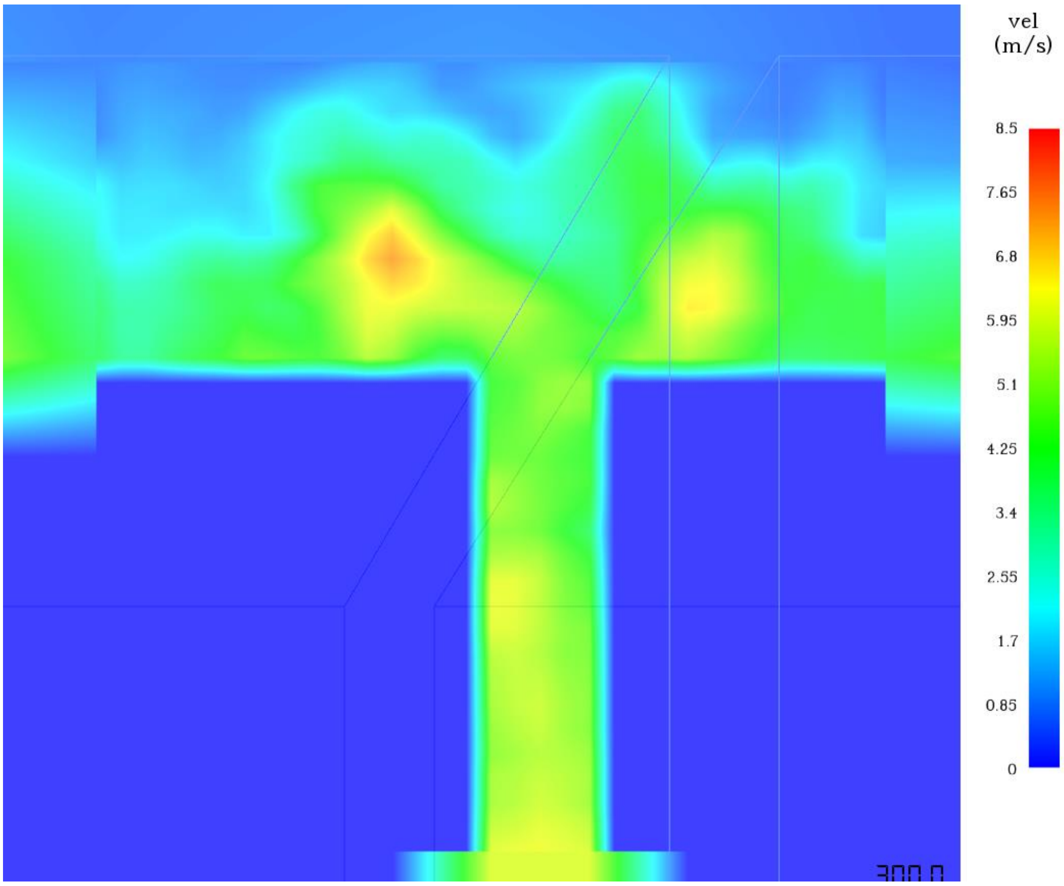


Figure 162 Diagram of the air flows around the bales at 1.5 m

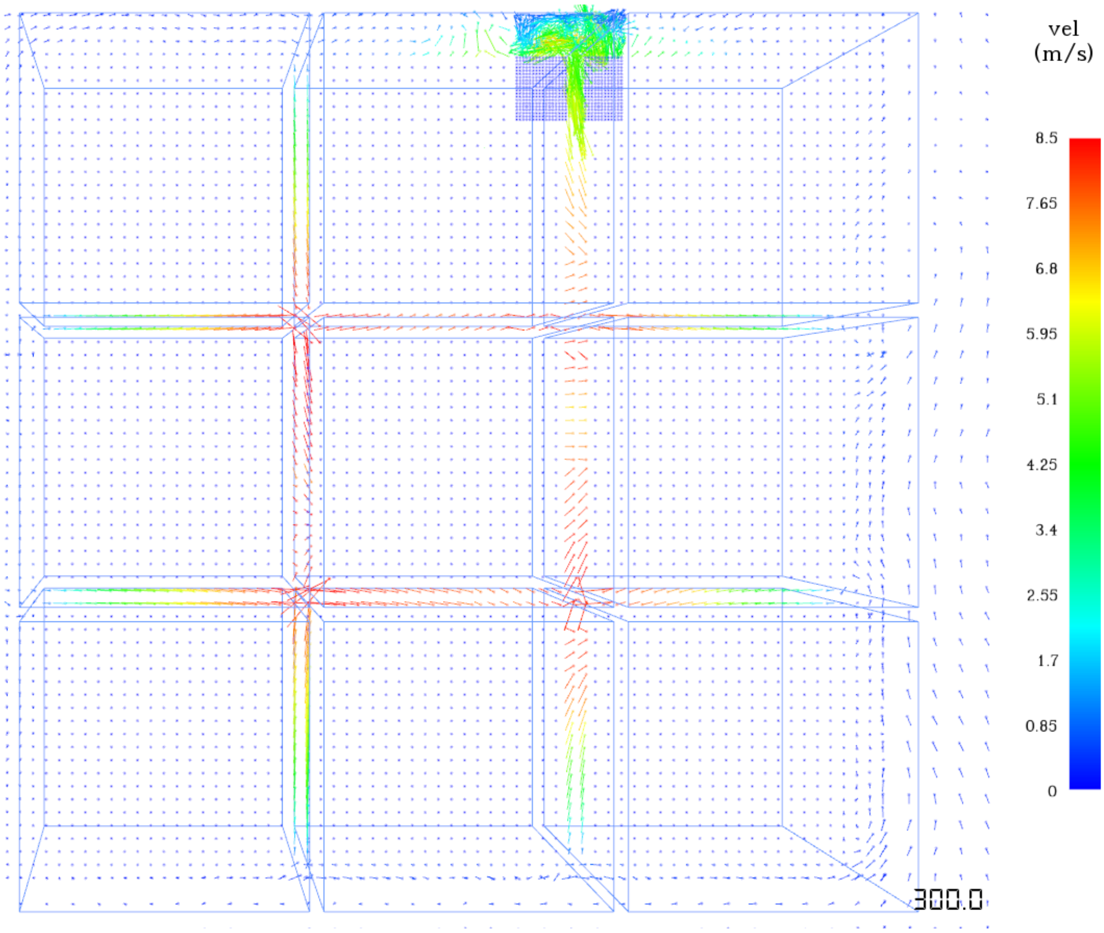


Figure 163: Vector slice of the CFD model

It is clear that when the two detached flame fronts begin to interact with sufficient flame velocity, they generate the fire vortex which quickly becomes the dominant system in the progression of the fire. The CFD model which was deliberately modelled with smooth linear sides and edges as opposed to the experimental condition which all had irregular surface. This provides a strong case to state that the formation of the vortex fire is the result of the influence of the Coriolis effect and not the irregular fuel bed. Once the opposing flame fronts begin to rotate around each other the convection currents provide the momentum to the system which continues to the vortex behaviour observed.

However, it, was necessary to provide the surface of the stacks with a thin layer of "mattress material" to allow the fire to take hold. Experience of modelling fires at unusual angles while working in the waste management industry has shown that the FDS combustion model from stock, struggle with unusual geometries. This then begs the question how much the CFD is the result of the modelling and how much would be repeated in the real world. The CFD modelling is, however, extremely useful in determining the type and location of instruments necessary to obtain empirical data in a new full-sized experiment.

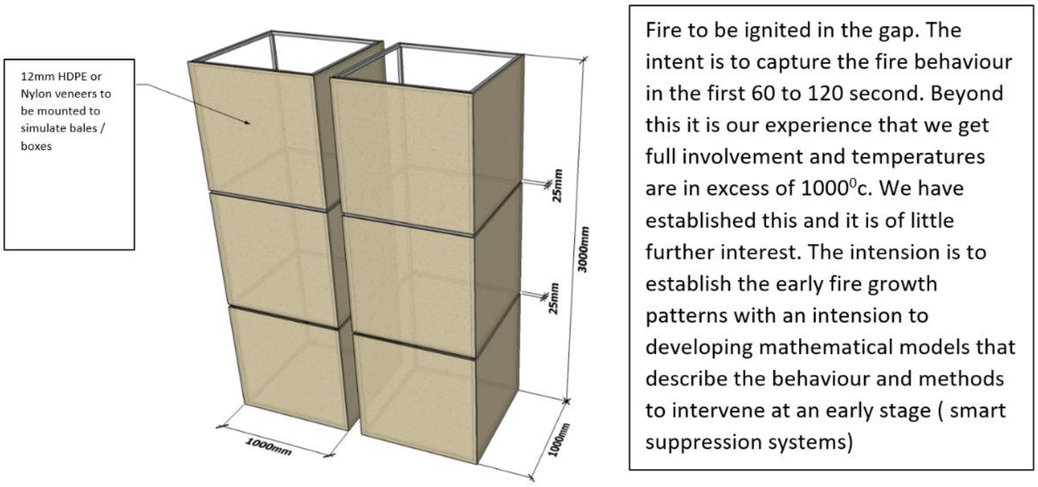


Figure 164 Diagram of proposed new experiment

The experiment detailed in figure 161 above is currently under development and further funding is being sort to conduct this experiment. The regions around the gaps will be monitored with thermocouples and pitot tubes both in the gaps and around the regions of interest indicated by the CFD modelling. This will provide validation for the CFD approach and provide the necessary data to be able formulate a mathematical model to describe the formation of a vortex fire with two vertical fuel beds.

Chapter 7 Safe separation of stored waste

This chapter details how the data obtained during the fire tests has been used to establish safe storage conditions. Two approaches are examined the first is the safe separation distance between stored waste based on the incident radiated heat transfer between the fire and the adjacent waste. The second method introduces fire resisting construction. The waste management industry favour portable concrete block. These tend to be sizable and designed to interlock. There are a number of manufactures of these blocks however, LEGIO provided sponsorship for this project and as a result only their concrete blocks were tested.

10. Radiated heat analysis

10.1 Calculation of safe separation distance to prevent fire spread due to radiated heat transfer.

An in-house computer program was used to perform 3-dimensional thermal radiation heat transfer simulations considering a number of user-defined input data.

This computer program is developed in Microsoft Excel and linked with VBA (using a Visual Basic Script). It carries out 3-dimensional analysis of heat transfer by radiation. The analysis is based on the fundamental physics of thermal radiation, as shown below.

The radiative heat flux emitted is calculated from the following equation.

$$I_e = \varepsilon \sigma T^4$$

Where: I_e = Radiation flux emitted (kW/m^2)

ε = Emissivity (in this analysis, taken as 0.9)

σ = Stefan-Boltzmann constant (5.670367×10^{-8} $Wm^{-2}K^{-4}$)

T = Absolute temperature of emitter (K)

Equation 19 Stefan Boltzmann radiated flux equation

For any small radiating surface, the level of radiation that is received can then be calculated from the following.

$$I_r = (A \cos \theta_1 \cos \theta_2 I_e)/(pS^2)$$

Where:

I_r = Incident radiation flux received (kW/m^2)

A = Area of emitter (m^2)

θ_1 = Angle between a normal to the emitting surface and a line between the emitter and receiver (degrees)

θ_2 = Angle between a normal to the receiving surface and a line between the emitter and receiver (degrees)

S = Separation distance between emitter and receiver (m)

The calculation above is accurate for 'small' radiating surfaces. When dealing with large radiating surfaces it is necessary to break the radiating surface into a number of smaller units. The same applies to the receiving surface, which needs to be broken down into a number of units. The more the units used in the analysis the more accurate the results. The above calculation is performed for i * j times where i is the units consisting of the emitter's surface and j is the number of units consisting of the receiver's surface. As there are many combinations of i and j, the calculation is very intensive and so a computer program has been used. This is further demonstrated below.

Initially the real fire data was analysed by comparing the K Type thermocouple data of the data point collecting data at the surface of the pile only. From this a stylised typical fire curve was derived see the proceeding to figure.

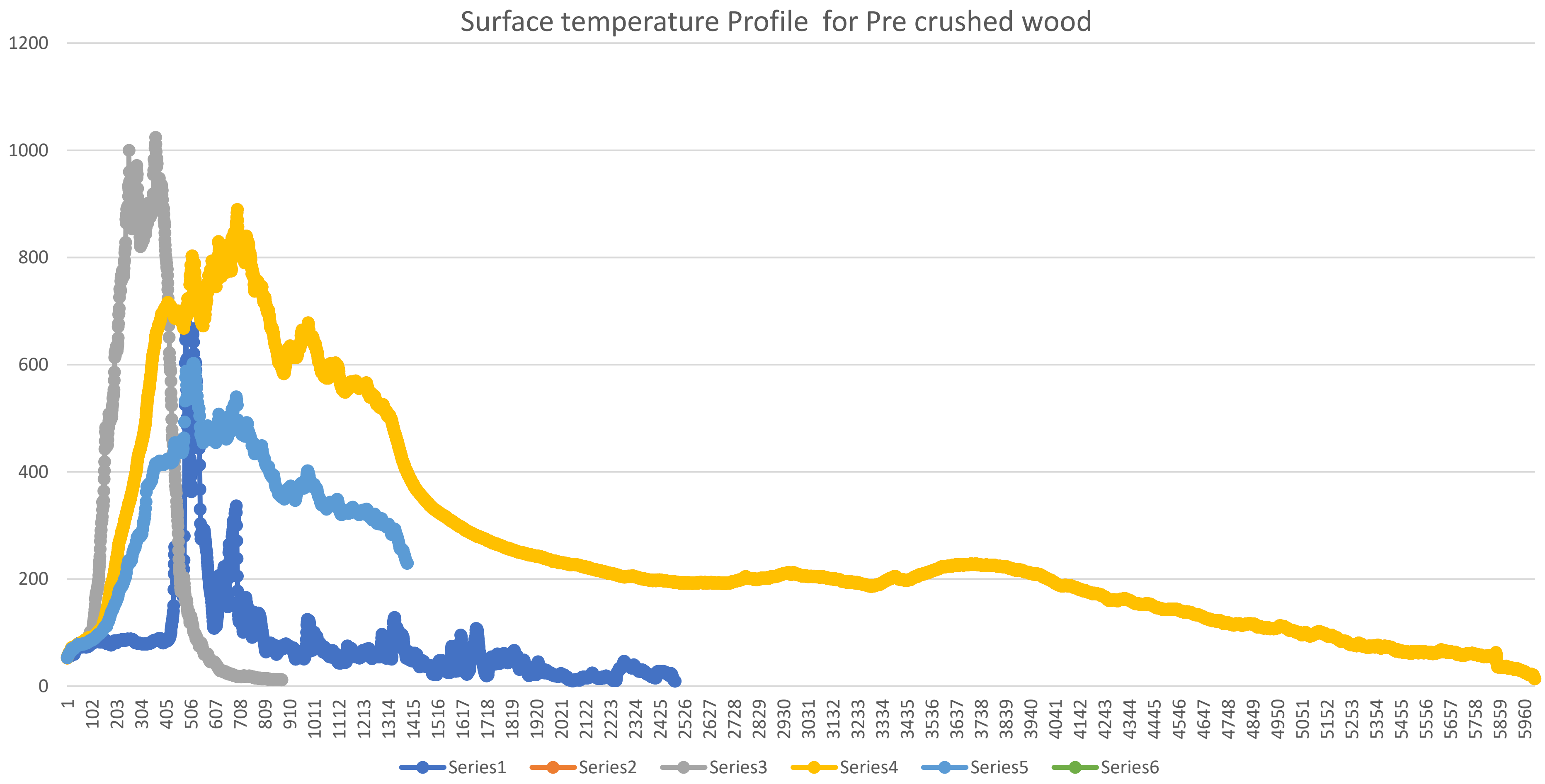


Figure 165: thermal data collected at the surface of the pile

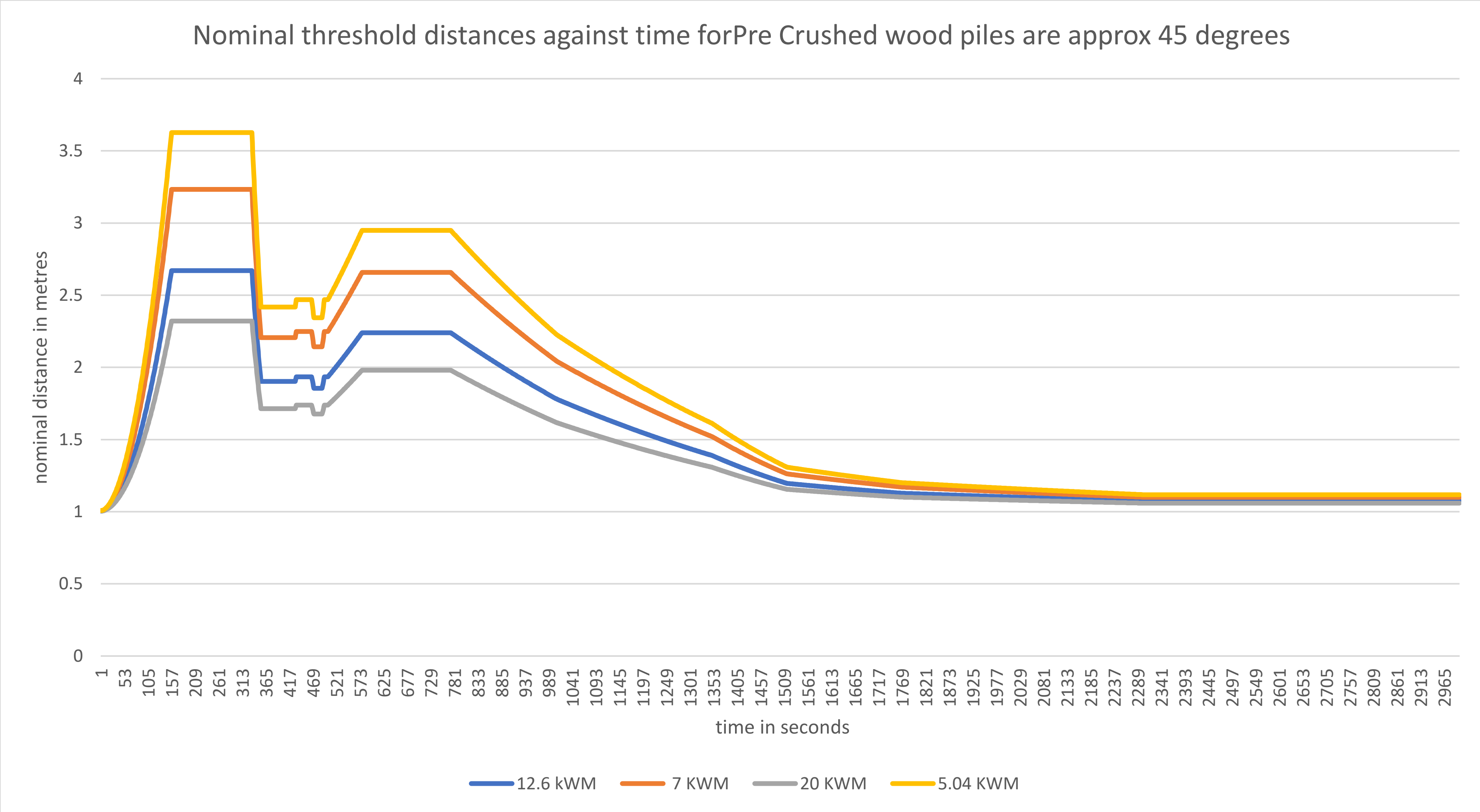


Figure 166: boundary distances based on designated thresholds

The heat flux thresholds were set after a review of relevant literature Babrauskas (26) was particularly useful for wood. The 5.04 KWm^{-2} was the average of the lowest stated figures and 20 KWm^{-2} was a consistent rate that would generate un-piloted ignitions. 12.6 KWm^{-2} is the stated threshold in the English Approved Document B for the application of the building regulations, 7 KWm^{-2} was used to provide a mid-way point for display proposes at the information is intended for the consumption of lay persons

This project approach was further developed is to establish the safe separating distance between waste bale stacks, piles or buildings to avoid fire spreading in a waste recycling site.

To estimate these safe separation distances, two approached were followed. It was concluded that method 2 is a more robust approach to be followed for such an analysis.

Determine the emitted thermal radiative heat flux from the bale stack or pile on fire. This can be done by examining the results of the on-site full scale test that were carried out and documented in report Sangster 2016 (90). Having determined the emitting radiative heat flux the thermal and ignition properties of the materials on the receiver (adjacent bale stack, pile or building) should be determined. The thermal properties include the; thermal conductivity, density and specific heat whereas the ignition properties include the; ignition temperature and latent heat. Having determine these, a transient state 3-dimensional heat transfer analysis can be performed using a Finite Element Analysis (FEA) software to predict the separating distance required to avoid ignition on the receiver under consideration for a certain time period.

Determine the emitted thermal radiative heat flux from the bale stack or pile on fire. This can be done by examining the results of the on-site full scale test that IFC carried out and documented in the report (90). A preliminary examination of the radiation expected at 6m was carried out later that year Sangster 2016 (91). WISH supplied a series of emitters and target that they wanted analysing to complete the second edition of the WISH Guide (5). Determine the critical received radiative heat flux on the receiver (adjacent bale stack, pile or building) that will cause ignition. Perform an advanced 3-dimentional radiative heat transfer analysis to determine the critical separation distance to avoid spread of fire by evaluating the radiative heat flux on the receiver's surface.

On this basis proposed to follow method 2 and undertake an in depth research with the view of determining a credible critical radiative heat flux for the waste types under consideration, similar to the one recommended in the Building Regulations Guidance (12.6kW/m^2) for wood.

The critical heat flux to ignite a bale stack or a pile has been established through literature as discussed. With the assistance of Marios Alexandro to peer review the modelling.

The worst case scenarios were considered based on the experimental data and the following model was produce in a report Alexandro & Sangster 2017 (71) for the WISH committee.

10.2 The emitting fires

Stacked bales (or cut out piles) with a flame temperature of 950^0C

This test was repeated 4 times in varying weather conditions typical maximum flame height observed was 1 m and peak flame temperature was 950^0C. Each bale stack consists of wood, paper, textiles, SRF, RDF & Card. The red line shows how the emitting surface has been modelled.

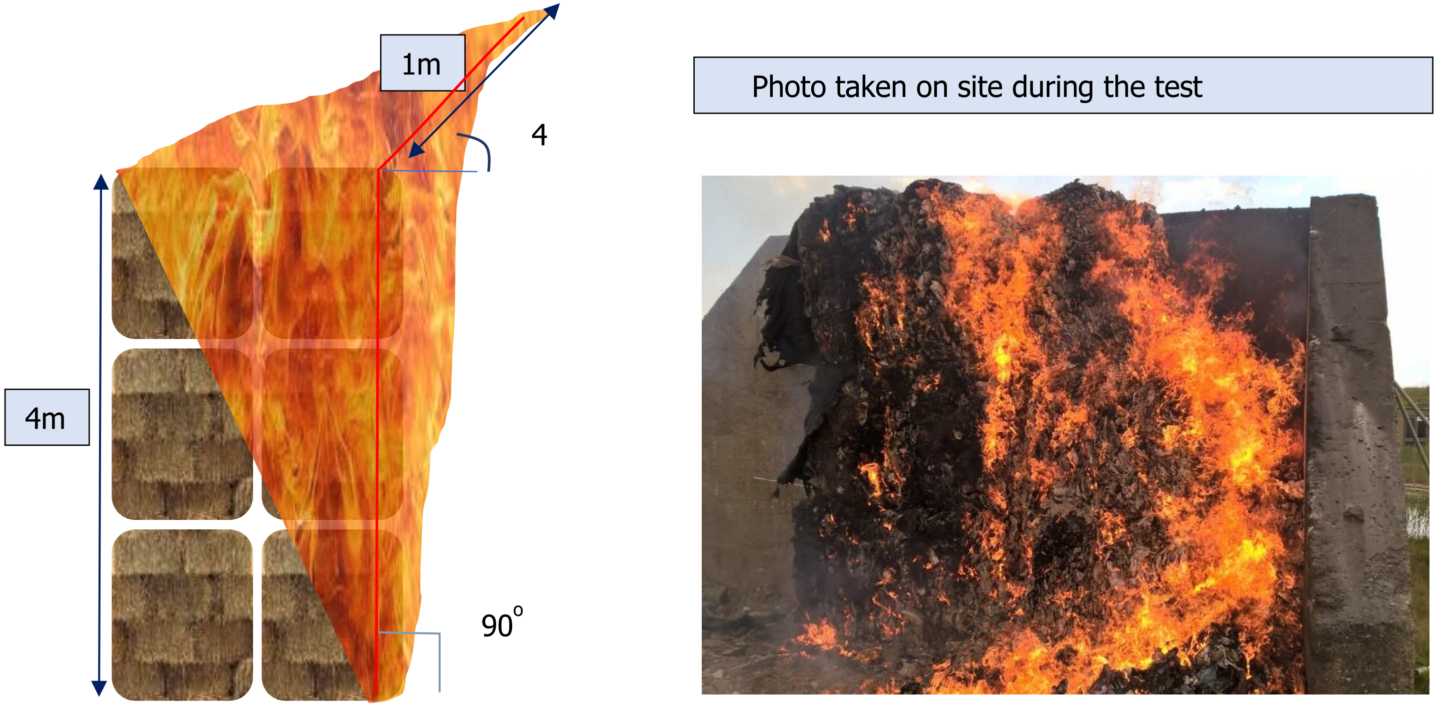


Figure 167: General wastes stacked bales resulting in flame temperature of 950°C

Stacked bales (or cut out piles) with an emitting surface of 1200^0C

During the tests, bale stacks consisting only plastic resulted in 1200^0C flame temperature and extended flame column of 3m. The red line shows how the emitting surface has been modelled.

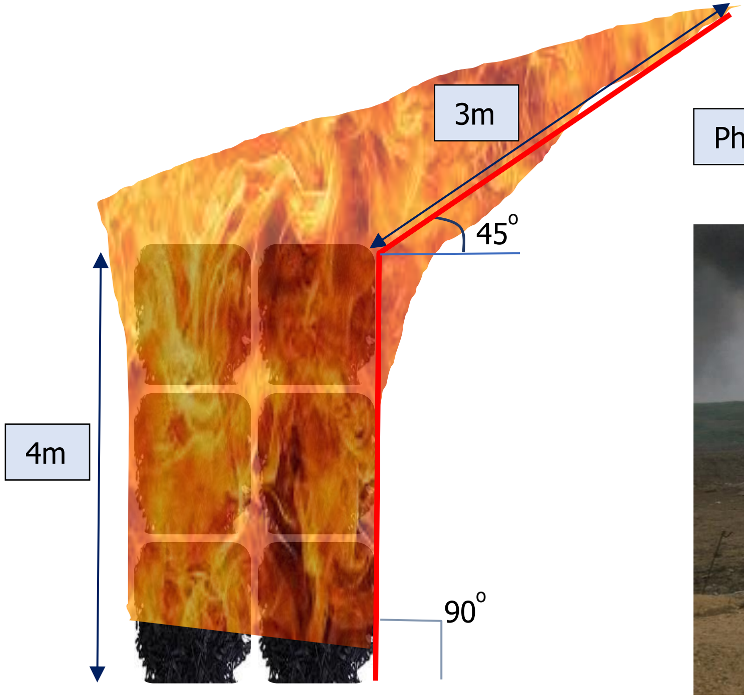


Photo taken on site during the test

Figure 168: Plastic waste stacked bales resulting in flame temperature of 1200^oC

Piled waste with 45^0 emitting surfaces deep seated ignition 950^0C

Deep seated ignition has been observed to result in a fuel controlled fire with steady state heat output of 950^0C flame temperature and a typical 1 m flame length. The pile consists of wood, paper, textiles, SRF, RDF & Card. The red line shows how the emitting surface has been modelled.

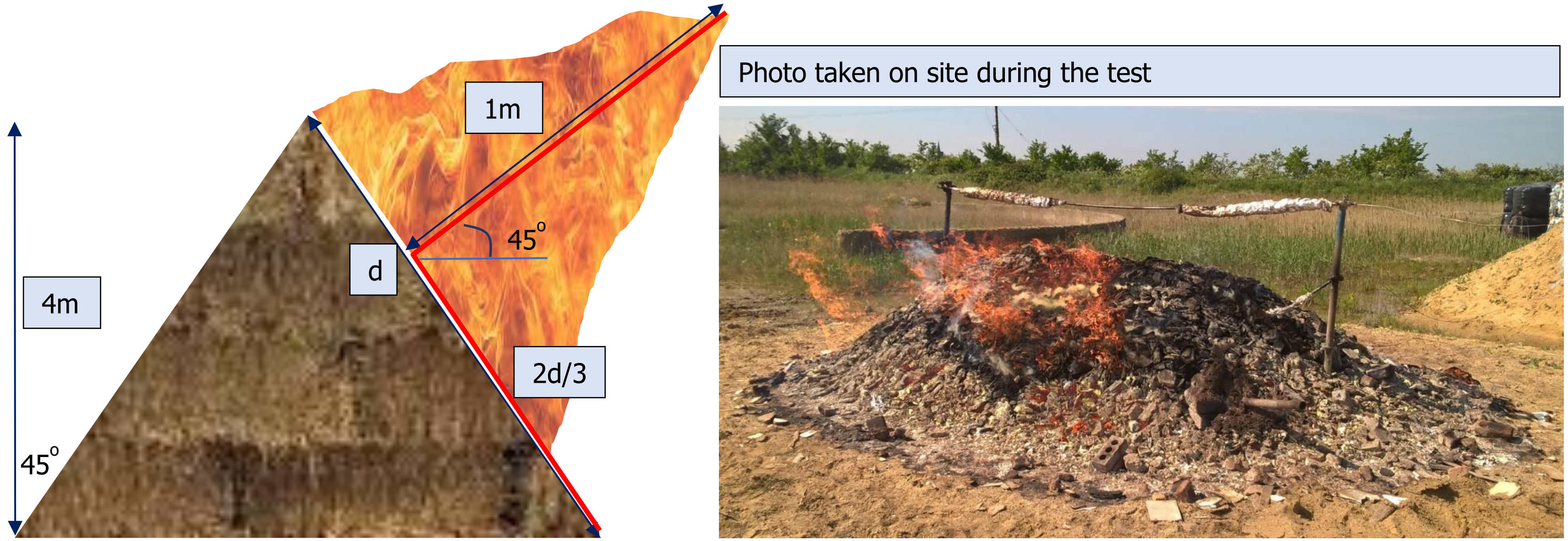


Figure 169: General piled wastes resulting in flame temperature of 950°C

Piled waste with 45^0 emitting surfaces deep seated ignition 1200^0c

The rubber piled waste resulted in a flame temperature of 1200^0C and an extended flame column of 3m similar to the plastic pile. The red line shows how the emitting surface has been modelled.

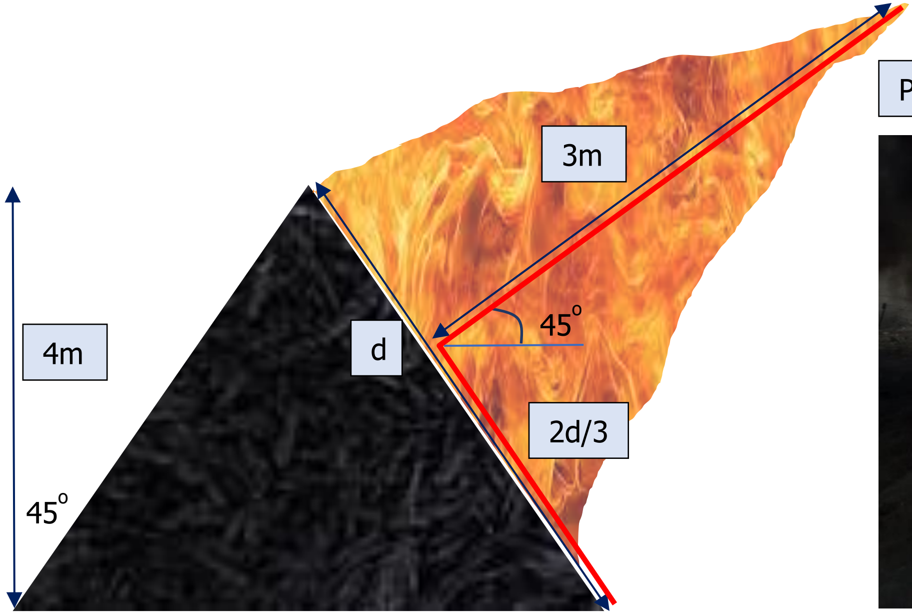


Photo taken on site during the test

Figure 170: Plastic piled wastes resulting in flame temperature of 1200°C

The Receivers

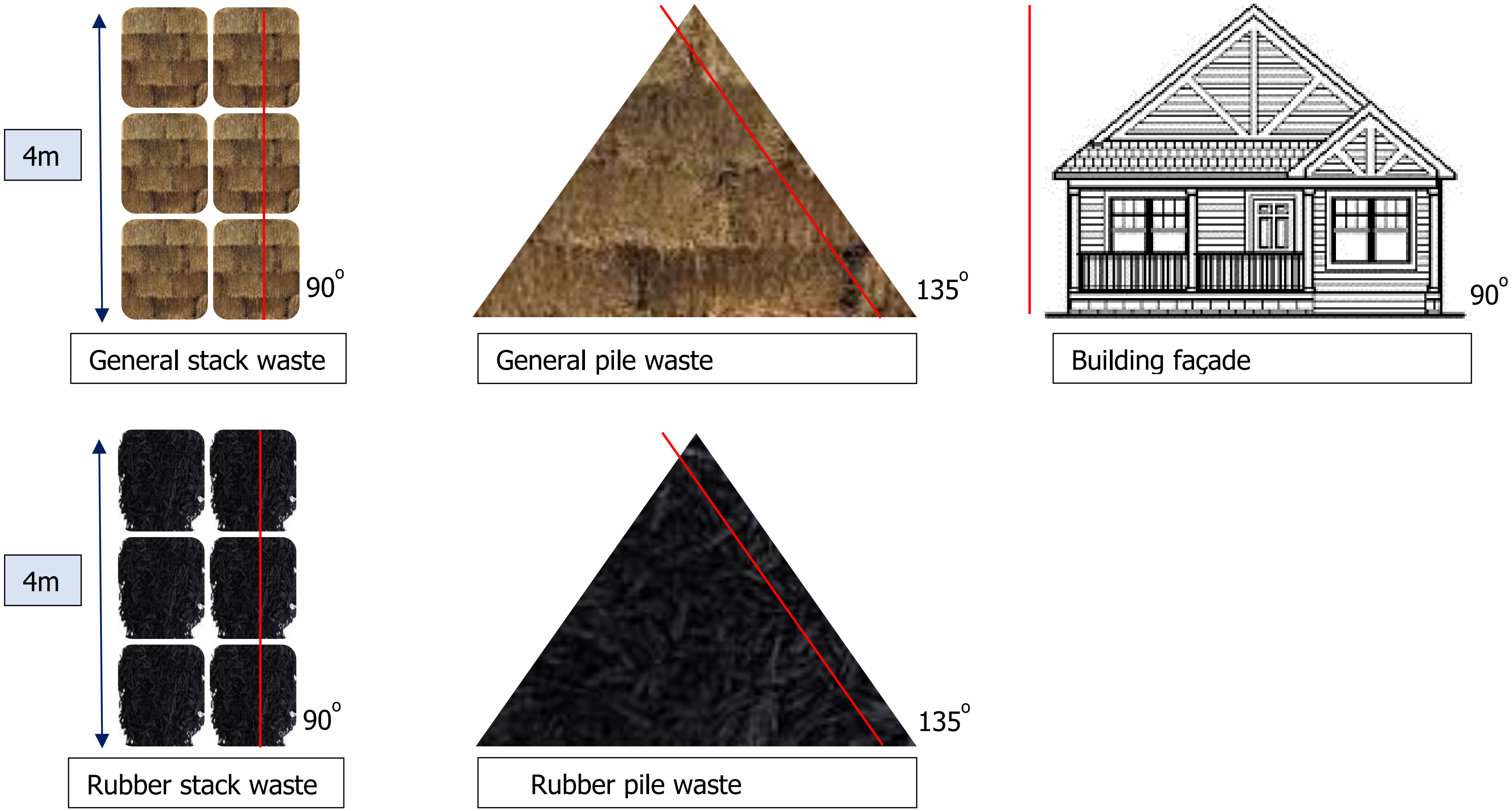


Figure 171: Modelled receivers

Note: The red lines indicate the modelled surface of the receivers.

Modelled geometry

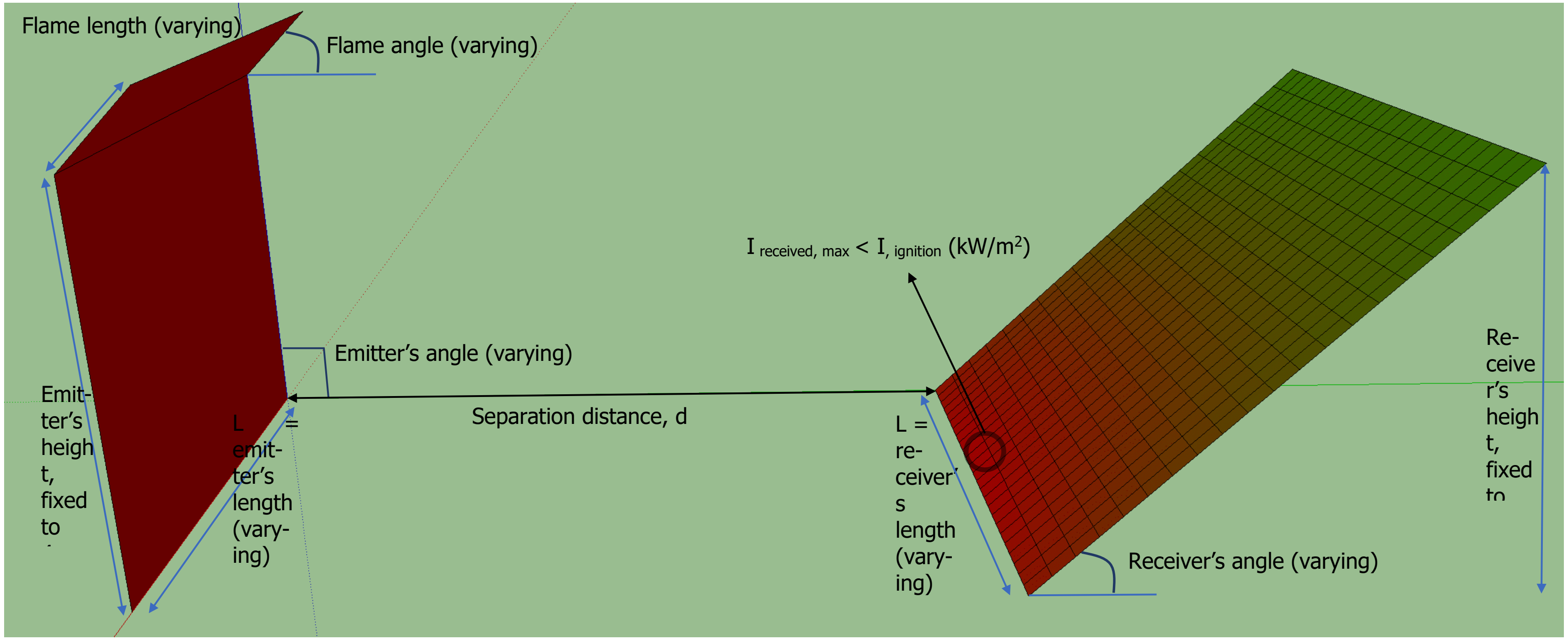
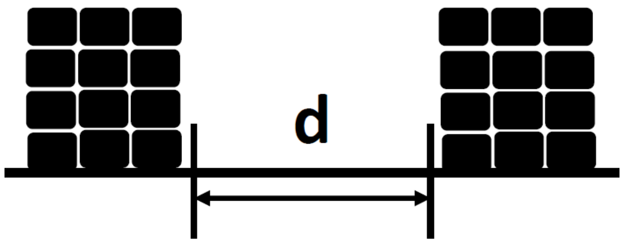


Figure 172: Modelled geometry

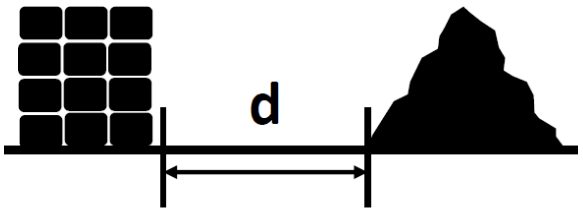
All dimensions other than the height of the receiver and the emitter vary according to each scenario.

Assessed Scenarios

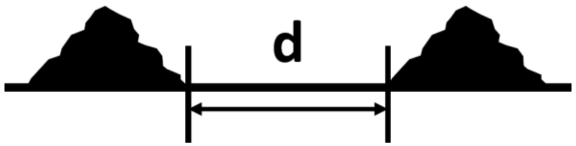
Scenarios 1-6: 90º emitter @ 950ºC – 90º receiver

A. General wastes (wood, paper, SRF, RDF etc) max burn temperature 950°C							**Waste stack to waste stack**
Scenario No.	Emitter Temperature (ºC)	Max allowable thermal heat flux on receiver (kW/m²)	Height of the waste stacks (m)	Length of emitter and receiver (m)	Angle of emitter and receiver	Separation distance, d (m)	Example
1	950	10	4	5	Both 90º	9.1	
2	950	10	4	10	Both 90º	12.6	
3	950	10	4	15	Both 90º	15.0	
4	950	10	4	20	Both 90º	17.0	
5	950	10	4	30	Both 90º	19.7	
6	950	10	4	50	Both 90º	23.0	

Scenarios 7-12: 90° emitter @ 950°C – 45° receiver

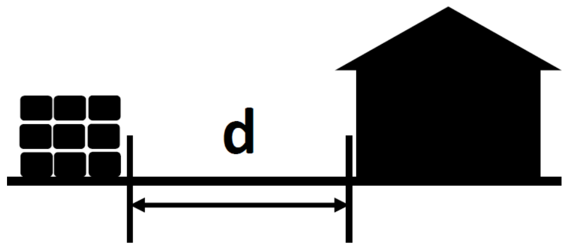
A. General wastes (wood, paper, SRF, RDF etc) max burn temperature 950°C						**Waste stack to waste stack**	
Scenario No.	Emitter Temperature (°C)	Max allowable thermal heat flux on receiver (kW/m^2)	Height of the waste stacks (m)	Length of emitter and receiver (m)	Angle of emitter and receiver	Separation distance, d (m)	Example
7	950	10	4	5	Emitter 90° - receiver 45°	8.1	
8	950	10	4	10	Emitter 90° - receiver 45°	11.2	
9	950	10	4	15	Emitter 90° - receiver 45°	13.3	
10	950	10	4	20	Emitter 90° - receiver 45°	14.8	
11	950	10	4	30	Emitter 90° - receiver 45°	16.9	
12	950	10	4	50	Emitter 90° - receiver 45°	19.2	

Scenarios 13-18: 45º emitter @ 950ºC – 45º receiver

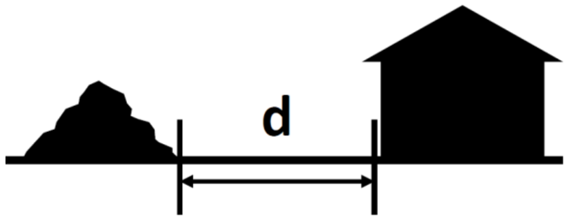
A. General wastes (wood, paper, SRF, RDF etc) max burn temperature 950°C						**Waste stack to waste stack**	
Scenario No.	Emitter Temperature (ºC)	Max allowable thermal heat flux on receiver (kW/m^2)	Height of the waste stacks (m)	Length of emitter and receiver (m)	Angle of emitter and receiver	Separation distance, d (m)	Example
13	950	10	4	5	Emitter 45° - receiver 45°	4.9	
14	950	10	4	10	Emitter 45° - receiver 45°	7.2	
15	950	10	4	15	Emitter 45° - receiver 45°	8.7	
16	950	10	4	20	Emitter 45° - receiver 45°	9.7	
17	950	10	4	30	Emitter 45° - receiver 45°	11	
18	950	10	4	50	Emitter 45° - receiver 45°	12.1	

Scenarios 19-24: 90° emitter @ 950°C – building

B. General wastes (wood, paper, SRF, RDF etc) max burn temperature 950°C						**Waste stack to waste stack**	
Scenario No.	Emitter Temperature (°C)	Max allowable thermal heat flux on receiver (kW/m²)	Height of the waste stack (m)	Length of emitter and receiver (m)	Angle of emitter and receiver	Separation distance, d (m)	Example
19	950	12.6	4	5	Both 90°	8	
20	950	12.6	4	10	Both 90°	11.1	
21	950	12.6	4	15	Both 90°	13.1	
22	950	12.6	4	20	Both 90°	14.7	
23	950	12.6	4	30	Both 90°	16.9	
24	950	12.6	4	50	Both 90°	19.3	

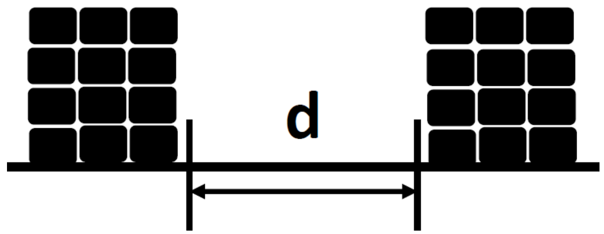


Scenarios 25-30: 45° emitter @ 950°C – building

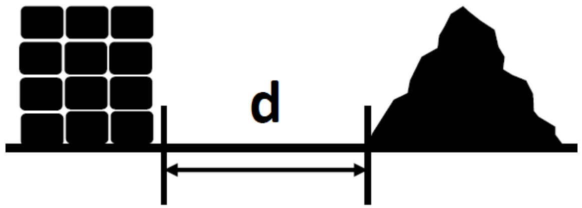
B. General wastes (wood, paper, SRF, RDF etc) max burn temperature 950°C						**Waste stack to waste stack**	
Scenario No.	Emitter Temperature (°C)	Max allowable thermal heat flux on receiver (kW/m^2)	Height of the waste stack (m)	Length of emitter and receiver (m)	Angle of emitter and receiver	Separation distance, d (m)	Example
25	950	12.6	4	5	Emitter 45° - receiver 90°	6.5	
26	950	12.6	4	10	Emitter 45° - receiver 90°	9.4	
27	950	12.6	4	15	Emitter 45° - receiver 90°	11.4	
28	950	12.6	4	20	Emitter 45° - receiver 90°	12.9	
29	950	12.6	4	30	Emitter 45° - receiver 90°	14.9	
30	950	12.6	4	50	Emitter 45° - receiver 90°	17.1	

Scenarios 31-36: 90° emitter @ 1200°C – 90° receiver

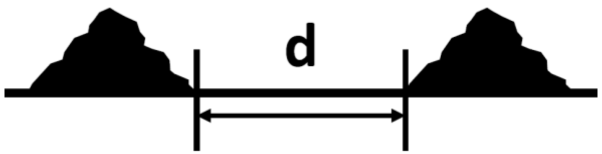
C. Plastic and rubber wastes max burn temperature 1,200°C						**Waste stack to waste stack**	
Scenario No.	Emitter Temperature (°C)	Max allowable thermal heat flux on receiver (kW/m²)	Height of the waste stacks (m)	Length of emitter and receiver (m)	Angle of emitter and receiver	Separation distance, d (m)	Example
31	1200	10	4	5	Both 90°	14.1	
32	1200	10	4	10	Both 90°	19.6	
33	1200	10	4	15	Both 90°	23.8	
34	1200	10	4	20	Both 90°	27	
35	1200	10	4	30	Both 90°	32.3	
36	1200	10	4	50	Both 90°	39.8	



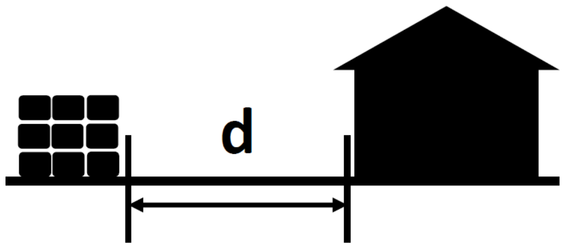
Scenarios 37-42: 90° emitter @ 1200°C – 45° receiver

C. Plastic and rubber wastes max burn temperature 1,200°C						**Waste stack to waste stack**	
Scenario No.	Emitter Tempera-ture (°C)	Max allowable thermal heat flux on receiver (kW/m²)	Height of the waste stacks (m)	Length of emitter and receiver (m)	Angle of emitter and receiver	Separation distance, d (m)	Example
37	1200	10	4	5	Emitter 90° - receiver 45°	12.7	
38	1200	10	4	10	Emitter 90° - receiver 45°	17.5	
39	1200	10	4	15	Emitter 90° - receiver 45°	20.9	
40	1200	10	4	20	Emitter 90° - receiver 45°	23.6	
41	1200	10	4	30	Emitter 90° - receiver 45°	27.9	
42	1200	10	4	50	Emitter 90° - receiver 45°	33.6	

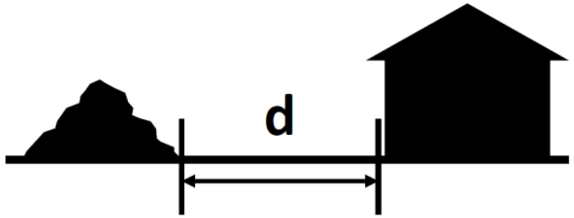
Scenarios 43-48: 45° emitter @ 1200°C – 45° receiver

C. Plastic and rubber wastes max burn temperature 1,200°C						**Waste stack to waste stack**	
Scenario No.	Emitter Temperature (°C)	Max allowable thermal heat flux on receiver (kW/m^2)	Height of the waste stacks (m)	Length of emitter and receiver (m)	Angle of emitter and receiver	Separation distance, d (m)	Example
43	1200	10	4	5	Emitter 45° - receiver 45°	10.7	
44	1200	10	4	10	Emitter 45° - receiver 45°	15.4	
45	1200	10	4	15	Emitter 45° - receiver 45°	18.7	
46	1200	10	4	20	Emitter 45° - receiver 45°	21.3	
47	1200	10	4	30	Emitter 45° - receiver 45°	25.4	
48	1200	10	4	50	Emitter 45° - receiver 45°	30.9	

Scenarios 49-54: 90° emitter @ 1200°C – building

D. Plastic and rubber wastes max burn temperature 1,200°C						**Waste stack to waste stack**	
Scenario No.	Emitter Temperature (°C)	Max allowable thermal heat flux on receiver (kW/m²)	Height of the waste stack (m)	Length of emitter and receiver (m)	Angle of emitter and receiver	Separation distance, d (m)	Example
49	1200	12.6	4	5	Emitter 90° - receiver 90°	12.5	
50	1200	12.6	4	10	Emitter 90° - receiver 90°	17.4	
51	1200	12.6	4	15	Emitter 90° - receiver 90°	21	
52	1200	12.6	4	20	Emitter 90° - receiver 90°	23.8	
53	1200	12.6	4	30	Emitter 90° - receiver 90°	28.1	
54	1200	12.6	4	50	Emitter 90° - receiver 90°	34.5	

Scenarios 55-60: 45° emitter @ 1200°C – building

D. Plastic and rubber wastes max burn temperature 1,200°C						Waste stack to waste stack	
Scenario No.	Emitter Temperature (°C)	Max allowable thermal heat flux on receiver (kW/m^2)	Height of the waste stack (m)	Length of emitter and receiver (m)	Angle of emitter and receiver	Separation distance, d (m)	Example
55	1200	12.6	4	5	Emitter 45° - receiver 90°	12.5	
56	1200	12.6	4	10	Emitter 45° - receiver 90°	17.9	
57	1200	12.6	4	15	Emitter 45° - receiver 90°	21.8	
58	1200	12.6	4	20	Emitter 45° - receiver 90°	24.9	
59	1200	12.6	4	30	Emitter 45° - receiver 90°	30.2	
60	1200	12.6	4	50	Emitter 45° - receiver 90°	37.4	

The results are considered to be highly reliable whilst are on the conservative side. The reasons for this are.

- It is assumed that each surface of the ignited bale stack or pile is involved in the fire.
- The temperature on each emitting surface has been considered to be uniform throughout and entire emitting surface and constant at a value equal to the highest flame temperature captured in the tests for the case under consideration.
- The emissivity of the flames has been assumed to be 0.9. (Normally lower for both cellulosic and plastic materials)
- The emitter and receiver orientation has been selected based on the most "reasonable worst case" scenario, i.e., facing each other, resulting in the highest possible configuration factor.
- It has been assumed that the wind will be lining the flame towards the receiver at 45^o.

The minimum required heat flux to ignite the pile is assumed to be 10 kW/m^2. (Literature considered 15 kW/m^2 for similar cases.)

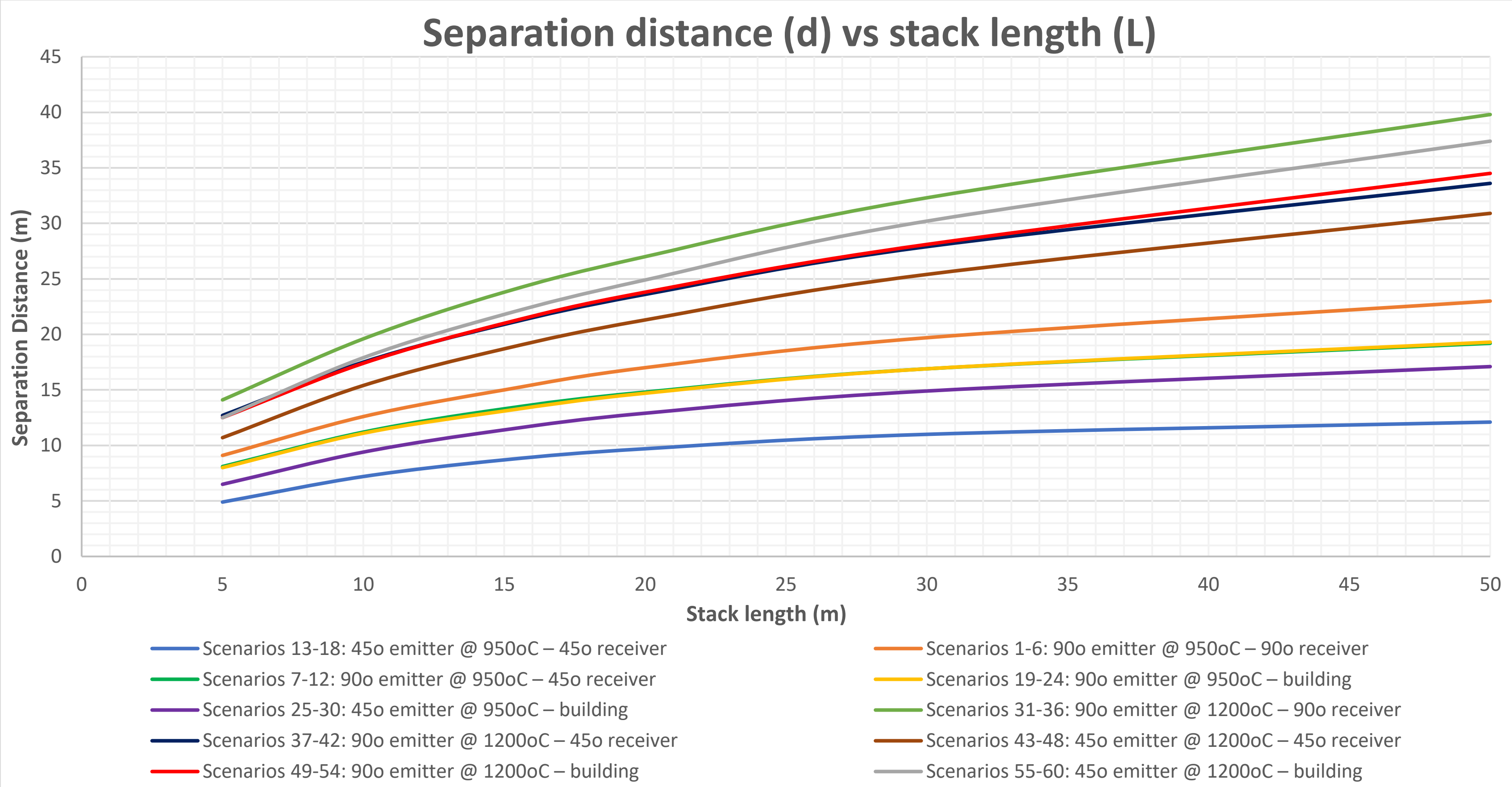
The thermal radiation attenuation has been assumed to be 1 i.e., no thermal losses due to humidity or winds.

It is assumed that the flames retain their dimensions (length) and orientation regardless the natural fluctuations in length or variability of the wind direction.

The spread of fire through flying burning debris has not been considered.

Results

The results of the simulations are provided below in a graphical representation.



Note: Dimensions d and L are as show

Figure 173: Graph showing separation distance of a 4 m high stack

11. Real fire data and direct observation.

11.1 Analysis of PHE/EA/Fire Service data.

Part of the research included analysis of prolonged fires over a 6-year period from 2011 to 2017. To give context on the matter, a total number of 54 real incidents identified by PHE from EA and Fire Service real incident data were examined throughout the UK, including information requests by the author as per the Freedom of Information Act 2000. Various Fire and Rescue Authorities were contacted to obtain details of the fire service actions during these fires. These waste fires range from mixed waste sites to plastics and woodchip/pellet sites and occurred over a 6-year period from 2011 to 2017. The prolonged fires in question presented several challenges for Fire and Rescue Services in the fact that it took several hours/days to extinguish each blaze and required large proportions of available resources.

After delving into the logistics and highlighting the specific dates, days of the week and times these incidents started, the statistics give rise to several queries that require an in-depth investigation post report. Based on the statistical trends seen in the existing data, fires are more likely to occur at the very start or end of a month. Fires are also more likely to start at the start or end of a week, including over the weekends, and fires are most likely to occur between 08:00 and 17:59, and at mixed waste sites.

It is common practice at waste management sites to clear the input halls towards the end of the working week to make way for fresh collection on Mondays. Many sites close over the weekend or use the weekend for maintenance and to catch up on processing during busy periods for example after Christmas. This often entails heavy plant dragging the bucket of a bulldozer across the floor to scoop up the waste. The teeth on the buckets get heated due to the friction of the steel bucket being dragged along a concrete surface. The author has directly observed numerous small ignitions caused by this practice while visiting waste management sites. Another common practice is for heavy plant to drive over waste. This is a practice known as "tracking" in the industry. This is acknowledged to be a poor practice due to the risk of crushing aerosols and batteries within the waste stream and thus generating an ignition. However, data obtained during this project and also observed by Woodward during the Hawkins series of test on timber (insert ref) demonstrates the additional hazard of the temperature being raised by the act of compression of the materials. Woodward observed significant temperature rise when the heavy plant tracked over the edge of their test bed. During the construction of the firefighter tests a small temperature rise was recorded as people walked over the thermocouple locations.

As previously stated, analysis of the fire-related incidents in question reveals statistical trends. Figure 171 located in the appendix shows a chart which illustrates incidents that have happened at the start/end of the calendar month. Figure 172 displays a bar chart to display days of the week where incidents have started. For example, 29 of these incidents occurred within the first and last week of the calendar month. Which, when expressed as a percentage equals 53.7% of incidents starting at either end of the month. The reasoning behind this total figure remains an uncertainty however and bears further investigation.

Delving further to look at days of the week, the results equate to a staggering 92.6% of incidents occurring between Thursdays and Tuesdays, although strangely, the total number of fires occurring on the Wednesdays is only 4 incidents. The figures rise between the days of Saturday, Sunday, Monday and Tuesday and total 70% of the fires. Sunday, Monday and Tuesday specifically total 55.5% of incidents. Seemingly, the results indicate a common trend in fire likelihood across the days of the week and this should be investigated further by the relevant authorities to see why this is and what might be done about it.

To specify, Figure 173 shows a bar chart to present blocked time frames where incidents have started. The time frames in which these fires have occurred have been split accordingly into three categories: early hours, working hours and late hours. For example, from 00:00 to 07:59 expressed as a percentage sum up to 33.3%. However, from the working hours of 08:00 to 17:59 sees the largest percentage equalling to 44.4%. The final category from the evening hours of 18:00 to 23:59 equates to a modest 22.2%. Again, the results indicate a common trend of peak incident numbers at during specific time frames and therefore should be investigated further by the relevant authorities as is appropriate.

Ultimately, to conclude, the specific material types of each site were also considered when conducting this research and the statistics showed the largest proportion of incidents at mixed waste facilities equalling 33.3%. Wood and woodchip/ pellets on the other hand totalled 27.7%. However, the final figure is that mixed waste, wood, plastics, tyres and chemical sites all account for 83.2% of the total number of waste site fires.

Date Incident started	Time Incident started	Day
01/12/2012	12:00:00	1
01/12/2014	00:00:00	1
02/03/2014	23:23:00	2
02/06/2014	08:10:00	2
02/03/2017	19:00:00	2
02/05/2017	22:00:00	2
03/08/2013	04:30:00	3
03/09/2013	11:00:00	3
04/12/2012	12:00:00	4
04/12/2016	05:57:00	4
05/02/2017	08:21:00	5
06/07/2011	04:14:00	6
06/01/2013	00:00:00	6
07/07/2013	14:10:00	7
07/07/2015	01:57:00	7
08/08/2016	20:26:00	8
11/10/2011	12:25:00	11
11/10/2011	12:25:00	11
11/11/2012	01:00:00	11
13/11/2014	22:20:00	13
15/09/2012	22:30:00	15
16/06/2011	13:00:00	16
16/06/2013	17:19:00	16
16/01/2014	08:37:00	16
16/11/2015	12:00:00	16
16/04/2016	18:39:00	16
17/11/2015	11:21:00	17
18/01/2011	12:00:00	18
18/10/2012	01:00:00	18
18/03/2013	05:47:00	18
18/08/2014	06:48:00	18
18/07/2015	00:51:00	18
18/11/2016	12:00:00	18
20/08/2013	21:00:00	20
21/10/2012	21:35:00	21
21/07/2014	17:47:00	21
21/08/2016	00:00:00	21
21/09/2016	10:30:00	21
23/12/2013	06:00:00	23
25/09/2011	08:20:00	25
25/04/2015	10:25:00	25
25/04/2015	21:00:00	25
26/06/2013	03:24:00	26
26/11/2013	05:14:00	26
28/09/2011	14:23:00	28
28/09/2012	12:00:00	28
28/01/2014	16:30:00	28
29/12/2014	00:00:00	29
29/08/2015	00:00:00	29
29/09/2015	22:15:00	29
30/01/2014	23:10:00	30
30/01/2015	15:20:00	30
31/05/2015	17:00:00	31
31/08/2016	05:23:00	31

Figure 174: list of waste fires for which data PHE (92)

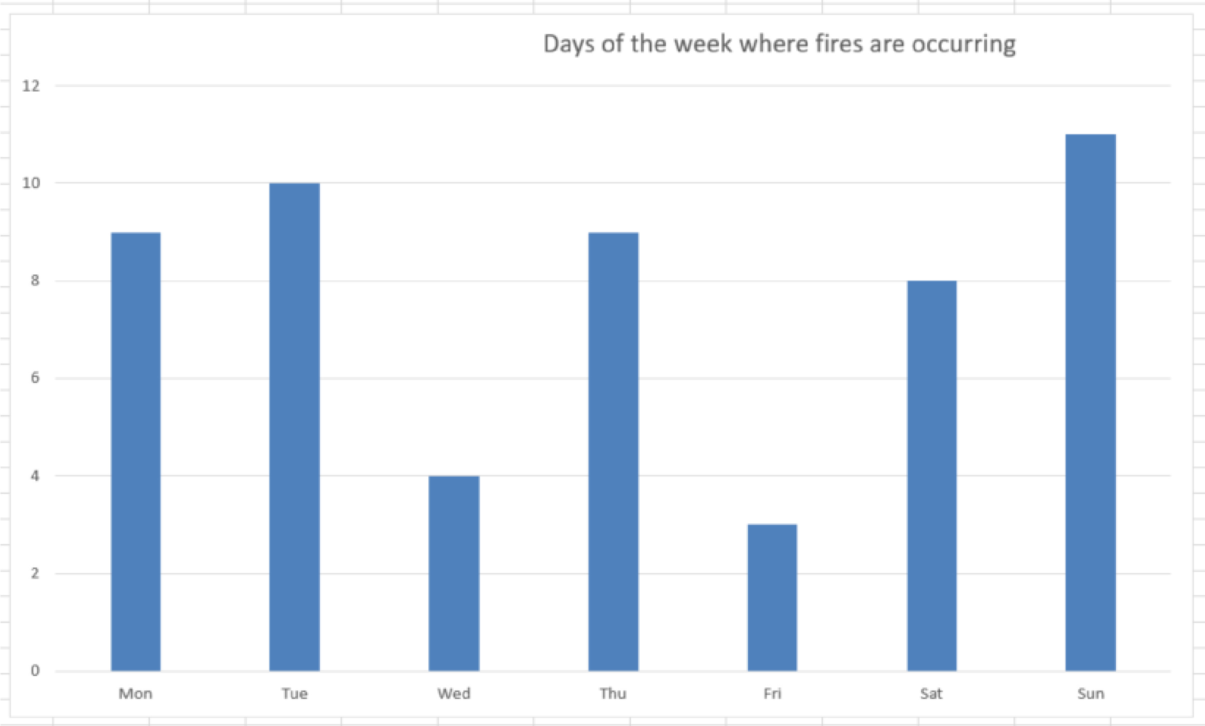


Figure 175: Bar chart showing blocked time frames where incidents have started. IFC (93)

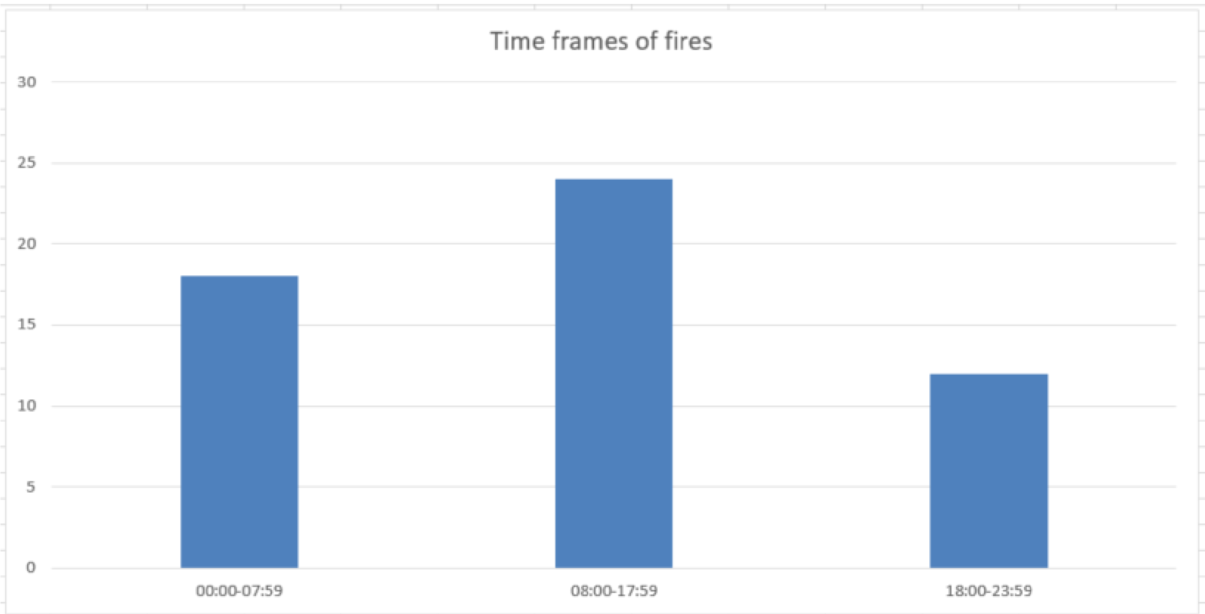


Figure 176: Times of day that the fires were reported IFC (93)

11.2 Fire engineering parameters

Based on the mass loss rates calculated during this research and using heat of combustion data from the SFPE handbook (15) the following table has been produced.

Materials	Mass loss Rate kg/s	Heat of combustion kj/kg	Heat Release Rate KJ/s	Time to burn 1Ton (hour)	Time to burn a typical pile 450m^3 (days)
Pre crushed wood surface ignition	0.15	19.5	2.925	1.85	8.2 days
Pre crushed wood surface ignition	0.04	19.5	0.78	6.9	31 days
Wood fines surface ignition free burn	0.01	19.5	1.95	2.8	18.8 days
Wood fines surface ignition char controlled	0.01	19.5	0.195	27.8	188 days
RDF surface ignition	0.03	8 (8-30)	0.24(0.4-0.9)	9.26	49.8 days
SRF surface ignition	0.07	13	0.91	3.97	24.2 days
Shredded tyres ventilated combustion	0.67	43.28	29	0.41	2.8 days
Shredded tyres char controlled	0.22	43.28	9	01.39	9.5 days
HDPE Bales	0.68	46.2	31	0.41	6.12 days
Pre crushed wood deep seated ignition	0.24	19.5	4.68	1.16	5.2 days

Table 14: Fire Engineering Parmiters

The typical waste pile is assumed to be a code compliant 450 m^3 which is a storage size that is applicable to all the materials in table 13. The densities have been assumed to be consistent with the values stated in the experimental details table 9 and HDPE compressed bales as 800 Kg based on invoice and weigh bridge data from the Barling landfill site. The masses are calculated using equation 2.

9.2 Maximum pile sizes

Waste type	Loose and more than 150mm	30 to 150mm or baled	Less than 30mm
Tyres and rubber	450 cubic metres	300 cubic metres	300 cubic metres
Wood	750 cubic metres	450 cubic metres	300 cubic metres
Compost and green waste (excluding during the active composting process)	750 cubic metres	450 cubic metres	450 cubic metres
RDF and SRF	450 cubic metres	450 cubic metres	450 cubic metres
Plastics	750 cubic metres	450 cubic metres	300 cubic metres
Paper and cardboard	750 cubic metres	750 cubic metres	450 cubic metres
Textiles	750 cubic metres	750 cubic metres	400 cubic metres
WEEE containing plastics, including fridges, computers and televisions	450 cubic metres	450 cubic metres	450 cubic metres
Metals other than WEEE (including crushed ELVs, which are classed as 'baled' waste for the purpose of this table - for whole ELVs see the section 'Whole end of life vehicles')	750 cubic metres	450 cubic metres	450 cubic metres
Fragmentiser fluff	450 cubic metres	450 cubic metres	450 cubic metres

For all waste piles, the maximum height allowed is 4m.

When measuring height, you must use the longest measurement between the base of the pile and the top. This is to allow for any uneven ground beneath the waste. For all waste piles, the maximum length or width allowed (whichever is the longest) is 20m.

If your waste piles contain a mixture of combustible wastes, you must work out the maximum limits based on the type of waste that makes up most of a mixed pile.

You must consider the design, access and layout of a building when storing waste so a fire can be extinguished easily.

Avoid using general terms such as wood and metal. In your plan you must describe the fraction sizes or grades of material and where they are stored.

Figure 177: extract for FPP guidance (2)

12. Assessment of Concrete block as a substitute for separation.

Figure 178: Legio wall being constructed

Figure 179 Intumescent mastic used to seal joins in one elevation

Concrete blocks are a popular method of providing compartmentation on a waste management site at around 2 ¼ tonnes they make a very good push wall for heavy plant. I resent years they have also been employed as fire walls although no rating has been given to these systems as there in currently no agreed test methodology that is appropriate for the application. As these were being used for the fire tests and noting that the primary purpose of the wood fire was to establish a reliable method of ignition it seemed to be a good opportunity to test all the data collection systems and obtain some useful data. Three thermocouples were placed in the gap between the blocks as pictured. One on the surface of the test fire on 200mm into the gap (midpoint) and one on the inner wall surface. The gaps in this wall were filled with an intumescent mastic with a BS 476 (96) rating of 4 hours.

Figure 180: Test pile ready to light

The remaining walls were left unfilled. This was to observe if flames would penetrate the gaps. It was observed that the wind would drive flames through the unfilled gaps although no flaming or passage of heat and smoke was observed below the level if the pile on the inside of the wall.

Figure 181: approximately 1 hour after ignition by 3 hours before breaching the surface

Figure 182: Fire fully developed

The far right bay was used for the initial wood test. This test was designed to determine a reliable method of generating a deep seated fire. Several methods were employed around the remotely activated ignition of hydrocarbon fuel. Initially a fire lighter block and then a propane supply piped into the seat of the fire along a 110mm diameter steel duct. All these methods failed. Looking along the duct it was apparent that the hydro-carbon fuel was consuming the available oxygen supply too quickly.

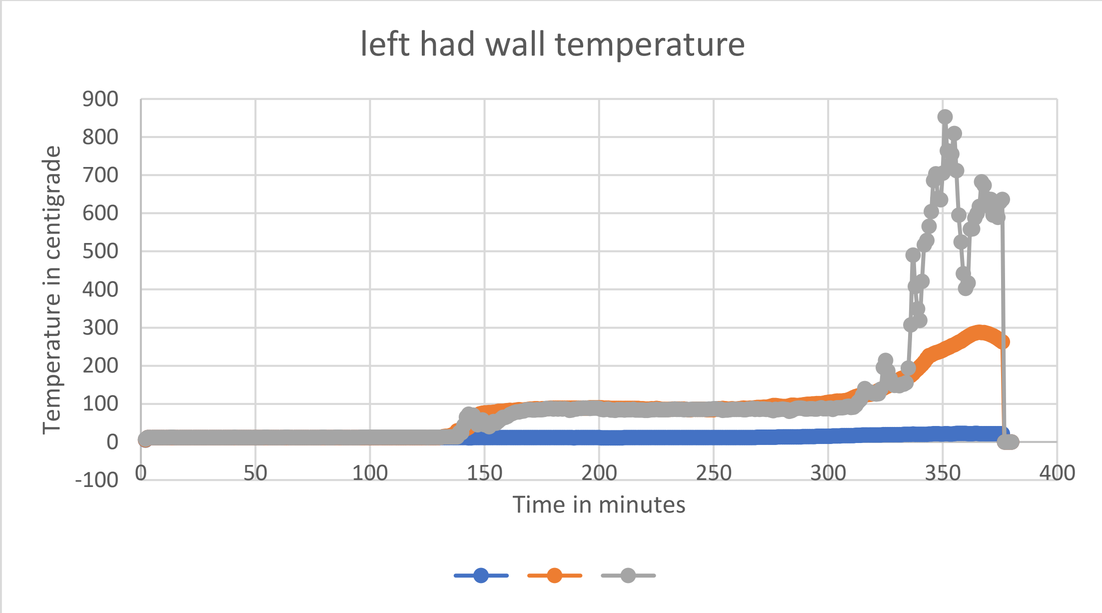


Figure 183: thermocouple data through the wall between bays

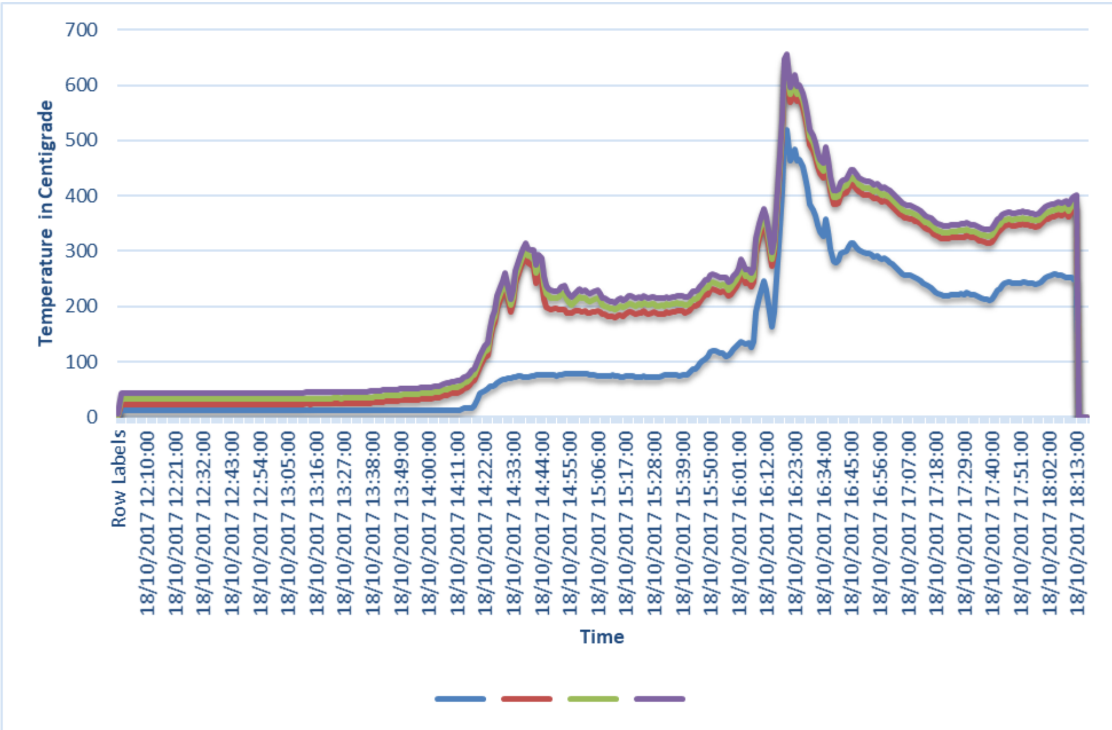


Figure 184 thermocouple data in the vertical plain through the middle of the pile

Eventually the method of diamond drilling a 115mm hole at the rear of the bay and igniting the fire with the use of an oxi-propane lance was selected. Even so the lance had to be held in place for 20 minutes to generate a self-sustaining combustion. The thermal penetration data was useful. At the height of the fire and some 12 hours after the start of the fire test the external wall temperature with the fire stopping had reached 20.9^{0}c the temperature through the gap was only slightly higher reaching around 25^{0}c. The un-fire stopped walls reached 35^{0}c it is difficult to attribute this entirely to the lack of fire stopping as the wind was blowing the flame front towards the un-fire stopped walls.

Bay	**Material**	**Duration of Test**	**Maximum Temperature Recorded**	**Comments**
Bay 1	RDF piled	50 hours	400-500^{0}C	Slight heating through the block but still able to hold a bare hand on the outside edge of the blocks. Flame penetration through gaps in the blocks down wind of the fire.
Bay 2	RDF piled	50 hours	400-500^{0}C	Slight heating through the block but still able to hold a bare hand on the outside edge of the blocks Flame penetration through gaps in the blocks down wind of the fire.
Bay 3	Plastic semi-piled	2 hours	1,100^{0}C	Slight heating through the block but still able to hold a bare hand on the outside edge of the blocks

Bay3	Pre-crushed wood piled	20 hours	950^{0}C	Post fire spalling of the inner face of the block but remained stable.

Table 15: observations of fire in concrete bays

Figure 185: Damage to the concrete (post fire)

Figure 186: Fire Damage to block work wall

Although the Legio block walls had been exposed to temperatures in excess of 900^{0}C for 18 hours and then rapidly cooled with firefighting jets, the spalling was relatively minor at around 10 to 15mm maximum. This bay was subjected to a further intense plastics fire for 2 hours at around 1100^{0}C and again rapidly cooled with water jets. The blockwork did not display any signs of instability or failure.

The fire was allowed to burn out after 18 hours the worst of the damage was around the pilot hole. The fire was extinguished and therefore, the majority of the spalling was likely to the result of rapid cooling. This bay was subject to a number of significant fires used for the firefighting tests with piles plastic being the most significant. After a week of constant use, the intumescent mastic was still in place although mostly comprising char no flames penetrated the fire stopped walls. The maximum depth of the spalling was 7.5 cm around the pilot hole. This content has been provided to WISH (6) in the report by Sangster (2018) ((97).

Chapter 8 Firefighting

This chapter examines the background to the development of firefighting tactics based on a combination of learning from this project and learning from experience gained by operational fire fighters. Operational experiences are brought to the NFCC committee (80) these are catalogued and over time the "Muddy Puddle" technique was developed. This was formalized and tested under scientific scrutiny at the Fire service college. The approach to tackling stacked baled fire on the other had been developed through observation and examination of the CFD modelling to identify the best place to apply firefighting media. Simultaneously the author was liaising with the Fire Industries Association in selecting the best water additives to test. CAFS was requested by the fire service while surfactants were generally accepted as a good option by the committee (80).

13. Development of firefighting tactics.

The issue of fires at waste management facilities can to a head in 2013 following the political impact of three major fires, Jayplas Smethwick, Lawrence Skip hire and an illegal waste site in Brereton Staffordshire. Not only had these fire been a drain on the public purse resulted in firefighter injuries and caused a public outcry, but they also had highlighted serious short comings in the firefighting response. Over a million litres of water had been used at each of these fires with the only discernible impact being server environmental impacts including large section of the Wolverley Canal and River Severn suffering large scale fish kills.

Fire Service experience was that waste piles were largely "waterproof". This observation was confirmed by the surface ignition fire tests described above. To aid Waste Industries Safety and Health Forum Waste Fire Committee, the NFCC set up an independent Waste Fires Committee (80) with the aim to urgently develop better response to firefighting in the waste industry. This committee sent personnel to aid with the fire tests so that they could use the findings to develop new techniques in parallel with this PhD research project. Initially there were five methods proposed,

- Encasement in sand/ inert soil
- Bulk CO_2
- Excavation
- Surfactant additive
- Foam

Encasement was employed at Barling due to the water sensitivity and was intern a method commonly used in the waste industry to control land fill site fires (insert Ref). This method was initially rejected by the NFCC as they had an obvious preference for water or water based solutions as this would be most cost effective. However, this method has been employed successfully in Staffordshire and Guernsey (80) It has the advantage of an almost instant removal of any detectable signs of smoke. From a long term environmental point of view, it often suppresses the fire and generates an anaerobic pyrolysis that emits CO_2 and other combustion gases over a long period of time and can result in a greater greenhouse gas emission overall (78).

Bulk CO_2 was suggested by a fire service in Eire who were collaborating with the NFCC. Records of one landfill fire was shared. This method was not particularly successful as the fire was eventually excavated. This method was rejects on this basis by the English Fire service due to the cost of bulk CO_2 and the impracticality of delivery to waste management sites.

Excavation had long been known to be the method of last resort but effective. The main issue with this system being that the Fire Service did not have access to the heavy excavating equipment necessary to deal with the large pile of waste that they encounter. Staffordshire purchased a small excavator and Essex employed a sub-contractor to supply heavy plant to excavate waste piles as both Counties were and still are experiencing a particular server problem with waste management fires. These schemes have proved so successful that it was developed into the "Muddy puddle" technique. The heavy plant excavates a trough into which water is poured by the fire crews. The excavator digs out the pile one bucket at a time. The content of this bucket is extinguished in the trough and then moved to a new pile away from the fire. As this activity breaks up the ash and char layer the firefighting jets that are employed to keep the fire on the pile under control now become more effective at penetrating the piled material thereby accelerating the firefighting process. The WISH Guidance recommend that heavy plant at waste sites should meet foundry standards as the hydraulic pipeline and fluid are heat resistant and better suited to this type of firefighing activity. This technique was validated during the tests detailed below.

Surfactants were an obvious choice for a trial as a means of finding a way for water to penetrate the ask/char layer that forms over waste fires. The main problem with the use of surfactants in Europe is that there is currently no British of EU standard for these water additives for firefighting. Therefore, there is no current method of accepted method of assessing the environmental impacts of the water runoff. The result of this is that surfactants were not able to be purchased by Fire Authorities. As part of this project the author has worked with the Fire Industries Associate to develop a test method for inclusion into the BS EN 13565-2 (94) based on the NFPA 18 (95) and extended to provide environmental impact criteria. In 2016 Essex Fire and Rescue service were able to deploy surfactant water additive on a large wood recyclers fire with great success. This in turn made it far easier for my project to obtain an environmental permit to use an experimental produce on the fire tests in September to October 2017. Again, these proved to be more effective that water or A class foam on waste fires.

Class A foams had been considered as an option. However, waste piles tend to be quite large and therefore, the quantities of foam required would be equally sizable. This has two serious implications for the fire service firstly the cost of this additive used at scale in and environment in England where significant fires are currently running at 1 per day could not be justified without firm scientific justification and secondly and probably more pressing are the environmental impact of the use of foams for firefighing. The fire service is be placed under close scrutiny as a polluter and has to justify the use of foams or face sanction by the Environment Agency.

During September and October 2017, a series of full-scale fire tests were conducted at the National Fire Service College, Gloucestershire. The fire tests were designed to represent the worst-case fire types likely to be faced by the fire service at a normal waste site. An additional output was the testing of different extinguishing agents, their application and effectiveness.

The materials selected were RDF (RDF), e.g., black bag waste collected from domestic street collections, and refined baled plastic. In addition, pre-crushed wood was used to demonstrate the test method and to evaluate the effectiveness of video heat and smoke detection technologies.

Two separate firefighting tests were conducted using RDF and one using plastic bag residue. Each of the tests were conducted within purpose-built bays constructed using blocks supplied by Legioblock®. The first test consisted of setting alight pile which contained pre-crushed wood. The purpose of this initial test was to establish a reliable method of initiating the deep seated fire. After a number of failed attempts an oxy-propane lance was selected as the pilot for this test program. It was observed that highly volatile fuels consumed all of the available air too quickly. Even attempts to supply air through a pipe could not sustained a sufficient fire to generate a self-sustaining fire.

The second set of tests consisted of a stack of baled plastic which was ignited from the upwind direction and allowed to burn for fourth minutes before firefighters extinguished the fire.

13.1.1 Surface fires (impermeable and semi –impermeable fuel beds)

A fire initiated on the surface of a pile of material will remain on the surface and tends to become ash and char controlled.

13.1.2 Deep seated fires

A fire that initiates within the mass of the pile will form a hot core in excess of 250^{0}C and can develop anaerobically, i.e., without a supply of oxygen. The developing fire will find a passage to the surface of the material and ultimately, breach the surface. This breach will provide an air supply to the hot core gasses resulting in a fuel-controlled fire burning at the peak heat release rate for the material.

13.1.3 Stacked bale fires

When baled material is stacked above 1m in height, a surface fire that affects the vertical space between the individual pillars will generate vortices driven by the convection currents. The fluid dynamic flows produced by the vortices can be sufficient to strip any ash and char away from combustible material and accelerate phase change in low grade plastics to a point where the process is almost instantaneous. This can result in an unusually high heat release rate for any given material within this region.

Two methods were employed to attempt to disrupt this fluid dynamic system

- Force air fans were directed at the base of the column in an attempt to disrupt the convection currents at the base of the column. This proved unsuccessful as the air stream from the fans lacked focus and sufficient velocity to have any discernible impact and secondly the heat flux was too great for the equipment of the crew.
- Directing jet of water, foam or water/surfactant at the base of the column and allowing the steam to be carried in the convection currents.

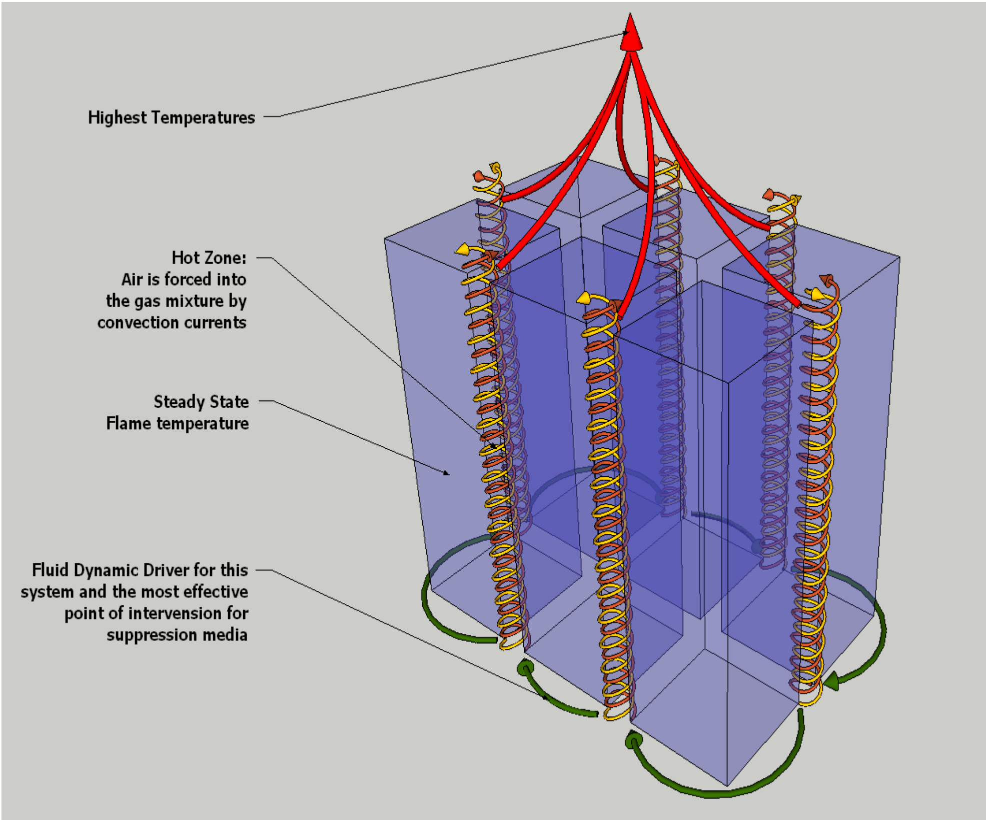


Figure 187:Theoretical fire model in graphical form

Figure 188: Low grade plastic. Surface temperatures are in excess of 1,100 ^{0}C

During test with high grade plastic, HDPE plastic bottles, the stack was observed to become unstable which resulted in a burning bale falling off the top of the stack this is obviously an additional hazard for firefighting.

Note: the RDF tested generally had a plastics content of 30 to 40% this was sufficient to suppress the fire growth. The other materials tested contained 85 to 95 % plastic and in all these cases the fires were very intense.

Piled Waste tests

Figure 189: Preliminary wood fire test, October 2017.

The piled test of wood presumed that the provisions of the WISH Guidance [1] regarding fire resistant separation had been applied. The configuration used presents some key challenges for firefighting crews compared to an open pile of material. These challenges are:

- The material is only accessible from one side and therefore all firefighting operations must be undertaken from this elevation.
- The material displays a high degree of water resistance.
- The volume of material involved which will require the use of heavy plant to aid in the excavation of the pile to expose the core of the fire.

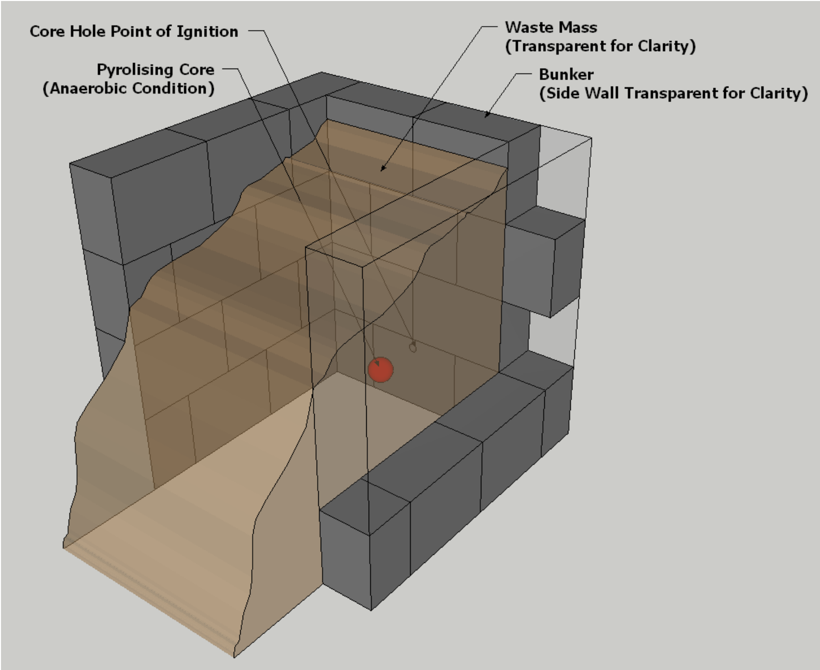


Figure 190: diagram of the test rig configuration.

Both RDF fires were ignited at the same time as baled plastic was ignited. Both RDF fires were allowed to develop for 48 hours and were monitored using thermocouples buried throughout the mass of the piled waste and thermal imaging cameras.

Both fires developed significant anaerobic pyrolyzing cores with temperatures recorded between 400^{0}C and 500^{0}C. Waste fires have apparent similarities to coal seam fire behaviour in this respect.

The surface of both RDF fires was eventually ignited manually, approximately 52 hours after initial ignition, as neither fire had breached the surface as expected. The surface fires were then allowed to develop for two hours prior to the fire extinguishing test.

13.2 Extinguishing Methods – Piled Waste

13.2.1 Water Test

Water jets were applied to the surface fire and it was noted that application of the medium had a good knock down effect. However, water did not have any impact on the temperature reading obtained from the thermocouple 1m below the surface, and the application of copious amounts of water did not appear to have any impact of the water's ability to penetrate the pile; the water merely ran off.

13.2.2 Wet Class a Compressed Air Foam System (CAFS) Foam

The foam solution was applied to the RDF fire. It was noted that this too displayed a similar ability to knock down the flames however, with CAFS, it was also noted that the temperature was reduced 1m below the surface of the fire showing a degree of penetration. Again, the application of copious quantities of foam did not show any better performance and just contributed to runoff. Foam however, displayed a degree of resistance to burn-back not display by water.

13.2.3 Wetting Agent

The water and wetting agent solution were applied to the RDF fire test. It was noted that the wetting agent did knock the fire down quickly resulting in a reduced temperature 2m below the surface of the pile. It was also noted that, in common with the other agents, the application of copious quantities did not improve its efficiency but just added to the water runoff. However, this method would be effective on a surface fire or employed are part of the "Muddy puddle" process if use sparingly environmental impacts due to excessive water run off could be avoided.

13.2.4 Re-ignition of Piled Waste

A jet of wetting agent mixture was applied to the piles through the holes used to pilot the ignition and allowed to run until water agent mixture was running freely through the joins in the Legio block walls. The thermocouple readings were observed to have dropped to ambient temperature and therefore, it was assumed that the fires had been extinguished and the site was left overnight for approximately 12-hours. However, it became apparent the next morning that the cores of both fires had returned to their original fire conditions and had reached the pre-extinguished temperature. This behaviour was also observed at the earlier test site at Barling in Essex. This therefore leads the Author to believe that the core residue has become chemically pre-disposed to re-ignition. This is not understood at present and will require further research to establish the cause of these repeated re-ignitions. However, firefighting crews should be cautious and isolate burnt material for a number of days to establish that the material will not reignite.

The configuration of the bay acts like a room and as a result the flame is stretched up the "overboard[1]" by air being entrained. This is a well-documented phenomenon in fire dynamics. In practical terms it is unlikely that the overboard could be raised high enough to overcome this problem although it may theoretically be possibly. This is discussed by Drysdale (65). It is more likely however, that fire crews would have to consider this effect and position covering jets to the material either side of the bay that is on fire.

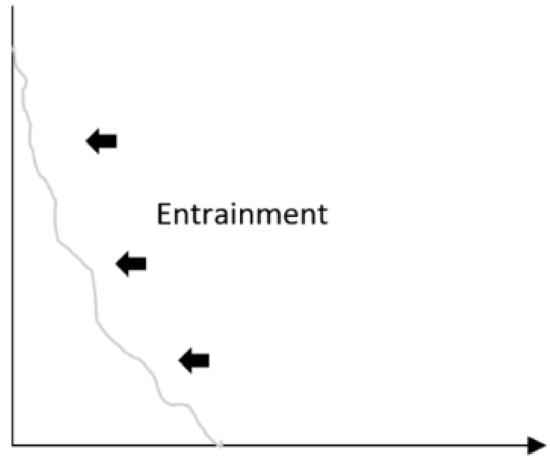


Figure 191: illustrates a diagram of entrainment – Drysdale (65)

Figure 192: Bay 1 and 2 with RDF piles.

13.3 Baled Plastic Fire Tests

[1] A section of wall above the top of the waste pile. Generally, the overboard is 1m high

Recycled mixed-plastic bales were piled three bales high and three bales in each other direction forming a stack of 27 bales. Plastic was selected due to the intense heat release rate observed in earlier tests. All the fires were piloted by the application of a naked flame at the base of the gaps between the stacks on the up-wind elevation. All the fires behaved in a similar way.

The fire spread in the virgin material was quick: from point of ignition to full involvement within four minutes. The test beds were built 6 m from the previous fire to establish the effectiveness of the separation distances suggested in the Environment Agency FPP (2). In figure 183 below, which was the water with wetting agent test, all three test beds were fully involved in under 12 minutes of the pilot flame being applied to the first stack.

In all, baled plastic stacks have been the subject of 9 fire tests using various plastic compositions. In these tests, it was noted that the plastic did not enter the liquid phase but rather appeared to enter the vapour phase and combust almost instantaneously. The heat output, therefore, between the different grades and types of plastic was not as significant as earlier research see appendix D would have suggested and would appear to be a function of the fluid dynamic regime that the orientation of the fuel bed has on the fire behaviour. Typically, the surface temperatures of the burning stacks are likely to be in the region of 1100^0C to 1200^0C or more. The impact of the heat flux on fire crews and surroundings cannot be underestimated and it is suggested appliances and equipment should be a minimum of 40 m away from a plastic bale fire.

Figure 193: Test No 22 with two target fire to time fire spread between targets 6 m apart

13.4 Water Test

Two 70mm jets were applied. The jets were applied to the base of one of the gaps to use the fluid dynamic flows driving the system to transmit the steam through the fire as postulated following work package 1, 2 and 3 of the WISH fire test programs. One jet remains in the original position to prevent the fire burning back while the second jet is worked around the base of the stack to extinguish the fire

This system worked well and supports the theoretical model.

Water usage was 19,000 litres (2x70 mm jets at 7 bars delivering 475 l/min for 20 mins). There was a considerably quantity of fire water run off especially in the latter stages of the firefighting operation. It was estimated that around 50% of the fire water was absorbed into the waste and or evaporated leaving a residue of around 9500 l of water runoff.

13.5 Compressed Air Foam System (CAFS)

The attack used in test 1 was repeated using CAFS. A Class A wet solution was used and was markedly more effective.

Water usage 1,800 litres of water (7 mins 2x 128 l/min)

While there was minimal fire water residue there were some challenges to the use of this system. Firefighting foam is made by adding a chemical to the water that forms small bubbles much like washing up liquid or bubble bath. Consequently, firefighing foams are traditionally only applied on flat horizonal surfaces and are applied by flowing the foam blanket over the surface. The distance that a jet of firefighting media can be projected from a hose is called the throw. Standard firefighting foam has a throw of a metre or so and therefore, the crews would have to be standing next to the fire to apply foam. To overcome this limitation the firefighting industry has developed CAFS. This equipment uses a specially developed foam compound that makes a foam with very small and robust bubble structure that can be pressurised without breaking down. The resulting foam resembles uncooked meringue and is equally sticky. This means that a coating of foam can be applied on vertical surfaces. These qualities make class A CAFS as good firefighting media for surface waste fires. However, in practice the throw from the firefighting jets quickly fades once the control branch is opened. Consequently, the firefighters must get much closer to the fire than either of the other two firefighting media. They also must pulse the jets to obtain a useable throw.

Wetting Agent

The wetting agent resulted in the quickest knock down of all the media used and produced the least run off.

(2x 45mm jets at 7 bars using 0.3% induction of agent (5 litres). Time to extinction: 2 minutes.

The water surfactant mixture penetrated the waste and resulted in only a few litres of run off. This made obtaining a water sample for environmental analysis challenging although a sample was obtained and analysed see Appendix. There are a number of advantages of this additive over CAFS and water.

- No specialist equipment was required to use the additive. The water/surfactant mixture was mixed in a water dam made of a salvage sheet and triple extension ladder and lifted into the fire appliance using hard suction hose. This is a standard practice for the UK fire service. (31)).
- The jets had the same throw as the standard water jet so crew could operate at a safe distance.
- The water/surfactant jets had an instantaneous knock down effect and showed a remarkable resistance to burn back due the saturation of the waste material that it struck. This in turn resulted in sharp drop in heat flux allowing the firefighters to make a much more aggressing attack on the fire.
- The procedures are far more standard than CAFS as there is not specialized equipment therefore, there is minimal additional training requirement.
- No capitol cost associated with the provision of specialist equipment.

Test Photos

Figure 194: the bale of plastic ignited by the application of naked flame. The image is taken approximately 1 minute after ignition

Figure 195: Image taken from the testing facility showing the fire spreading

Figure 196: shows the full involvement of the stack.

<u>Recommendations</u>

1. Water or other firefighting media should not be continuously directed onto a pile of waste as it has no effect other than adding to pollution. Jets should be used to knock flames down and then stopped once excessive water runoff is observed. At this stage the surface material has reached a point where saturation is at its greatest and the application of water serves no purpose. It is quite possible that the flames are being emitted from an exposed core. Such a core must be fully exposed to allow for it to be extinguished or smothered to suppress the smoke and flames with earth or sand.

2. Research conducted during this program would indicate that partially burnt waste materials possess a pre-disposition to reignite readily and therefore the wisdom of landfilling partially burnt waste materials is questionable. It is therefore, recommended that material directly affected by fire should be sent to EFW facilities and incinerated. This material must be kept separate for the EFW main fuel stream to avoid a fire at this facility.

3. Piled materials should be excavated and the "muddy puddle" principle is currently the most appropriate approach. (Muddy Puddle: fire crews excavate a gently sloping hole which is filled with water the waste in excavated from

the main pile and submerged in this hole where fire crews can spray the material with water.)

4. Where this is not a practical approach to extinguishing a fire, the material should be buried under earth or sand to reduce noxious emissions. The material is likely to continue to pyrolyze slowly until the fuel is consumed.

5. Controlled burns may be an option, but the mass loss rate is fairly slow, so this is likely to mean that the resolution of the incident will be protracted.

6. Flooding a Burning pile of material with water is not likely to be successful and is likely only to protract the incident and cause pollution but the uncontrolled production of leachate.

7. Surface fire in piled material can readily be extinguished but the surface should be stripped back to unburnt material to ensure that the fire was not piloted by a deep seated and concealed fire. Surfactants are likely to be effective.

8. Crews should not walk on piles of waste as deep seated cores are not obvious and may not give any indication of their presence on the surface of the pile.

9. Temperature readings of the surface material are not a guarantee that there is not a hot core below the surface, waste materials are good insulators.

10. Baled and stacked materials are predominantly surface fires and consequently extinction of the fire is relatively achievable.

11. Stacked baled material fires are driven by the convection current in the gaps between the stacks. Jets should be directed at the base of the stack and into the gaps, crew should resist the temptation to direct the jet at the flames. Surfactants provide a good alternative to water alone and if used correctly will reduce the potential for environmental pollution from both smoke and water emissions form the fire.

12. RDF, SRF, paper and textile bales burn with less ferocity than plastic and consequently given time the bales fail and form piles. Once the bales have failed, they will form piles. These piles should be fought as pile fires.

13. Waste management sites could consider providing a supply of wetting agent that is compatible with the types of waste they process and with their Local Authority Fire and Rescue Services pumping equipment.

14. Waste management sites should specify foundry standard for heavy plant to assist in managing their fire risk.

This content has been provided to WISH (6) in the report by Sangster (2018) ((96).

Chapter 9 Summary and Findings

14. Summary of Findings

14.1 Returning to the initial questions

1. Can a surface fire find a pathway from the surface to a point deep within the pile without involving the majority of the mass of the pile?

The short answer to this question is no. No evidence of fire spread along hole created by pests, fire spread along the boundary between the fuel and the ground has been found. On the contrary this behaviour better describes a fire that is generated deep inside the pile. Deep seated ignition resulting from a chemical reaction deep or biological self-heating combined with an as yet unidentified process accounts for deep seated fires. However, deep seated fire can and do generate surface fires. It was observed that there are two other mechanisms that could account for this apparent behaviour and subsequent miss reporting are:

- A surface fire with particle sizes on the border of being a Permeable fuel bed

  Has been shown to allow the flame to pass through the matrix of the pile. It is conservable that this could cause confusion as the fire transits to a semi-Permeable fuel bed.

- The second is in a large pile approaching a vertical face a surface fire can cause the face to collapse burying the seat of the fire. (calving)

2. How credible is ignition by a naked flame?

   - In most lose piled conditions it is difficult to cause these materials to catch fire. However, it is noted that in dry condition or within a built environment where the is a significant dust layer ignition is likely to be more achievable. It is apparent that the moisture content and thermal thickness of the fuel bed are critical factor in their ignitability. Stacked bales are vulnerable to ignition form modest ignition sources due to the influence of fluid dynamic flows around the vertical column formed by stacked bales two metre high and above.

3. Establish accurate separation distances for the safe storage of waste materials based on the empirical heat flux data obtained.

- A range of computer fire models were develop using a radiation model. The peak surface temperatures for each of the fire tests were developed and plotted in graphical form. This information was provided to the WISH committee to inform the 2nd edition of the WISH Guide 28(1) see appendix C

4. What impact does the storage conditions have on fire properties of the stored materials?

    - The storage condition can fundamentally change the fire behaviour any material. The principal of fire compartmentation using concrete blocks present a significant advantage over separation alone. See appendices C and E

5. How much influence does the material properties have on fire growth?

    - Not unexpectedly the material properties have a significant influence on the fire behaviour. However, the fluid dynamics of stacked bales will significantly influence the severity of a fire irrespective of the materials involved.

6. Can this understanding lead to improved fire suppression and detection?

    - Significant improvements have been made in firefighting see appendix F. In the time that the WISH Guide 28 (Waste Industry Safety and Health Forum, 2017) the severity of the fires at licenced waste sites has been significantly reduced. It is hoped the new approached to detection will be developed as a result of this research.

14.2 New discoveries

The discoveries can be categorised in to three areas:

- new technical method of examination of fire spread within a pile of material
- real fire data for waste piles
- new scientific discoveries

14.2.1 New technical method

1. To obtain the data from within the piles waste a new test rig and methodology had to be developed and refined over the series of tests. The result is a test rig design to measure surface fires see Figure 8.

2. A new approach using the relationship between mass and volume was developed to calculate the mass loss rates for piled material fires.

3. This test rig proved unsuitable for the deep seated fire test as it become physically too congested at the bottom of the pile. This together with the thermocouple leads being exposed to the fire required a different approach with the thermocouples fed into the pile from outside in order to overcome these technical issues. The ultimate result of this development was the fire tests 20, 28a and 28 b conducted at Morton in the Marsh.

4. A new type of gas sample collection tube was developed for the self-heating test with piled wood fines (Test No18). The classic instruments are made of stainless steel. However, plastic pipe was selected for this task as this material was less likely to conduct heat away from the core of the pile. The main tube had several holes drilled in the sample collection point the inner plastic tube had hole are the bottom middle and top with sealed sample tubes (the clear plastic tube below). These tubes corresponded to the collection point on a gas calorimetry device available to the fire service Hazmat teams in the London Fire Brigade. The intention was to collect samples of gas at three points in the main tube arranged at a 45^0 angle. This was to allow for a degree of gas stratification. This method did appear to work well. As expected, methane was collected at the top of the tube with an array of heavier gasses collecting at the bottom of the tube, mostly sulphated hydrogen compounds. Traces or acetylene were also detected. Unfortunately, this test did not result in a self-heating fire, so these results are of little use to this research.

Figure 197: Gas sample tubes for test No18

5. The baled fire tests presented significant challenges in obtaining direct measurements given that only K type thermocouples were available. The leads proved very susceptible to damage form the radiated form these fires as the heat release rate was so much higher than anticipated see test No 13. To

overcome these short comings the scope for the Morton in Marsh test included an array of thermocouples at set distances from the fire tests with a view to calculating the surface temperature of the fires from the temperatures recorded on the various thermocouple see figure 81.

6. This led to the development of a mathematical approach to calculate the flame temperature of the surface of the test fire from the temperature recorded at remote thermocouples. See section 9.3.1.

14.2.2 New scientific discoveries

1. Definition of piled material as fuel beds.

$\tilde{\varphi}_{ave} \approx 0$ the fuel bed will be impermeable – fire behaviour will tend towards slow smouldering combustion. Deep seated ignition will be unobserved.

$\tilde{\varphi}_{ave} \leq L^*$ the fuel bed will tend to be semi – permeable. Surface fires will tend towards ash and charr controlled fires. Deep seated fire will generate convection currents that are readily detected on the surface. Deep seated fire will be relatively server where the convection currents will drive off the ash and charr resulting in fire around the peak heat release rate (fuel-controlled fire).

$\tilde{\varphi}_{ave} \geq L^*$ the fuel bed will tend to be permeable – the flames can pass through the mass of the pile producing a fuel controlled fire.

2. Theoretical models explain 6 general fire types that were observed during these fire test and can be summarised as:

   - Impermeable surface fuel bed fire
   - Semi-permeable surface fuel bed fire
   - Impermeable deep seated fuel bed fire
   - Semi-permeable deep seated fuel bed fire
   - Permeable fuel bed fire
   - Fluid dynamically driven surface fuel bed fire

3. These can be characterised into four theoretical models

- Permeable fires: where the gaps between the individual particles in the pile are sufficiently wide to allow flame and air to pass through the mass of the pile.
- Surface fires (semi permeable and impermeable fuel beds): where the gaps between the individual particles are insufficient to allow flame to pass through the mass of the fuel bed. The fire remains on the surface.
- Deep seated fires where the ignition is generated within the mass of the material and migrates to the exterior this process is accelerated in semi-permeable fuel beds and the fire gains a greater access to air as it progresses towards the surface of the material and as a result are more acute than impermeable deep seated fuel bed fires.
- Fluid dynamically driven surface fire: this is a unique fire behaviour observed in compressed baled materials stacked in multiple pillars which is common practice in the waste management industry but may have implications for other industries that store materials in this configuration. See section 9.

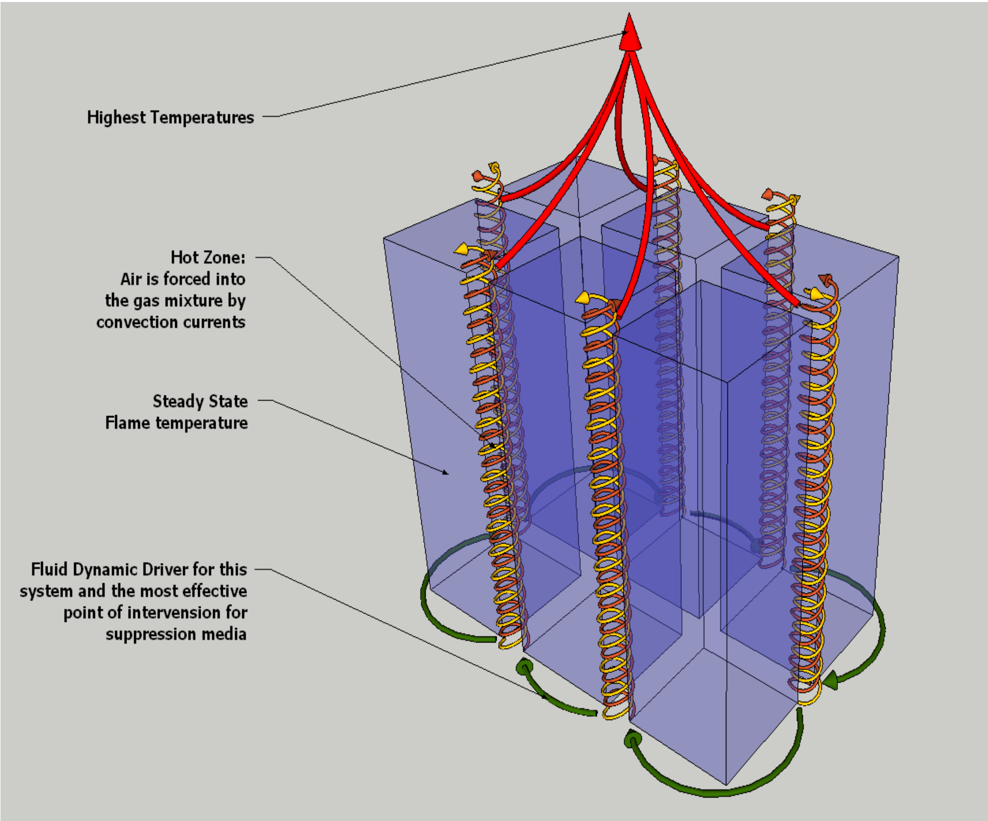


Figure 198 Vortex fire theory

14.3 Firefighting techniques

- This project has provided the scientific proof for the use of the Muddy Puddly firefighting technique currently employed by UK Firefighter.
- Identified the benefit of surfactants in penetrating surface fires.
- This project has identified a previously unknown fire phenomenon and develop the appropriate tactical approach and appropriate fire water additive.
- Aided in the development of UK Fire Service Tactical Advisor Role for Waste Fires.

14.4 Recommendations

1. Water or other firefighting media should not be continuously directed onto a pile of waste as it has no effect other than adding to pollution. Jets should be used to knock flames down and then stopped once excessive water runoff is observed. At this stage the surface material has reached a point where saturation is at its greatest and the application of water serves no purpose. It is quite possible that the flames are being emitted from an exposed core. Such a core must be fully exposed to allow for it to be extinguished or smothered to suppress the smoke and flames with earth or sand.

2. Research conducted during this program would indicate that partially burnt waste materials possess a pre-disposition to reignite readily and therefore the wisdom of landfilling partially burnt waste materials is questionable. It is therefore, recommended that material directly affected by fire should be sent to EFW facilities and incinerated. This material must be kept separate for the EFW main fuel stream to avoid a fire at this facility.

3. Piled materials should be excavated and the "muddy puddle" principle is currently the most appropriate approach. (Muddy Puddle: fire crews excavate a gently sloping hole which is filled with water the waste in excavated from the main pile and submerged in this hole where fire crews can spray the material with water.)

4. Where this is not a practical approach to extinguishing a fire, the material should be buried under earth or sand to reduce noxious emissions. The material is likely to continue to pyrolyze slowly until the fuel is consumed.

5. Controlled burns may be an option, but the mass loss rate is fairly slow, so this is likely to mean that the resolution of the incident will be protracted.

6. Flooding a Burning pile of material with water is not likely to be successful and is likely only to protract the incident and cause pollution but the uncontrolled production of leachate.

7. Surface fire in piled material can readily be extinguished but the surface should be stripped back to unburnt material to ensure that the fire was not piloted by a deep seated and concealed fire. Surfactants are likely to be effective.

8. Crews should not walk on piles of waste as deep seated cores are not obvious and may not give any indication of their presence on the surface of the pile.

9. Temperature readings of the surface material are not a guarantee that there is not a hot core below the surface, waste materials are good insulators.

10. Baled and stacked materials are predominantly surface fires and consequently extinction of the fire is relatively achievable.

11. Stacked baled material fires are driven by the convection current in the gaps between the stacks. Jets should be directed at the base of the stack and into the gaps, crew should resist the temptation to direct the jet at the flames. Surfactants provide a good alternative to water alone and if used correctly will reduce the potential for environmental pollution from both smoke and water emissions form the fire.

12. RDF, SRF, paper and textile bales burn with less ferocity than plastic and consequently given time the bales fail and form piles. Once the bales have failed, they will form piles. These piles should be fought as pile fires.

13. Waste management sites could consider providing a supply of wetting agent that is compatible with the types of waste they process and with their Local Authority Fire and Rescue Services pumping equipment.

14. Waste management sites should specify foundry standard for heavy plant to assist in managing their fire risk.

15. Thermal image and or smoke detection is very effective when applied to waste piles that will readily allow the passage of convection currents such as pre crushed wood piles. These is no evidence that this type of system is any more effective than point detection on impervious material piles although it may still be beneficial to use video detection in open sites where ventilation would render gas detection ineffective.

16. The waste industry would benefit from developing a set of waste specific standards for application in this unique environment rather than relying on adapting more generic standards such as NFPA 850 and BS9999.

17. Concrete blocks are an effective passive fire prevention method provided the gaps are fire stopped. The material should not project beyond the wall's limits.

18. An agreed standard for the type, size, aggregate and test method would be of benefit to maintain a minimum standard for concrete block for use in passive fire walls.

These recommendations are presented without prioritisation as this is such a diverse industry each stakeholder will have differing priorities

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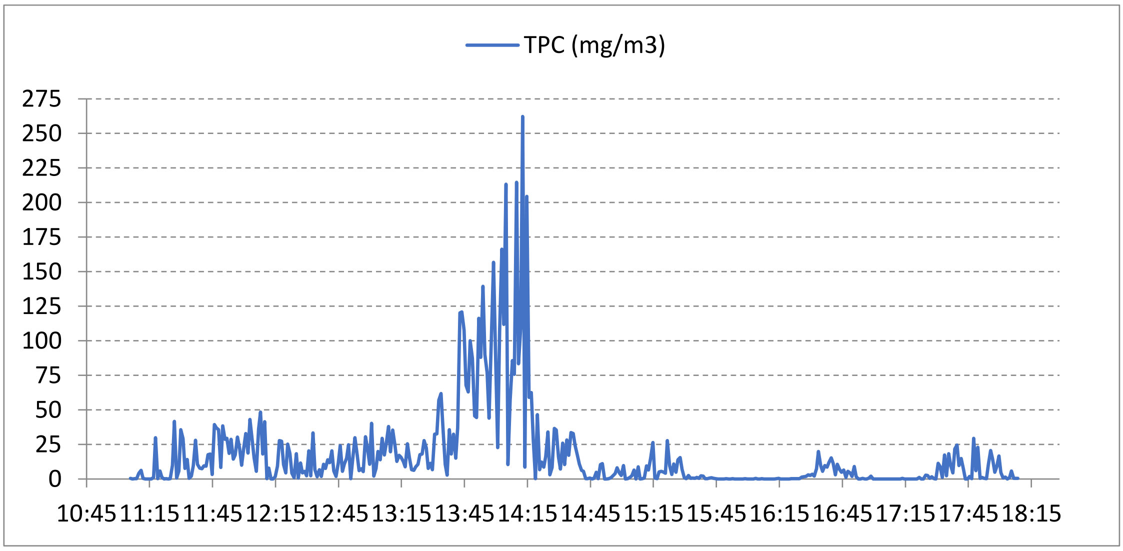
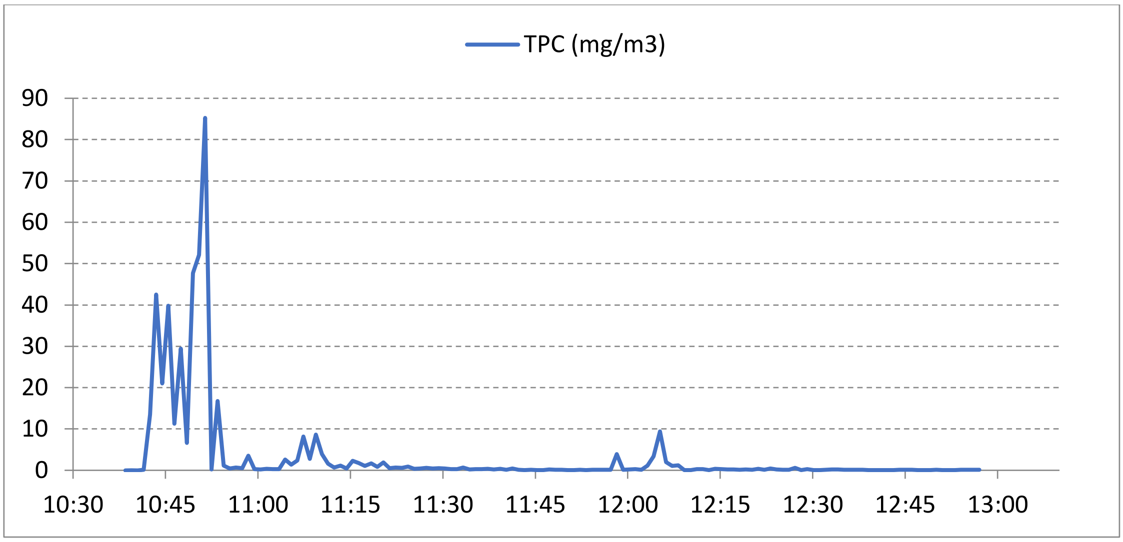
APPENDIX A Pollington emissions Data

Gas data capture at Pollington airfield

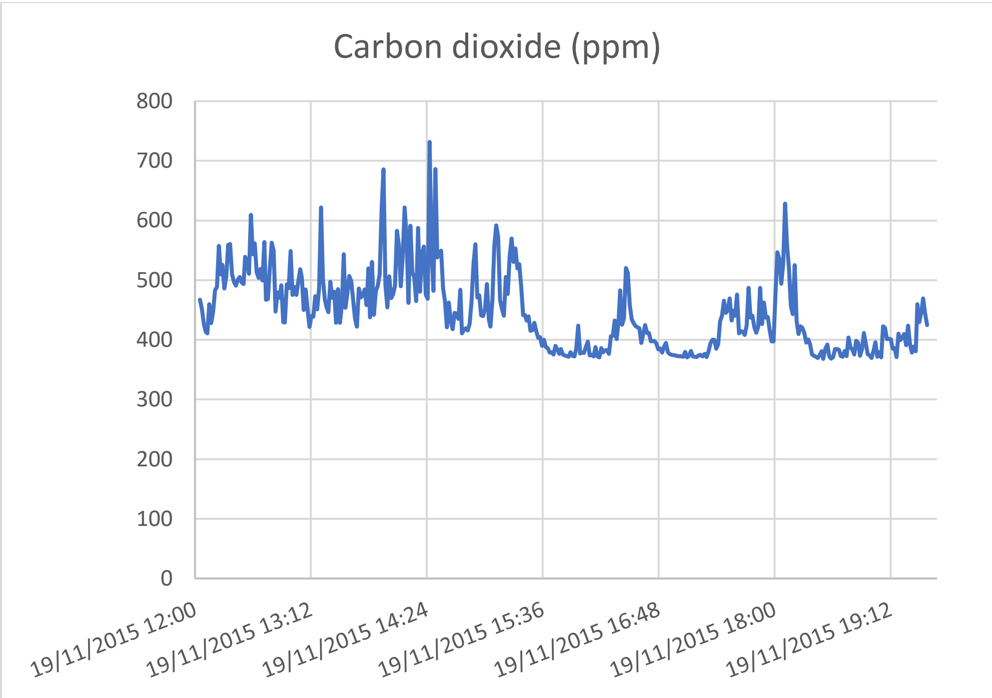
The first series of fire tests included fire gas analysis to support Public Health England with a project to be able to provide projected smoke plume predictions. This data is near field data of un-screened wood emissions. This line of research was not perused in subsequent tests due to the prohibitive cost of hiring the equipment and the withdrawal of funding by key partners.

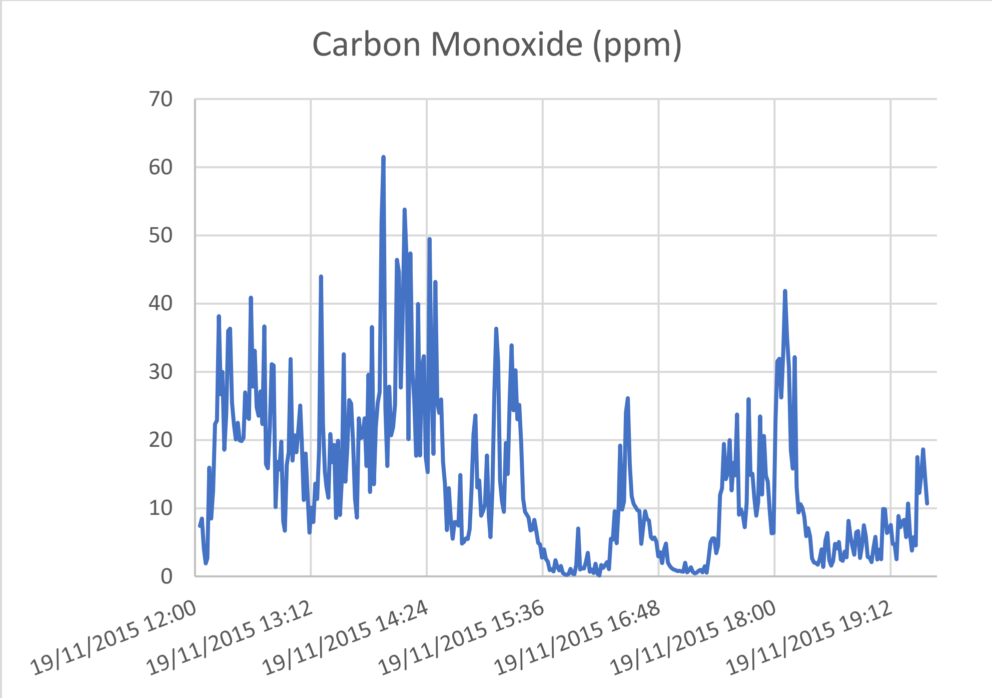


Micro dust data (soot)



Micro dust data (soot)




Carbon Monoxide (ppm)
70
60
50
40
30
20
10
0
19/11/2015 12:00
19/11/2015 13:12
19/11/2015 14:24
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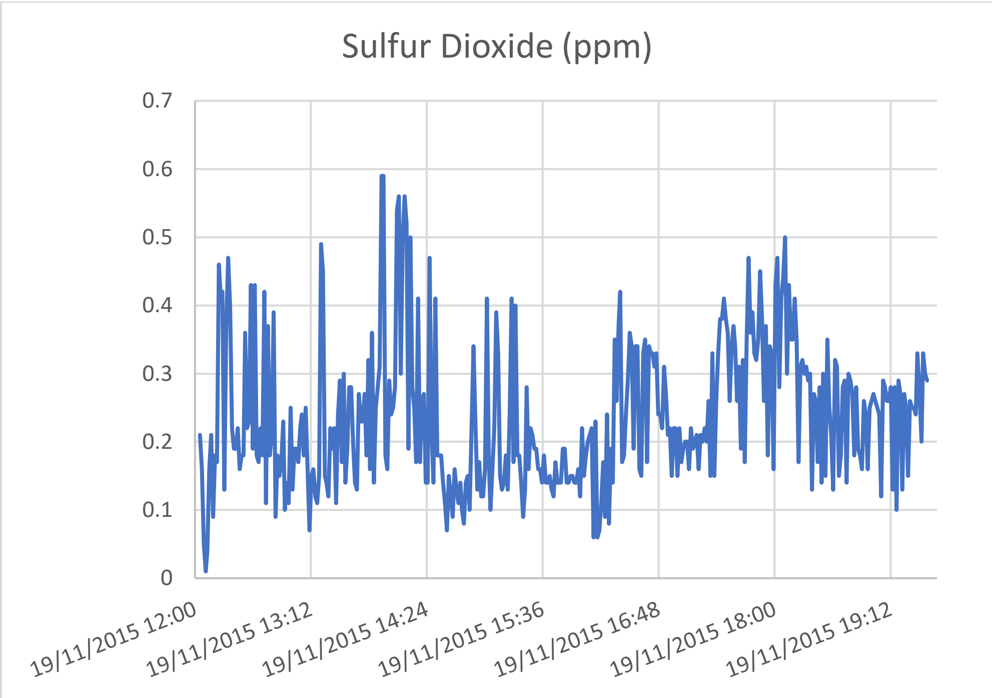
19/11/2015 19:12


Sulfur Dioxide (ppm)
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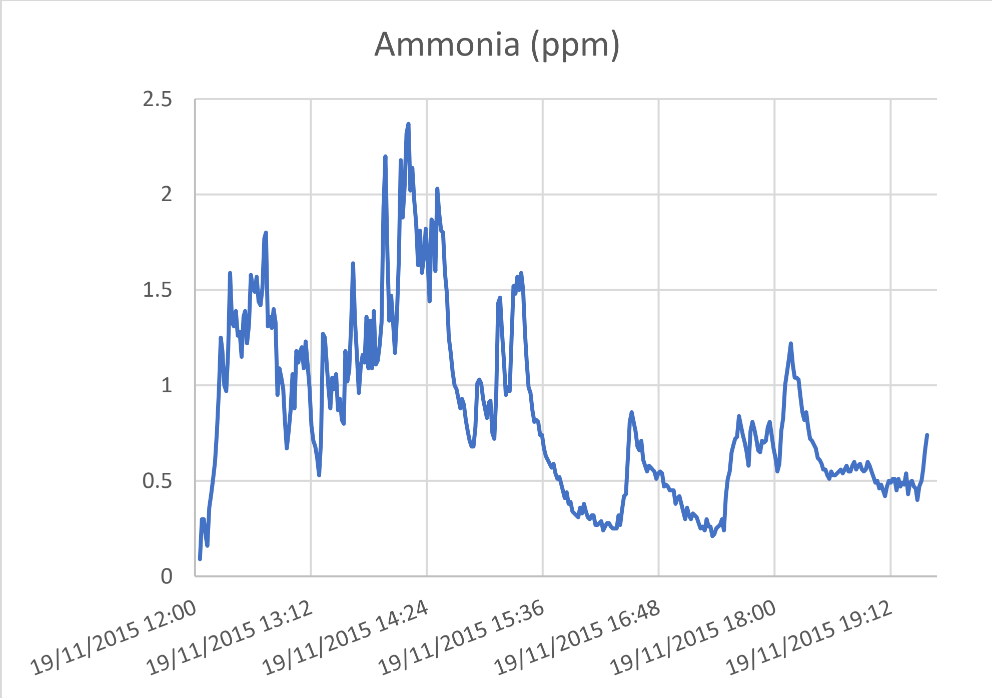
0.6
0.5
0.4
0.3
0.2
0.1
0
19/11/2015 12:00
19/11/2015 13:12
19/11/2015 14:24
19/11/2015 15:36
19/11/2015 16:48
19/11/2015 18:00
19/11/2015 19:12


Ammonia (ppm)
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2
1.5
1
0.5
0
19/11/2015 12:00
19/11/2015 13:12
19/11/2015 14:24
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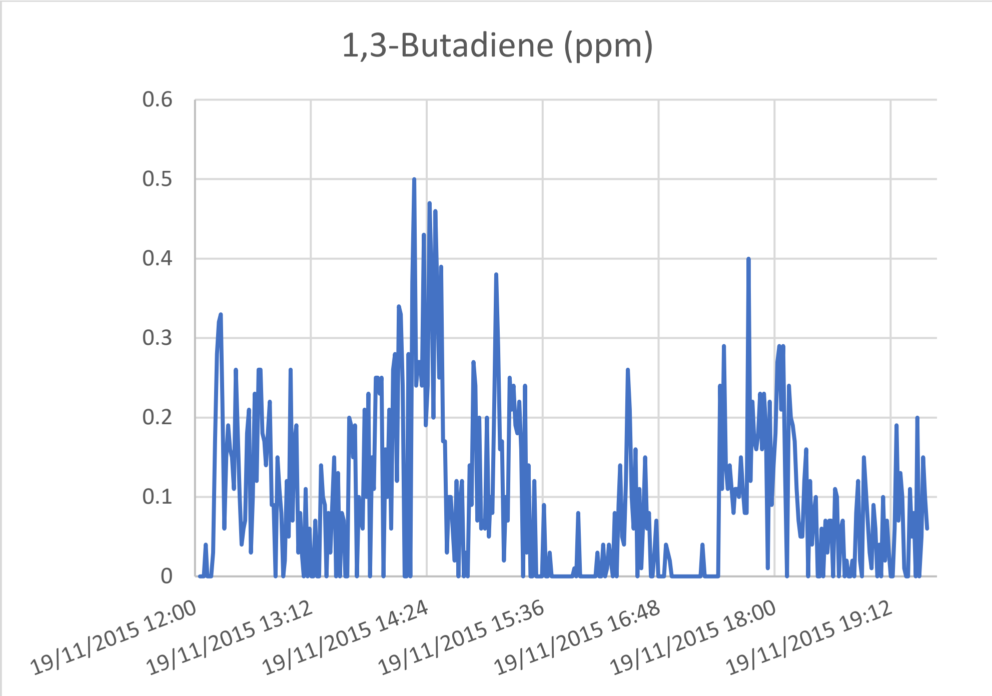
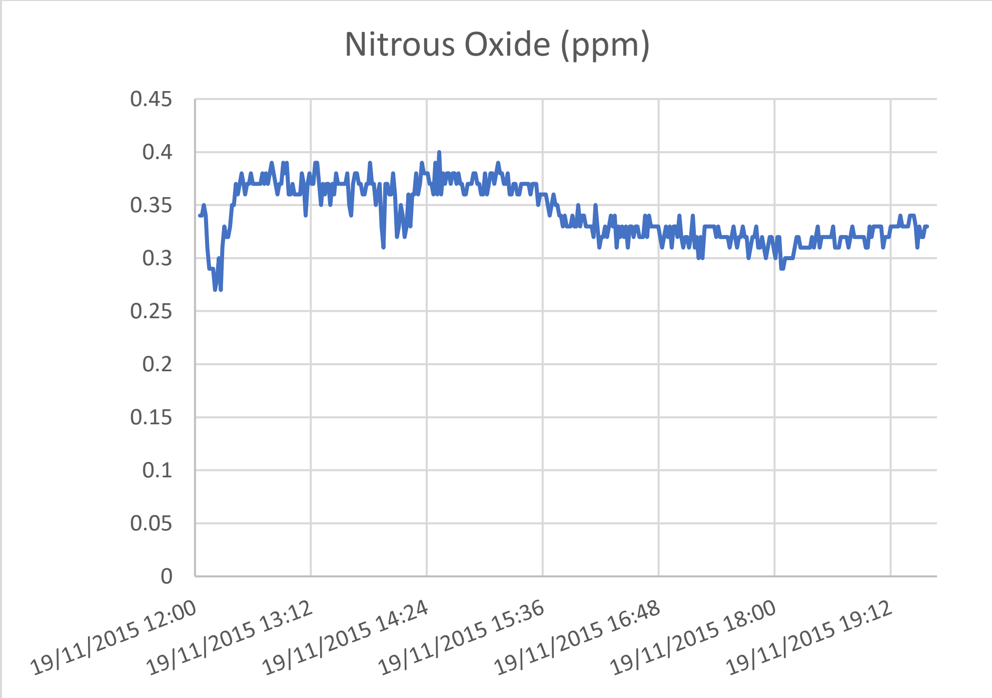
19/11/2015 19:12


1,3-Butadiene (ppm)
0.6
0.5
0.4
0.3
0.2
0.1
0
19/11/2015 12:00
19/11/2015 13:12
19/11/2015 14:24
19/11/2015 15:36
19/11/2015 16:48
19/11/2015 18:00
19/11/2015 19:12


Nitrous Oxide (ppm)
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0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
19/11/2015 12:00
19/11/2015 13:12
19/11/2015 14:24
19/11/2015 15:36
19/11/2015 16:48
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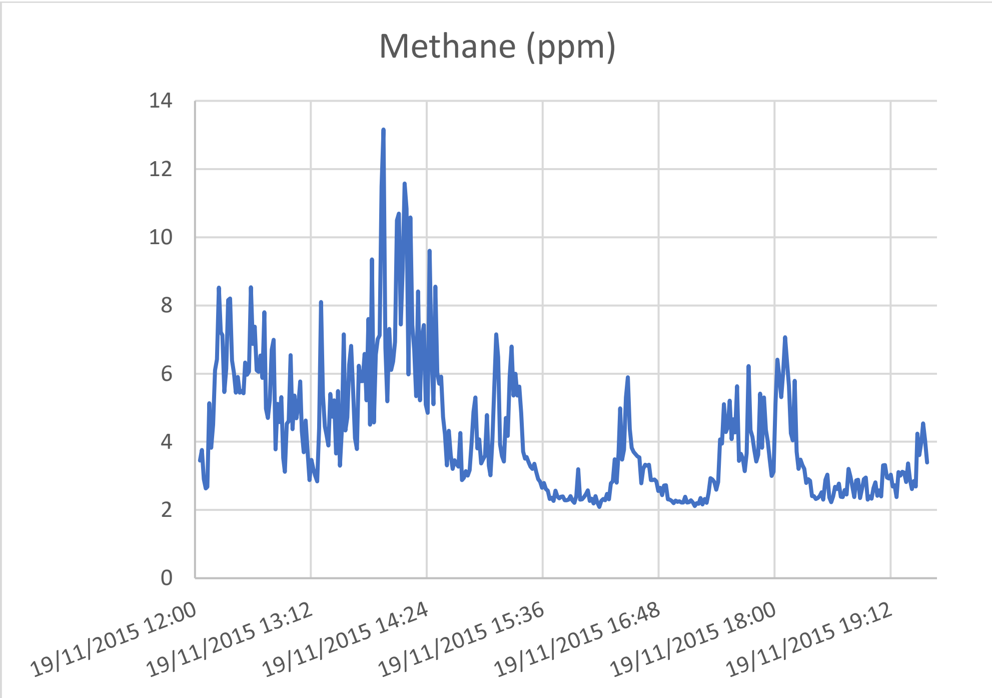
19/11/2015 19:12


Methane (ppm)
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12
10
8
6
4
2
0
19/11/2015 12:00
19/11/2015 13:12
19/11/2015 14:24
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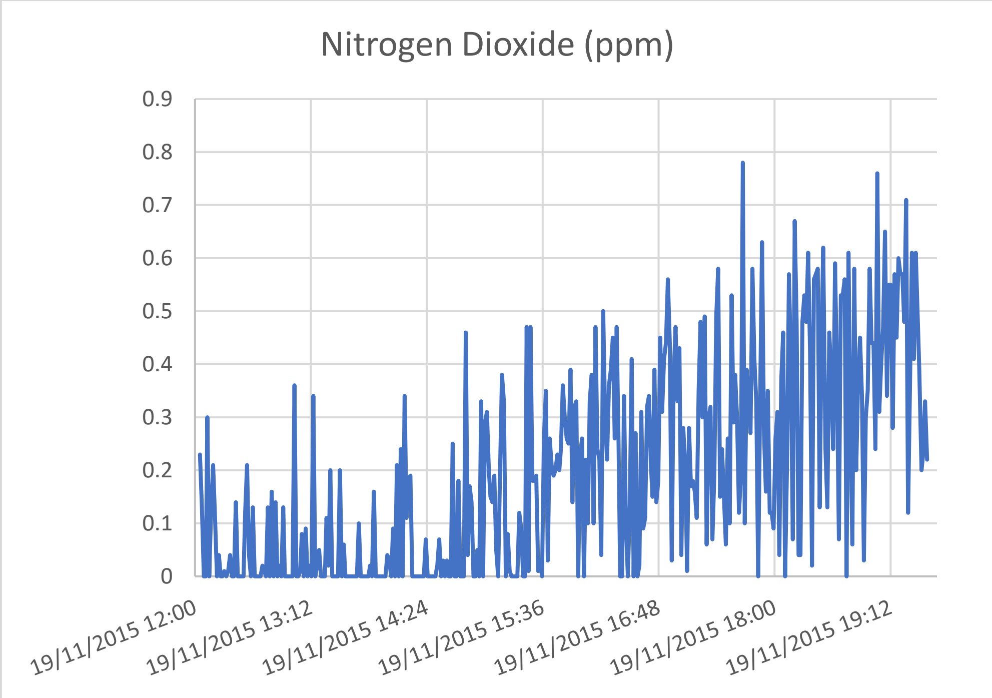
19/11/2015 19:12


Nitrogen Dioxide (ppm)
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0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
19/11/2015 12:00
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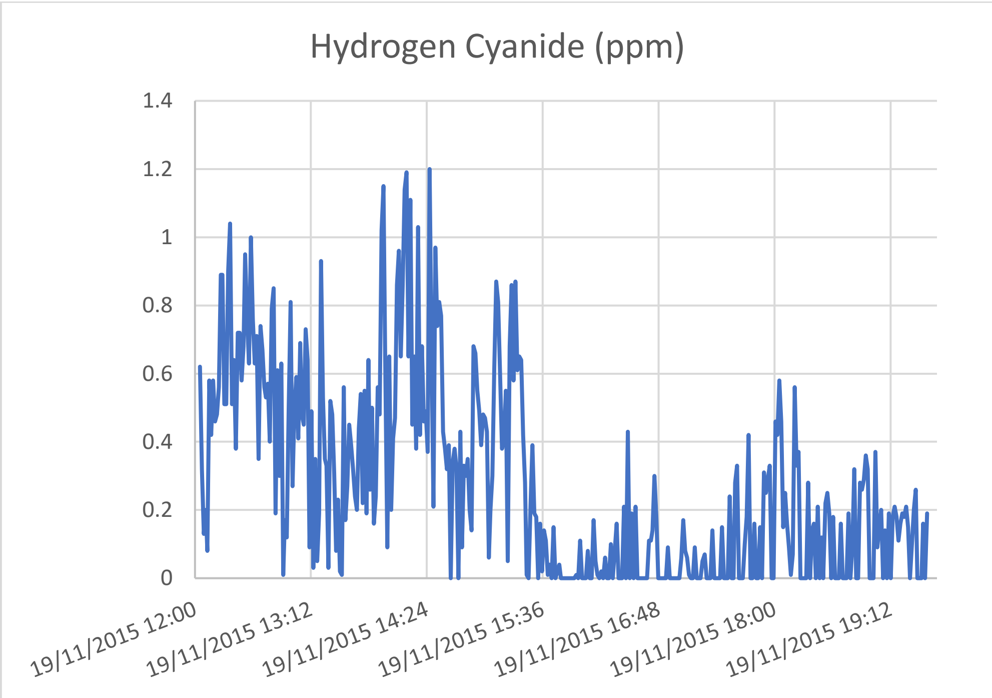
19/11/2015 19:12


Hydrogen Cyanide (ppm)
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1.2
1
0.8
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0.2
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19/11/2015 12:00
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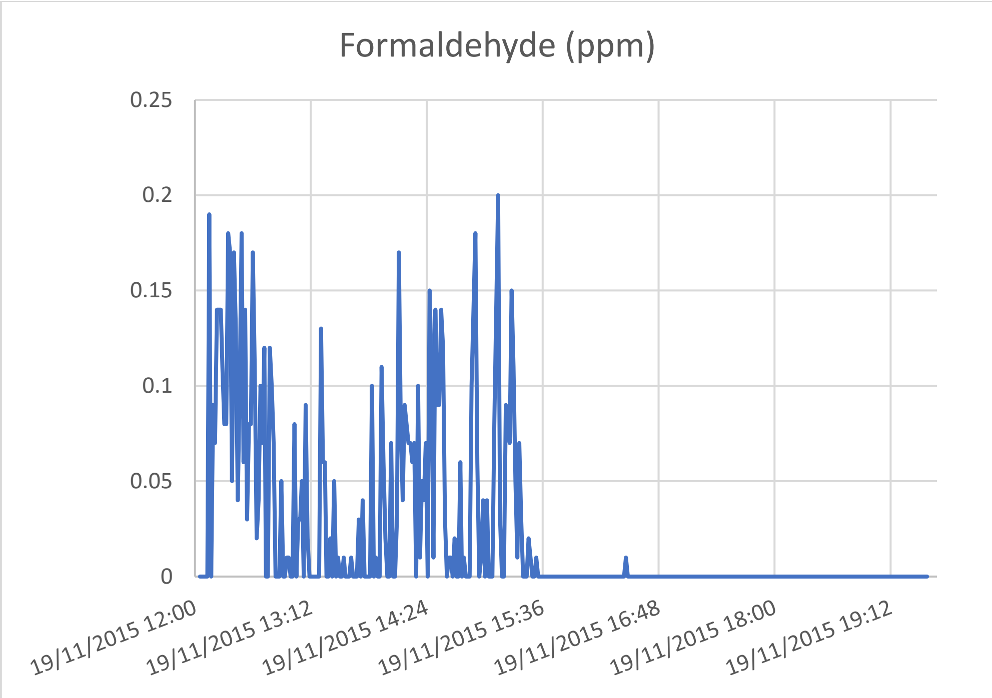
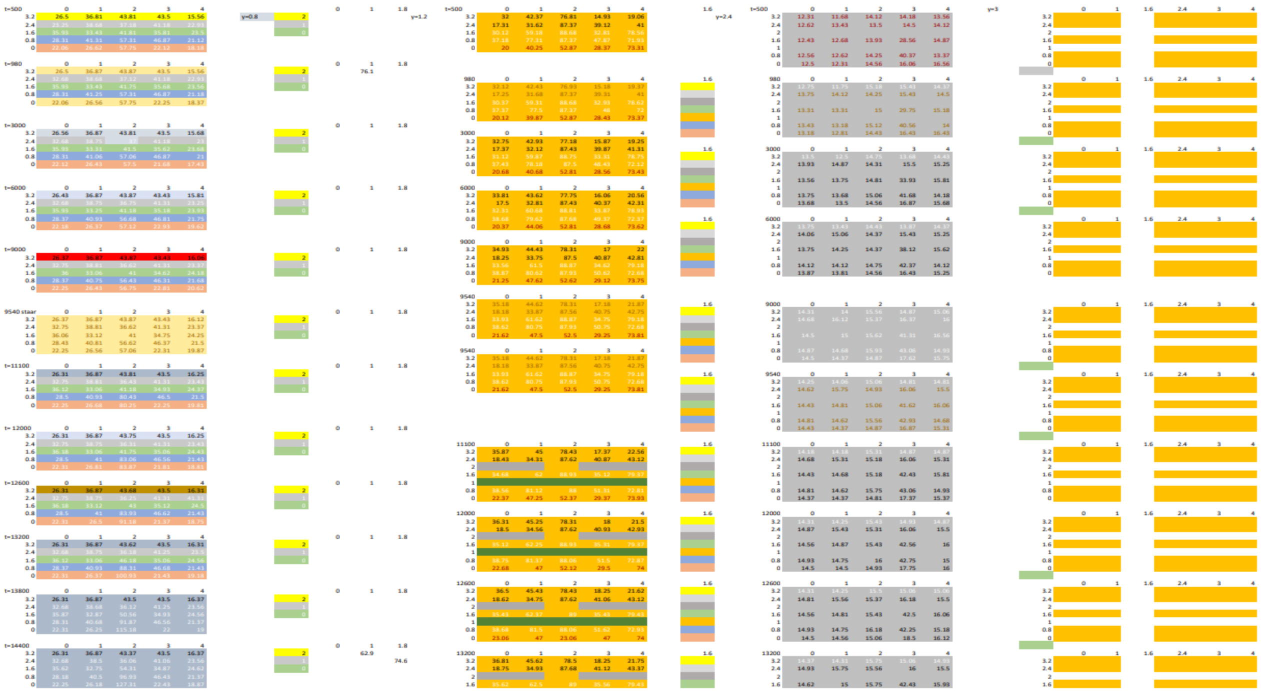


Broad spectrum gas data

APPENDIX B Deep seated fire Data



14760	0	1	2	3	4
3.2	26.31	36.81	43.37	43.5	16.43
2.4	32.68	38.37	36.06	40.87	23.62
1.6	35.43	32.62	56	34.81	24.62
0.8	28.12	40.37	98.68	46.43	21.37
0	22.25	26.12	127.93	23.18	18.81

15600	0	1	2	3	4
3.2	26.31	36.68		43.5	16.5
2.4	32.62	38.06		40.62	40.62
1.6	35.12	32.43		34.81	24.62
0.8	28	40.12		46.31	21.37
0	22.18	26.12		22.87	18.43
16800	0	1	2	3	4
3.2	26.31	36.5		43.5	16.56
2.4	32.56	37.75		40.31	23.68
1.6	34.75	32.25		34.81	24.68
0.8	27.81	39.81		46.37	21.31
0	22.18	26.12		24.43	18.18
18000	0	1	2	3	4
3.2	26.31	36.31		43.5	16.62
2.4	32.43	37.5		40	23.75
1.6	34.43	34.43		34.87	24.75
0.8	27.68	39.56		46.5	27.68
0	22.12	26.25		26	18.06
19200	0	1	2	3	4
3.2	26.31	36.31		43.5	16.62
2.4	32.37	37.25		39.68	23.81
1.6	34.18	31.87		35	24.81
0.8	27.5	39.31		46.68	21.37
0	22.06	26.5		27.25	17.75
20400	0	1	2	3	4
3.2	26.31	36.25		43.5	16.68
2.4	32.31	37.06		39.43	23.87
1.6	33.93	31.81		35.06	24.87
0.8	27.37	39.12		47.06	21.43
0	22	26.62		34.56	18.43
21600	0	1	2	3	4
3.2	26.31	36.18		43.5	16.75
2.4	32.18	36.81		39.18	23.93
1.6	33.68	31.68		35	24.93
0.8	27.31	38.93		47.75	21.43
0	22	26.81		41.25	18.93
22800	0	1	2	3	4
3.2	26.25	36.18		43.5	16.75
2.4	32.12	36.68		39	24
1.6	33.43	31.56		34.87	24.93
0.8	27.18	38.75		49.12	21.56
0	21.93	27.18		47	20.25
24000	0	1	2	3	4
3.2	26.31	36.12		43.5	16.87
2.4	32.06	36.5		38.75	24.06
1.6	33.25	31.43		34.87	24.93
0.8	27.06	38.62		50.87	21.56
0	21.87	27.62		46.12	20.12
25200	0	1	2	3	4
3.2	26.18	36.06		43.5	16.87
2.4	32	36.37		38.5	24.06
1.6	33	31.43		34.75	34.75
0.8	26.93	38.5		52.93	21.75
0	21.87	28.25		50.5	21.18
26400	0	1	2	3	4
3.2	26.18	36		43.56	16.93
2.4	31.93	36.25		38.31	24.12
1.6	32.81	31.25		35	35
0.8	26.87	38.43		53.25	21.81
0	21.87	28.93		48.31	19.81
27600	0	1	2	3	4
3.2	26.18	35.87		43.5	17
2.4	31.87	36.06		38.18	24.18
1.6	32.62	31.31		34.81	34.81
0.8	26.81	38.43		57.25	21.93
0	21.81	29.81		62.25	25.12
28800	0	1	2	3	4
3.2	26.25	35.81		43.56	17.06
2.4	31.81	35.93		38	24.18
1.6	32.43	31.06		35.37	35.37
0.8	26.68	38.56		57.06	22.12
0	21.81	30.68		43.18	20.25
30000	0	1	2	3	4
3.2	26.31	35.75		43.62	17
2.4	31.75	35.81		37.87	24.18
1.6	32.25	31.06		35.81	35.81
0.8	26.62	38.56		56.18	22.18
0	21.75	31.5		38.12	18.5
31200	0	1	2	3	4
3.2	26.37	35.75		43.75	16.93
2.4	31.75	35.75		37.93	24.18

2
1
0

	0	1	1.8
14760		62.9	74.7
15600		64.5	74.7
16800		69.3	74.5
18000			
19200		83.7	74.5
20400		88.9	74.4
21600		92.9	74.4
22800		94.3	74.1
24000		94.9	74.2
25200		95.3	74.1
26400			
27600		95.7	73.9
28800			
30000		98.6	74
31200		104.8	74

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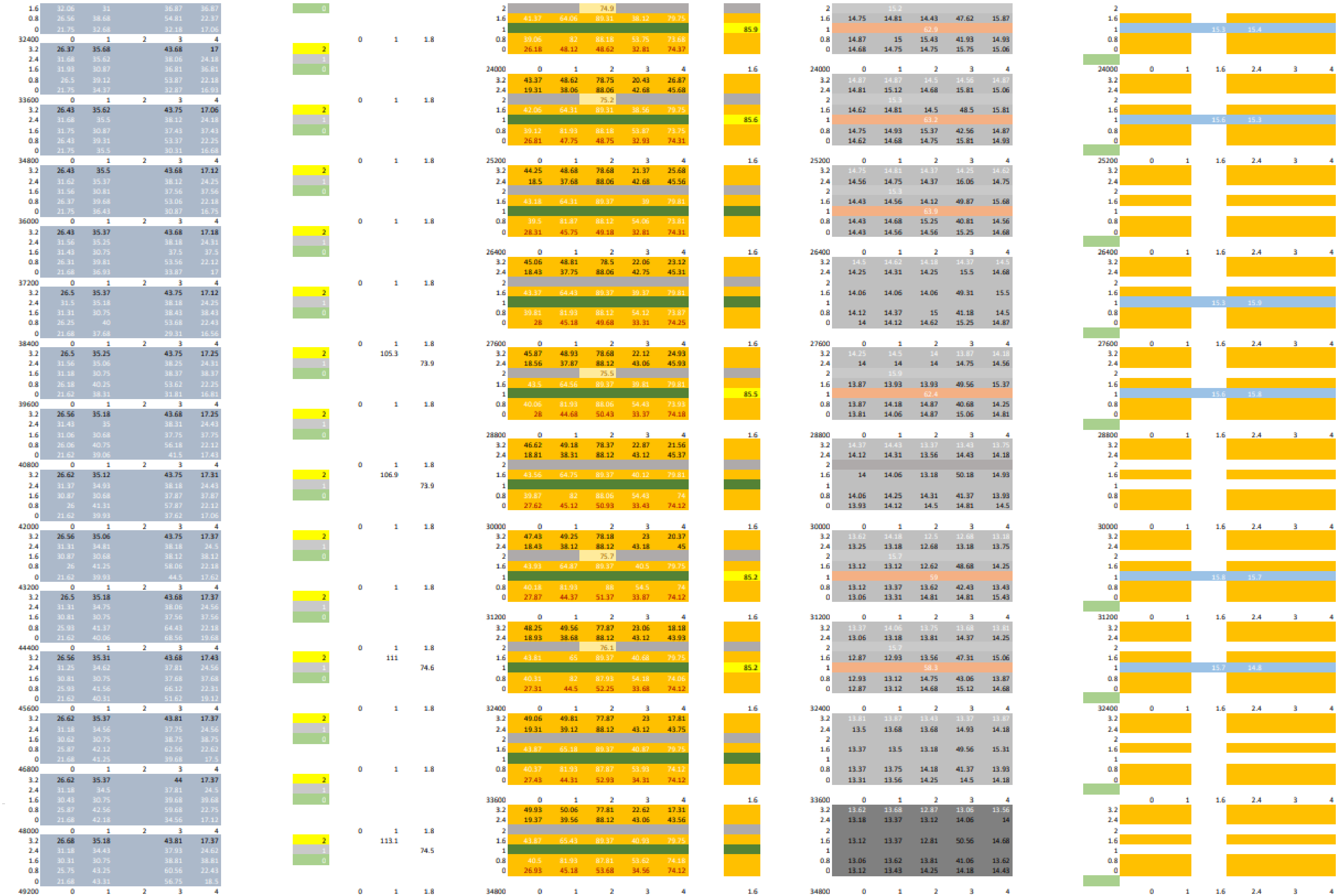
0.8	38.87	81.62	88.12	51.75	72.93
0	23.25	47.12	51.75	29.62	74.06
13800	0	1	2	3	4
3.2	37.12	45.75	78.5	18.5	21.93
2.4	18.81	35.12	87.68	41.12	43.43
2					
1.6	36	62.68	89	35.68	79.5
1					
0.8	38.93	81.68	88.12	51.87	73
0	23.43	46.93	51.37	29.75	74.12
14400	0	1	2	3	4
3.2	37.37	45.93	78.56	18.75	21.68
2.4	19	35.37	87.68	41.18	43.43
2			73.9		
1.6	36.18	62.81	89.06	35.87	79.56
1					
0.8	39.31	81.75	88.18	51.93	73.06
0	23.5	47.62	51	29.93	74.12
14760	0	1	2	3	4
3.2	37.56	46.12	78.56	18.93	21.81
2.4	19.12	35.5	87.68	41.25	43.43
2			73.8		
1.6	36.31	62.87	89.06	35.93	79.56
1					
0.8	39.31	81.81	88.18	51.93	73.12
0	23.56	48	50.81	30.12	74.18
15600	0	1	2	3	4
3.2	38.18	46.31	78.62	19.18	21.75
2.4	19.18	35.81	87.75	41.43	43.62
2			74		
1.6	36.81	63	89.06	36.18	79.62
1					
0.8	39.25	81.87	88.18	52.06	73.18
0	23.75	48.37	50.37	30.37	74.18
16800	0	1	2	3	4
3.2	38.68	46.75	78.68	19.5	22.06
2.4	19.62	36.31	87.75	41.5	43.81
2			74		
1.6	37.25	63.18	89.12	36.43	79.68
1					
0.8	39.62	82	88.18	52.25	73.25
0	23.5	49.62	49.81	30.75	74.25
18000	0	1	2	3	4
3.2	39.37	47.18	78.68	19.56	22.31
2.4	19.93	36.68	87.81	41.62	44.12
2			74.2		
1.6	37.87	63.25	89.18	36.75	79.75
1					
0.8	39.43	82.06	88.18	52.5	73.37
0	23.62	50	49.31	31.18	74.31
19200	0	1	2	3	4
3.2	40.06	47.5	78.62	19.93	22.5
2.4	20.12	37.12	87.87	41.68	44.18
2			74.3		
1.6	38.56	63.43	89.18	37.06	79.81
1					
0.8	39.18	82.06	88.18	52.75	73.43
0	23.93	50.43	48.87	31.75	74.31
20400	0	1	2	3	4
3.2	40.81	47.81	78.68	19.87	23.75
2.4	19.62	37.18	87.87	41.93	44.75
2			74.6		
1.6	39.81	63.62	89.25	37.37	79.81
1					
0.8	38.81	82.06	88.18	53.06	73.5
0	25	48.87	48.75	32	74.37
21600	0	1	2	3	4
3.2	41.62	48.12	78.68	19.93	25.06
2.4	19.62	37.56	87.93	42.18	45.12
2			74.8		
1.6	40.31	63.87	89.31	37.75	79.75
1					
0.8	39.37	82.06	88.18	53.43	73.56
0	25.12	49.06	48.56	32.87	74.37
22800	0	1	2	3	4
3.2	42.43	48.37	78.75	20.25	26.62
2.4	19.43	37.75	88	42.56	45.5

	1.6
13800	
14400	86.7
14760	86.8
15600	86.7
16800	86.7
18000	86.4
19200	86.2
20400	86
21600	86.1
22800	

	0	1	2	3	4
1					
0.8	15.06	14.93	16.43	42.12	15.06
0	14.62	14.68	15.18	18.06	16.25
13800	0	1	2	3	4
3.2	14.37	14.31	15.75	15.31	15.25
2.4	14.87	15.62	15.56	16.5	15.81
2					
1.6	14.62	14.93	15.62	42.56	16.31
1					
0.8	15.06	14.87	16.31	42.68	15.25
0	14.62	14.75	15.25	18.37	16.5
14400	0	1	2	3	4
3.2	14.56	14.43	15.43	15.12	15.06
2.4	15.06	15.93	15.31	16.18	15.62
2		44.8			
1.6	14.81	15.18	15.37	42.68	16.12
1			59		
0.8	15.25	15.06	16.25	42.75	15.18
0	14.75	14.87	15.31	18.31	16.43
14760	0	1	2	3	4
3.2	14.56	14.43	15.43	15.12	15.06
2.4	15.06	15.75	15.31	16.06	15.68
2		43.8			
1.6	14.75	15.06	15.37	42.68	16.06
1			58.4		
0.8	15.18	15.06	16.18	42.87	15.18
0	14.75	14.81	15.43	18.25	16.25
15600	0	1	2	3	4
3.2	14.56	14.5	16.81	16.43	15.68
2.4	15	15.68	16.37	16.87	15.87
2		43.3			
1.6	14.81	15.06	16.43	42.87	16.5
1			57.7		
0.8	15.18	15.06	16.93	43.5	15.62
0	14.75	14.81	15.18	17.68	16.18
16800	0	1	2	3	4
3.2	15.37	14.93	15.25	15.12	15.43
2.4	15.75	16.18	15.25	16.5	15.5
2		43.4			
1.6	15.43	15.62	15.12	43.37	16.18
1			57.6		
0.8	15.56	15.68	15.87	44.68	15.31
0	15.43	15.43	15.06	16.93	16
18000	0	1	2	3	4
3.2	15	14.93	15.43	15.62	15.5
2.4	15.31	15.75	15.43	16.37	15.43
2		34.6			
1.6	15.06	15.31	15.31	43.75	16.25
1			57.9		
0.8	15.12	15.43	16.06	45.06	15.5
0	15.06	15.12	15.06	17.37	15.93
19200	0	1	2	3	4
3.2	14.93	15	15.62	15.43	15.37
2.4	15.5	15.75	15.5	16.43	15.5
2		14.8			
1.6	15.12	15.25	15.37	44.87	16.18
1			59.6		
0.8	15.31	15.25	16.12	44.87	15.37
0	15	14.93	15	16.93	15.62
20400	0	1	2	3	4
3.2	15	15	15.5	15.31	15.37
2.4	15.56	15.68	15.37	16.93	15.43
2		25.2			
1.6	15.18	15.18	15.18	45.37	16.37
1			60.3		
0.8	15.37	15.31	16.06	44.37	15.31
0	15.06	15	14.75	16.25	15.06
21600	0	1	2	3	4
3.2	15.12	15.06	15.12	15.31	15.31
2.4	15.56	15.62	15.06	16.56	15.37
2		15.3			
1.6	15.25	15.25	14.87	45.81	16.25
1			62.5		
0.8	15.43	15.37	15.81	43	15.31
0	15.12	15.12	14.75	16.25	15.18
22800	0	1	2	3	4
3.2	14.87	14.93	14.68	14.68	15
2.4	15	15.06	14.81	16	15.12

	0	1	1.6	2.4	3	4
1						
0.8						
0						
	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1						
0.8						
0						
14400	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1			14.6	14.5		
0.8						
0						
14760	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1			14.5	14.3		
0.8						
0						
15600	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1			14.7	14.6		
0.8						
0						
16800	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1			14.6	14.8		
0.8						
0						
18000	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1			14.8	15		
0.8						
0						
19200	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1			15.1	15.1		
0.8						
0						
20400	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1			15.3	15.3		
0.8						
0						
21600	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1			15.5	15.3		
0.8						
0						
22800	0	1	1.6	2.4	3	4
3.2						
2.4						



	0	1	2	3	4
3.2	26.62	35.06		43.68	17.31
2.4	31.12	34.37		37.93	24.68
1.6	30.18	30.75		38	38
0.8	25.75	44.43		68.68	22.62
0	21.75	45.43		75.18	31.06
50400	0	1	2	3	4
3.2	26.5	35.06		43.68	17.37
2.4	31.06	34.31		37.68	24.75
1.6	30.12	30.87		37.56	37.56
0.8	25.68	45.81		73.06	22.75
0	21.81	46.18		77.56	51.75
51600	0	1	2	3	4
3.2	26.62	35.06		43.68	17.31
2.4	31	34.25		37.5	24.75
1.6	30	30.87		37.68	37.68
0.8	25.68	46.31		74.56	22.81
0	21.93	46.31		78.12	52.43
52800	0	1	2	3	4
3.2	26.5	35.12		43.75	17.31
2.4	31	34.18		37.31	24.81
1.6	29.93	30.93		38	38
0.8	25.62	46.68		75.68	23
0	22	46.75		76.18	52.87
54000	0	1	2	3	4
3.2	26.43	35.12		43.75	17.31
2.4	30.93	34.18		37.18	24.87
1.6	29.81	31.06		38.25	38.25
0.8	25.62	47.18		76.18	23.25
0	22	47.37		78.25	55.5
55200	0	1	2	3	4
3.2	26.43	35.18		43.75	17.31
2.4	30.93	34.12		37.06	24.87
1.6	29.75	31.12		38.56	38.56
0.8	25.62	47		76.56	23.43
0	22.06	47.18		77.37	57.5
56400	0	1	2	3	4
3.2	26.37	35.18		43.81	17.37
2.4	30.87	34		36.93	24.93
1.6	29.68	31.25		38.87	38.87
0.8	25.56	46.87		75.81	23.68
0	22.06	47.06		74.93	52.37
57600	0	1	2	3	4
3.2	26.43	35.25		43.81	17.37
2.4	30.87	33.93		36.81	24.93
1.6	29.56	31.31		39.06	39.06
0.8	25.5	46.93		74.81	23.87
0	22.12	47.37		72.56	47.31
58800	0	1	2	3	4
3.2	26.43	35.18		43.81	17.31
2.4	30.87	33.87		36.75	25
1.6	29.5	31.37		39.25	39.25
0.8	25.5	47.93		74.68	24.12
0	22.18	48.75		75	48.31
60000	0	1	2	3	4
3.2	26.43	35.18		43.81	17.37
2.4	30.81	33.87		36.62	25.06
1.6	29.37	31.5		39.56	39.56
0.8	25.5	48.5		74.87	24.25
0	22.25	49.06		70.68	49.87
61200	0	1	2	3	4
3.2	26.5	35.18		43.81	17.37
2.4	30.81	33.81		36.56	25.06
1.6	29.31	31.62		39.68	39.68
0.8	25.43	48.93		74.06	24.31
0	22.37	49.81		70.62	45.93
62400	0	1	2	3	4
3.2	26.5	35.12		43.81	17.43
2.4	30.81	31.75		36.5	25.06
1.6	29.25	31.68		39.93	39.93
0.8	25.43	49.81		73.68	24.56
0	22.43	49.87		70	44.25
63600	0	1	2	3	4
3.2	26.5	35.06		43.81	17.5
2.4	30.75	33.68		36.43	25.06
1.6	29.18	31.87		40	40
0.8	25.37	50		73.25	24.62
0	22.56	50.31		72.25	42.68
64800	0	1	2	3	4
3.2	26.5	35.06		43.87	17.56
2.4	30.75	33.62		36.37	25.06
1.6	29.12	31.93		40.18	40.18
0.8	25.37	49.56		74.06	24.75
0	22.62	49.43		75	43.12
66000	0	1	2	3	4
3.2	26.43	35.12		43.87	17.56
2.4	30.68	33.56		36.31	25.06
1.6	29.06	32		40.37	40.37
0.8	25.37	49		74.62	24.81

2
1
0

0 1 1.8

114.2
74.6

	0	1	2	3	4	
3.2	50.81	50.56	77.87	22.75	17.43	
2.4	20.18	40.43	88.12	42.93	43.81	
2						
1.6	43.68	65.75	89.37	41	79.75	
1						
0.8	40.25	82	87.81	53.5	74.25	
0	25.62	46.37	54.43	35.12	74.12	
36000	0	1	2	3	4	1.6
3.2	51.75	50.75	78	22.81	17.56	
2.4	19.75	40.31	88.12	43	44.18	
2						
1.6	44.93	65.81	89.31	41.18	79.75	
1						
0.8	40.25	81.81	87.75	53.5	74.31	
0	27.18	45.12	55.31	35.62	74.18	
37200	0	1	2	3	4	1.6
3.2	52.75	50.75	77.62	22.5	16.68	
2.4	18.93	39.93	88.12	42.81	43.25	
2						
1.6	45.62	65.87	89.31	41.18	79.81	
1						
0.8	40.87	81.81	87.68	53.25	74.43	
0	28.31	43.62	56.68	35.37	74.18	
38400	0	1	2	3	4	1.6
3.2	53.62	51	77.81	22.43	16.81	
2.4	19.56	40.75	88.12	43	43.81	
2			75.9			
1.6	45.25	66.12	89.31	41.31	79.81	
1						85.1
0.8	41.12	81.87	87.68	53.12	74.43	
0	27.25	44	57.56	36	74.25	
39600	0	1	2	3	4	1.6
3.2	54.56	51.43	78.12	22.5	17.81	
2.4	20.18	41.37	88.12	43.18	44.81	
2						
1.6	44.81	66.43	89.31	41.56	79.87	
1						
0.8	40.93	81.93	87.62	53.18	74.56	
0	25.5	44.87	58.87	36.5	74.25	
40800	0	1	2	3	4	1.6
3.2	55.43	51.93	78.06	22.81	17.5	
2.4	20.75	41.93	88.12	43.31	44.43	
2			76			
1.6	45	66.62	89.31	41.75	79.93	
1						84.7
0.8	40.56	82	87.5	53.18	74.62	
0	24.93	46.18	60.12	36.75	74.31	
42000	0	1	2	3	4	1.6
3.2			78.06	22.43	17.56	
2.4			88.12	43.18	45	
2						
1.6			89.31	41.93	79.93	
1						
0.8			87.5	53.37	74.75	
0			61.31	37.06	74.31	
43200	0	1	2	3	4	1.6
3.2			78.43	22.37	19.75	
2.4			88.12	43.75	46.18	
2						
1.6			89.31	42.25	80	
1						
0.8			87.43	53.68	74.81	
0			62.87	37	74.37	
44400	0	1	2	3	4	1.6
3.2			78.31	22.68	19.5	
2.4			88.12	43.81	45.87	
2			75.9			
1.6			89.31	42.56	80.06	
1						84.9
0.8			87.31	53.81	74.93	
0			64.31	37.37	74.43	
45600	0	1	2	3	4	1.6
3.2			77.87	22.93	16.93	
2.4			88.12	43.81	44.87	
2						
1.6			89.31	42.75	80	
1						
0.8			87.25	53.68	74.93	
0			65.12	37.31	74.43	

	0	1	2	3	4
3.2	13.31	13.56	12.68	12.93	13.5
2.4	13	13.06	12.93	13.62	13.93
2					
1.6	12.93	13.06	12.81	50.56	15.06
1					
0.8	12.81	13.31	13.75	42.37	13.56
0	12.81	13.18	14.56	14.43	15.12
36000	0	1	2	3	4
3.2	13.06	13.56	12.25	12.68	13.25
2.4	12.81	12.62	12.43	13.18	13.5
2					
1.6	12.56	12.62	12.25	49.87	14.75
1					
0.8	12.37	12.93	13.37	43.93	13.37
0	12.43	12.87	14.5	14.37	15.56
37200	0	1	2	3	4
3.2	12.81	13.5	11.93	12.18	12.87
2.4	12.56	12.25	12.06	12.75	13.25
2					
1.6	12.31	12.31	12	49.25	14.37
1					
0.8	12.12	12.68	13.18	44.31	13.06
0	12.18	12.68	14.68	14.5	15.56
38400	0	1	2	3	4
3.2	12.62	13.37	11.68	12.06	12.5
2.4	12.5	12.31	11.81	12.56	13.25
2		14.9			
1.6	12.31	12.31	11.68	48.68	14.37
1			49.7		
0.8	12.12	12.56	12.87	44.12	12.93
0	12.18	12.43	15.12	14.37	15.62
39600	0	1	2	3	4
3.2	12.62	13.37	11.68	12.06	12.5
2.4	12.5	12.31	11.81	12.56	13.25
2					
1.6	12.31	12.31	11.68	48.68	14.37
1					
0.8	11.62	12.12	13.5	44.93	12.81
0	11.75	12.06	15	14.75	15.75
40800	0	1	2	3	4
3.2	12.62	13.31	12.5	12.62	13
2.4	12.43	12.31	12.37	13.12	13.56
2		14.9			
1.6	12.18	12.25	12.5	47.31	14.37
1			50.9		
0.8	12.12	12.5	13.62	45.18	13.25
0	12.18	12.5	15.56	15.18	15.37
42000	0	1	2	3	4
3.2	12.75	13.12	12.81	12.68	13.18
2.4	12.56	12.68	12.62	13.31	13.87
2					
1.6	12.37	12.43	12.68	46.75	14.68
1					
0.8	12.31	12.62	13.81	45.06	13.25
0	12.31	12.5	16.06	15.06	15.75
43200	0	1	2	3	4
3.2	12.93	13.06	13.31	13.18	13.68
2.4	12.93	13.25	13.12	13.81	14.25
2					
1.6	12.75	12.87	13.25	46.56	15
1					
0.8	12.81	13	14.37	46.56	13.68
0	12.68	12.81	16.06	15.62	16.12
44400	0	1	2	3	4
3.2	13.43	13.56	13.5	13.25	13.81
2.4	13.18	13.62	13.37	14.06	14.5
2		13.8			
1.6	12.93	13.12	13.37	46.37	14.93
1			56.6		
0.8	13.12	13.31	14.5	45.62	13.62
0	12.93	13.68	16.43	15.81	15.87
45600	0	1	2	3	4
3.2	13.5	13.68	13.56	13.31	13.81
2.4	13.31	13.68	13.5	14.18	14.5
2					
1.6	13.06	13.25	13.5	45.5	14.87
1					
0.8	13.25	13.5	14.68	46.68	13.62
0	13.06	14.12	16.68	15.75	15.43

	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1						
0.8						
0						
	0	1	1.6	2.4	3	4
38400	0	1	1.6	2.4	3	4
1				14.8	14.7	
40800	0	1	1.6	2.4	3	4
1				14.7	13.8	
44400	0	1	1.6	2.4	3	4
1				13.9	14.9	

0	22.62	48.81		75.68	52.25
67200	0	1	2	3	4
3.2	26.43	35.12		43.87	17.62
2.4	30.68	33.5		36.18	25.06
1.6	29.12	32.12		40.5	40.5
0.8	25.31	48.25		75.06	24.93
0	22.68	48.06		76.81	54.5
68400	0	1	2	3	4
3.2	26.37	35.18		43.93	17.75
2.4	30.68	33.43		36.06	25.06
1.6	29.25	32.18		41.12	41.12
0.8	25.31	47.68		75.81	25.43
0	22.75	47.5		72.93	53.18
69600	0	1	2	3	4
3.2	26.37	35.18		43.93	17.75
2.4	30.62	33.37		36	25.06
1.6	29.25	32.25		41.43	41.43
0.8	25.31	47.5		74.31	25.68
0	22.75	47.43		70.5	46.62
70800	0	1	2	3	4
3.2	26.37	35.25		44	17.87
2.4	30.62	33.37		35.93	25.06
1.6	29.25	32.31		41.68	41.68
0.8	25.37	47.06		73.56	25.75
0	22.81	47		68.5	42.93
72000	0	1	2	3	4
3.2	26.43	35.25		43.93	17.81
2.4	30.62	33.31		35.93	25.06
1.6	29.31	32.31		41.5	41.5
0.8	25.37	47		74.37	25.68
0	22.87	47		73.93	45.06
73200	0	1	2	3	4
3.2	26.43	35.25		43.87	17.75
2.4	30.62	33.25		35.81	25.06
1.6	29.25	32.37		41.87	41.87
0.8	25.31	46.68		73.93	25.75
0	22.87	46.87		70.31	42.56
74400	0	1	2	3	4
3.2	26.43	35.25		43.87	17.81
2.4	30.56	33.18		35.68	25.06
1.6	29.06	32.37		42.12	42.12
0.8	25.25	46.81		73.87	25.81
0	22.93	47.12		69.18	43.31
75600	0	1	2	3	4
3.2	26.5	35.18		43.81	17.81
2.4	30.56	33.12		35.68	25.06
1.6	28.75	32.62		42.5	42.5
0.8	25.18	50.12		73.68	25.93
0	23.18	52.56		70.5	44
76800	0	1	2	3	4
3.2	26.56	35.12		43.87	17.93
2.4	30.56	33.06		35.56	25.06
1.6	28.68	32.75		42.5	42.5
0.8	25.12	52.37		72.87	25.93
0	23.37	54.37		67.37	40
78000	0	1	2	3	4
3.2	26.68	35		43.93	18
2.4	30.5	33.06		35.5	25.06
1.6	28.56	32.93		42.5	42.5
0.8	25.12	54.75		72.56	26
0	23.56	56		70.43	39.31
79200	0	1	2	3	4
3.2	26.75	34.87		43.93	17.93
2.4	30.5	33		35.5	25.06
1.6	28.5	33.06		42.81	42.81
0.8	25.06	54.68		74.25	26.12
0	23.68	54.62		73.75	45.31
80400	0	1	2	3	4
3.2	26.75	34.68		43.87	18.06
2.4	30.5	33		35.43	25.06
1.6	28.5	33.25		42.81	42.81
0.8	25.06	54.06		74.56	26.12
0	23.81	54.06		74.12	43.37
81600	0	1	2	3	4
3.2	26.75	34.68			
2.4	30.5	33			
1.6	28.43	33.43			
0.8	25.06	55.06			
0	23.93	56.06			
82800	0	1	2	3	4
3.2	26.87	34.62			
2.4	30.43	32.93			
1.6	28.37	33.5			
0.8	25.06	54.81			
0	24	55.56			
84000	0	1	2	3	4
3.2	26.93	34.56			
2.4	30.43	32.87			

2	0	1	1.8
1			
0			
2	0	1	1.8
1			
0			
2	0	1	1.8
1			
0			
2	0	1	1.8
1			
0			
2	0	1	1.8
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0			
2	0	1	1.8
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0			
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0			
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1			
0			
2	0	1	1.8
1			
0			
2	0	1	1.8
1			
0			
2	0	1	1.8
1			
0			
2	0	1	1.8
1		118.6	
0			74.9
2	0	1	1.8
1		180.7	
0			77.3
2	0	1	1.8
1		181.4	
0			78.3
2	0	1	1.8
1		218.9	
			80.7

46800	0	1	2	3	4	1.6
3.2			77.68	22.43	15.87	
2.4			88.12	43.68	44.31	
2						
1.6			89.25	42.81	80	
1						
0.8			87.18	53.5	75	
0			65.81	37.43	74.43	
48000	0	1	2	3	4	1.6
3.2			78.18	22.75	17.62	
2.4			88.06	43.93	45.93	
2			75.9			
1.6			89.25	43	80	
1						85.5
0.8			87	53.56	75.06	
0			67	38.31	74.43	
49200	0	1	2	3	4	1.6
3.2			78.56	22.81	19.68	
2.4			88.06	44.62	47.25	
2						
1.6			89.25	43.25	80	
1						
0.8			86.81	53.81	75.18	
0			69.5	37.68	74.5	
50400	0	1	2	3	4	1.6
3.2			78.81	22.5	21.81	
2.4			88.06	44.93	48.06	
2			76.4			
1.6			89.25	43.62	80.06	
1						86.1
0.8			86.56	54.18	75.31	
0			71.37	38.12	74.5	
51600	0	1	2	3	4	1.6
3.2			78.93	22.43	23.43	
2.4			88.06	45.06	48.62	
2						
1.6			89.18	43.93	80.06	
1						
0.8			86.25	54.5	75.43	
0			72.25	38.62	74.5	
52800	0	1	2	3	4	1.6
3.2			79	22.68	24.37	
2.4			88.06	45.18	49.12	
2						
1.6			89.12	44.25	80.12	
1						
0.8			85.87	54.81	75.5	
0			72.93	38.93	74.5	
54000	0	1	2	3	4	1.6
3.2			79.12	22.5	25.81	
2.4			88.06	45.5	49.87	
2						
1.6			89	44.56	80.06	
1						
0.8			85.5	55	75.56	
0			73.75	39.18	74.5	
55200	0	1	2	3	4	1.6
3.2			79.18	22.31	26.93	
2.4			88	45.68	50.5	
2						
1.6			88.87	44.93	80.06	
1						
0.8			85.06	55.31	75.62	
0			74.31	39.56	74.5	
56400	0	1	2	3	4	1.6
3.2			79.25	22.5	27.5	
2.4			88	45.87	50.93	
2						
1.6			88.81	45.25	80.06	
1						
0.8			84.68	55.5	75.68	
0			74.56	39.87	74.43	
57600	0	1	2	3	4	1.6
3.2			79.31	22.75	27.62	
2.4			88	46.12	51.43	
2						
1.6			88.68	45.62	80	
1						

46800	0	1	2	3	4
3.2	13.68	13.87	13.56	13.25	13.87
2.4	13.56	14.06	13.37	14.06	14.62
2					
1.6	13.37	13.56	13.62	45.25	15
1					
0.8	13.56	13.75	14.62	46.62	13.62
0	13.37	13.68	16.87	16.06	16.06
48000	0	1	2	3	4
3.2	14.43	14.37	13.56	13.37	14
2.4	14.5	15.18	13.5	14.25	14.68
2		14.9			
1.6	14.31	14.43	13.75	44.18	15
1			53.1		
0.8	14.25	14.5	14.87	46.37	13.81
0	14.18	14.37	16.81	16.68	15.93
49200	0	1	2	3	4
3.2	14.62	14.43	13.62	13.43	13.87
2.4	14.75	15.25	13.56	14.37	14.56
2					
1.6	14.56	14.62	13.93	43.93	15.06
1					
0.8	14.56	14.75	15.06	46.25	13.87
0	14.37	14.5	16.68	17.37	15.93
50400	0	1	2	3	4
3.2	14.93	14.62	13.81	13.37	13.87
2.4	15.18	15.62	13.68	14.37	14.5
2		13.6			
1.6	15.06	15.06	14.25	43.93	15.18
1			52.5		
0.8	15	15.06	15.25	45.81	13.87
0	14.68	14.81	16.37	17.43	16.5
51600	0	1	2	3	4
3.2	15.06	14.75	13.93	13.62	14
2.4	15.5	15.87	13.87	14.62	14.75
2					
1.6	15.31	15.37	14.31	44.25	15.31
1					
0.8	15.25	15.37	15.25	47.37	14
0	14.93	15.12	17	17.12	16.25
52800	0	1	2	3	4
3.2	15.5	15.06	14.18	13.93	14.31
2.4	16.06	16.5	14.12	14.93	14.93
2					
1.6	15.81	15.93	14.5	45.31	15.5
1					
0.8	15.87	15.93	15.18	47.93	14.25
0	15.5	15.62	17.12	16.81	15.81
54000	0	1	2	3	4
3.2	16.12	15.37	14.31	14.12	14.5
2.4	16.75	17.25	14.43	15.06	15.06
2					
1.6	16.43	16.43	14.75	46.62	15.68
1					
0.8	16.37	16.43	15.37	48.62	14.5
0	16.12	16.18	17.12	17.06	15.87
55200	0	1	2	3	4
3.2	17.06	15.87	14.5	14.12	14.5
2.4	18.43	18.5	14.5	14.87	15.06
2					
1.6	18.06	17.93	15	47	15.81
1					
0.8	18	17.81	15.25	48.31	14.5
0	17.31	17.31	17.93	17.37	15.87
56400	0	1	2	3	4
3.2	16.93	16.37	15	14.81	15.18
2.4	17.81	17.87	14.81	15.31	15.5
2					
1.6	17.31	17.31	15.31	47.87	16.31
1					
0.8	17.37	17.37	15.62	48.37	14.93
0	17.06	17.12	18.12	16.68	16.68
57600	0	1	2	3	4
3.2	16.87	16.68	15.37	15	15.31
2.4	17.31	17.75	15	15.43	16
2					
1.6	16.87	17.06	15.62	46.87	16.5
1					

	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1						
0.8						
0						
48000	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1			14.8	13.7		
0.8						
0						
	0	1	1.6	2.4	3	4
3.2						
2.4						
1.6						
0.8						
0						
50400	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1			13.8	15.7		
0.8						
0						

	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1						
0.8						
0						
	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1						
0.8						
0						
	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1						
0.8						
0						
	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1						
0.8						
0						

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3.2						
2.4						
2						
1.6						
1						
0.8						
0						
	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1						
0.8						
0						
	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1						
0.8						
0						
	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1						

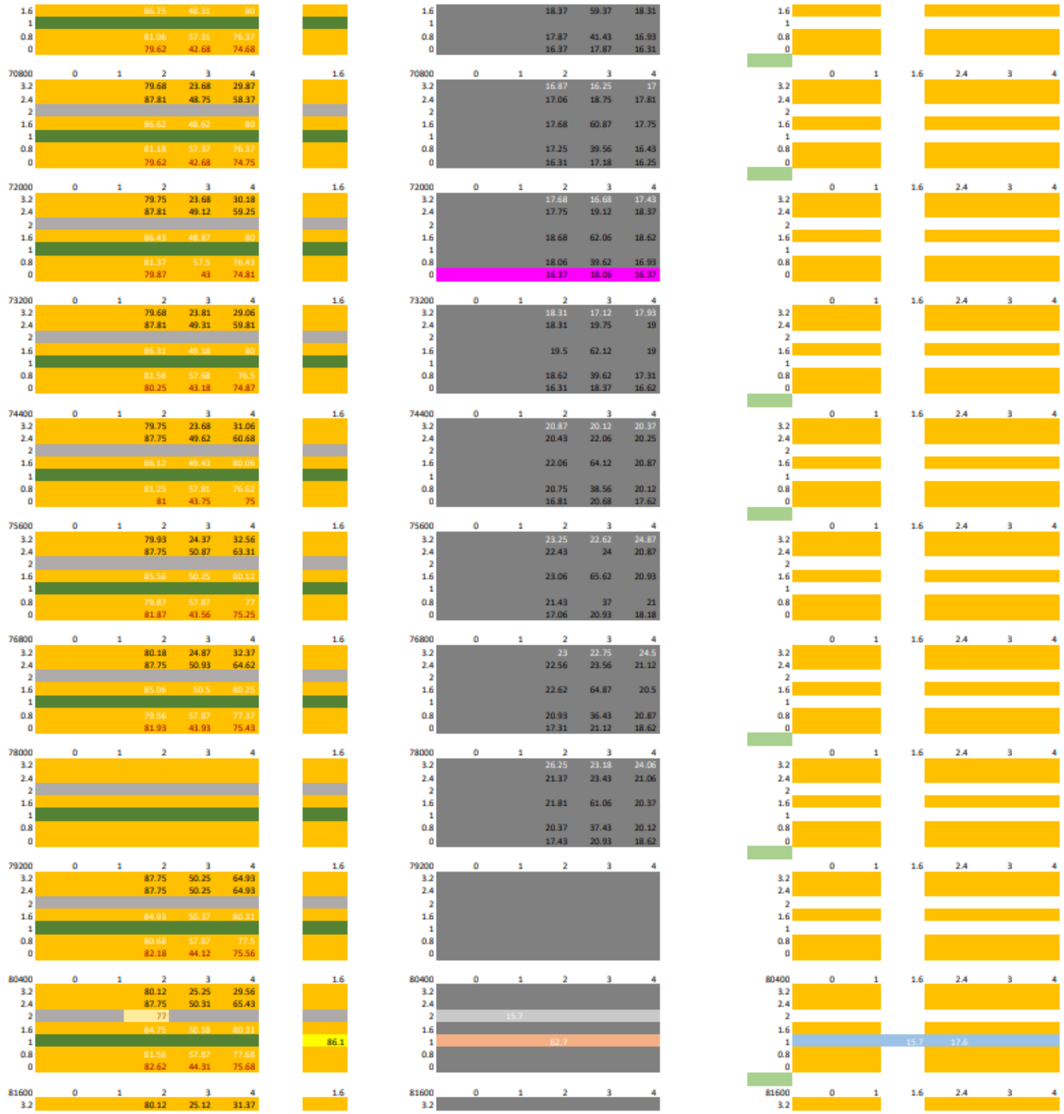
1.6	28.31	33.68			
0.8	25.06	55.18			
0	24.12	57.43			
85200	0	1	2	3	4
3.2	27.06	34.56			
2.4	30.37	32.81			
1.6	28.25	33.87			
0.8	25.06	57.37			
0	24.37	60.37			

0			
	0	1	1.8
2		231.5	
1			81.3
0			

0.8			84.25	55.68	75.68	
0			75	40	74.43	
58800	0	1	2	3	4	1.6
3.2			79.43	23.12	28.68	
2.4			87.93	46.68	52.25	
2						
1.6			88.5	46	80	
1						
0.8			83.81	55.93	75.75	
0			75.81	40.12	74.43	
60000	0	1	2	3	4	1.6
3.2			79.5	22.93	29.12	
2.4			88	46.87	52.75	
2						
1.6			88.31	46.37	80	
1						
0.8			83.31	56.18	75.81	
0			76.31	40.56	74.43	
61200	0	1	2	3	4	1.6
3.2			79.62	23.25	29.87	
2.4			87.93	47.31	53.5	
2						
1.6			88.12	46.68	80	
1						
0.8			82.87	56.31	75.81	
0			76.56	40.62	74.43	
62400	0	1	2	3	4	1.6
3.2			79.62	23.43	29.68	
2.4			87.93	47.31	53.93	
2						
1.6			87.87	46.93	80	
1						
0.8			82.43	56.43	75.87	
0			76.93	40.93	74.43	
63600	0	1	2	3	4	1.6
3.2			79.75	23.25	30.18	
2.4			87.93	47.75	54.75	
2						
1.6			87.68	47.18	79.93	
1						
0.8			82.06	56.62	75.93	
0			77.31	41.06	74.5	
64800	0	1	2	3	4	1.6
3.2			79.81	23	31.43	
2.4			87.87	48.06	55.43	
2						
1.6			87.5	47.43	79.93	
1						
0.8			81.68	56.75	76.06	
0			77.93	41.43	74.5	
66000	0	1	2	3	4	1.6
3.2			79.81	22.87	32.06	
2.4			87.87	48.18	56.12	
2						
1.6			87.31	47.62	79.93	
1						
0.8			81.37	56.93	76.12	
0			78.37	41.81	74.56	
67200	0	1	2	3	4	1.6
3.2			79.81	22.81	32.25	
2.4			87.87	48.25	56.81	
2						
1.6			87.12	47.87	79.93	
1						
0.8			81.18	57.12	76.18	
0			78.87	42.12	74.62	
68400	0	1	2	3	4	1.6
3.2			79.75	22.5	32.31	
2.4			87.81	48.37	57.43	
2						
1.6			86.93	48.06	79.93	
1						
0.8			81.06	57.25	76.25	
0			79.31	42.5	74.68	
69600	0	1	2	3	4	1.6
3.2			79.81	22.62	33.12	
2.4			87.81	48.93	58.25	
2						

0.8	17.12	17.06	15.68	47.75	15
0	16.81	16.87	18.5	16.75	16.93
58800	0	1	2	3	4
3.2	16.37	16.25	14.93	14.87	15.37
2.4	16.81	17.37	14.93	16.06	15.75
2					
1.6	16.43	16.68	15.56	50.18	16.43
1					
0.8	16.75	16.62	15.75	47.12	15
0	16.37	16.37	18	16.75	16.12
60000	0	1	2	3	4
3.2	16.56	16.37	15.43	15.43	15.68
2.4	17	17.62	15.37	16.18	15.93
2					
1.6	16.62	16.93	16.06	52.93	16.62
1					
0.8	16.93	16.81	16	47.43	15.43
0	16.56	16.56	17.87	17.31	16.43
61200	0	1	2	3	4
3.2	16.31	16.25	16.12	16.18	16.06
2.4	16.06	16.93	16	16.62	16.31
2					
1.6	15.87	16.25	16.37	52.93	17.06
1					
0.8	16.06	16.37	16.43	47.37	16
0	16	16.25	18.06	17.5	16.68
62400	0	1	2	3	4
3.2	16.37	16.18	16.37	16.25	16.43
2.4	16.75	17.5	16.18	17.18	16.68
2					
1.6	16.43	16.75	17	52.18	17.37
1					
0.8	16.87	16.68	16.87	47.75	16.18
0	16.37	16.37	17.68	17.62	16.68
63600	0	1	2	3	4
3.2	16.56	16.31	17.37	16.81	16.93
2.4	17.12	17.81	17.06	17.31	17.5
2					
1.6	16.75	17.12	17.93	51.81	17.62
1					
0.8	17.25	16.87	17.68	46.43	16.56
0	16.68	16.62	17.87	17.75	17
64800	0	1	2	3	4
3.2	18.12	16.75	18.81	18.5	18.31
2.4	19.43	20.06	18.68	19.31	18.25
2					
1.6	19.31	19.43	19.37	55.12	18.87
1					
0.8	19.68	18.87	18.93	44.87	17.93
0	18.68	18.56	17.37	18.93	17.06
66000	0	1	2	3	4
3.2	18.12	17.56	18.43	17.75	17.93
2.4	18.81	19.87	18.06	19.93	17.87
2					
1.6	18.37	18.81	19.12	59.62	19
1					
0.8	19.06	18.81	18.56	45.18	17.5
0	18.62	18.68	16.56	18.25	16.62
67200	0	1	2	3	4
3.2	19.5	18.5	17.25	16.81	17.43
2.4	20.56	22.31	17.31	18.81	17.93
2					
1.6	19.93	20.68	18.06	61.25	18.31
1					
0.8	20.81	20.43	17.81	42.5	16.87
0	20	20.18	16.5	17.75	16.37
68400	0	1	2	3	4
3.2	19.43	31.43	17.68	16.68	17.37
2.4	21.12	22.18	17.62	18.93	18.06
2					
1.6	20.25	21.81	18.43	61	18.37
1					
0.8	21.81	21	17.93	41.25	16.81
0	20.68	20.75	16.5	17.81	16.31
69600	0	1	2	3	4
3.2			17.37	16.68	17.37
2.4			17.37	19.87	17.87
2					

0.8						
0						
	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1						
0.8						
0						
	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1						
0.8						
0						
	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1						
0.8						
0						
	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1						
0.8						
0						
	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1						
0.8						
0						
	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1						
0.8						
0						
	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1						
0.8						
0						
	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1						
0.8						
0						
	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1						
0.8						
0						
	0	1	1.6	2.4	3	4
3.2						
2.4						
2						



	0	1	2	3	4	1.6
2.4			87.68	50.68	66.12	
2			76.9			
1.6			84.56	50.18	80.43	
1						83
0.8			80.56	57.93	77.87	
0			83.37	44.25	75.87	

82800	0	1	2	3	4	1.6
3.2			80.12	25.93	27.87	
2.4			87.75	50.18	66.06	
2			76.9			
1.6			84.43	50.12	80.5	
1						83.5
0.8			80.31	57.81	78.06	
0			83.56	44.31	76	

84000	0	1	2	3	4	1.6
3.2			80.12	26.93	23.87	
2.4			87.68	50.43	66.68	
2			82.4			
1.6			84.31	49.81	80.81	
1						83.5
0.8			79.68	57.31	78.81	
0			83.87	43.87	76.43	

85200	0	1	2	3	4	1.6
3.2			80.18	26.18	20.62	
2.4			87.75	49.43	65.18	
2			82.5			
1.6			84.18	49.31	80.87	
1						85.3
0.8			80.18	56.81	78.93	
0			84.06	42.31	76.56	

86400	0	1	2	3	4	1.6
3.2			80.12	25.18	19	
2.4			87.75	49.06	63.43	
2			82.3			
1.6			84.12	48.5	80.93	
1						87.3
0.8			81.93	56.06	79.12	
0			84.12	41	76.75	

	0	1	2	3	4
2.4					
2		17.3			
1.6					
1			60		
0.8					
0					

82800	0	1	2	3	4
3.2					
2.4					
2		17.9			
1.6					
1			56.6		
0.8					
0					

84000	0	1	2	3	4
3.2					
2.4					
2		17.3			
1.6					
1			47.7		
0.8					
0					

85200	0	1	2	3	4
3.2					
2.4					
2		17.3			
1.6					
1			46.6		
0.8					
0					

86400	0	1	2	3	4
3.2					
2.4					
2		16.5			
1.6					
1			45.4		
0.8					
0					

	0	1	1.6	2.4	3	4
2.4						
2						
1.6						
1			17	17.8		
0.8						
0						

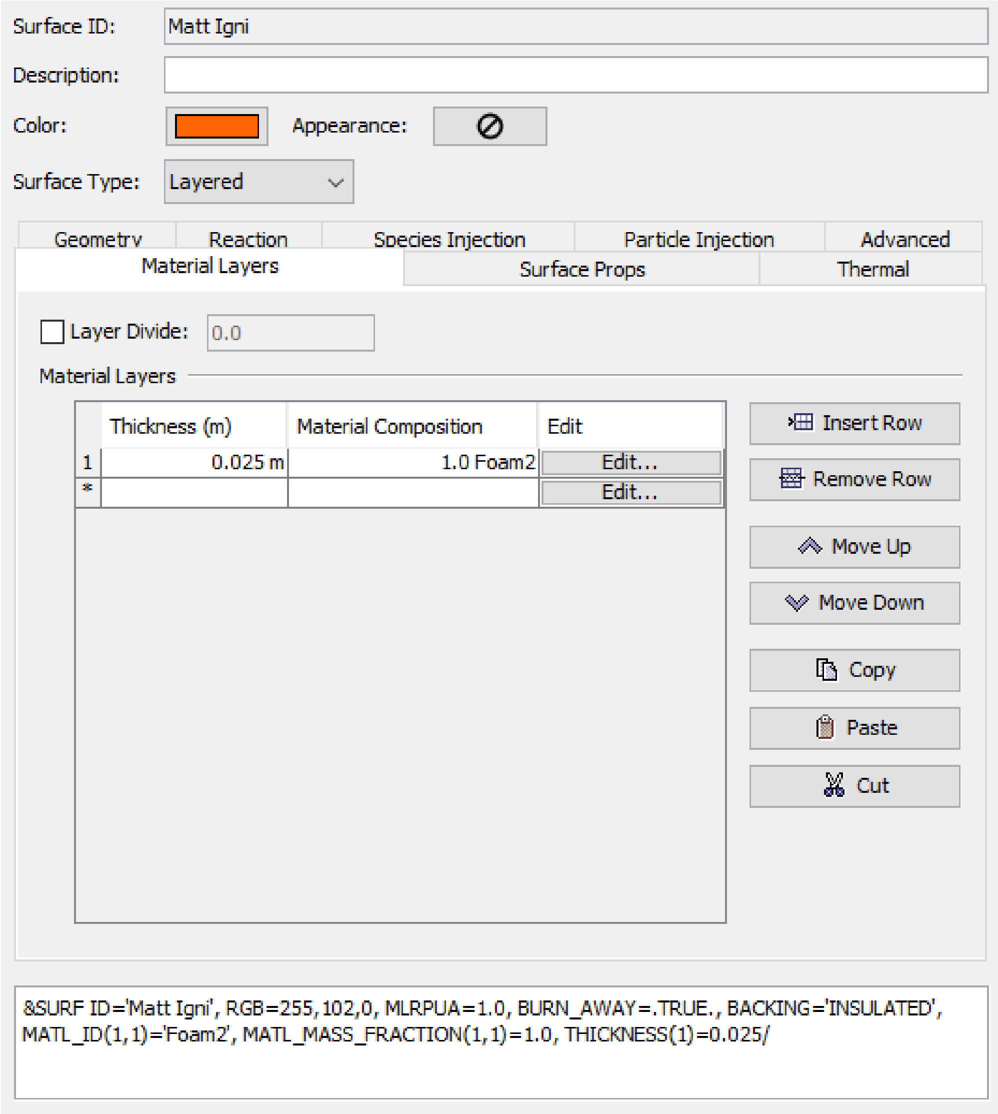
82800	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1			18.7	17.2		
0.8						
0						

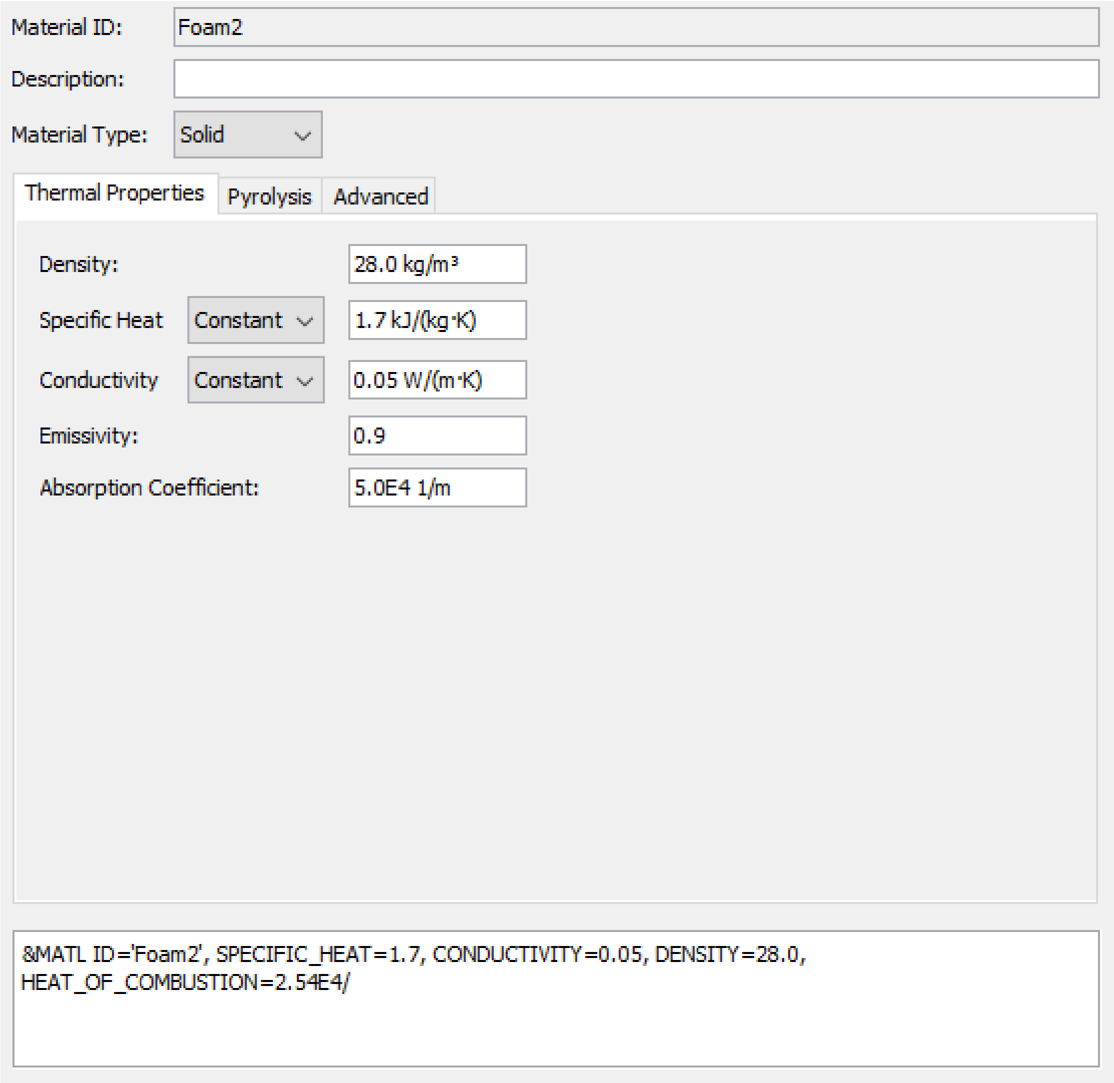
84000	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1			16.9	17.4		
0.8						
0						

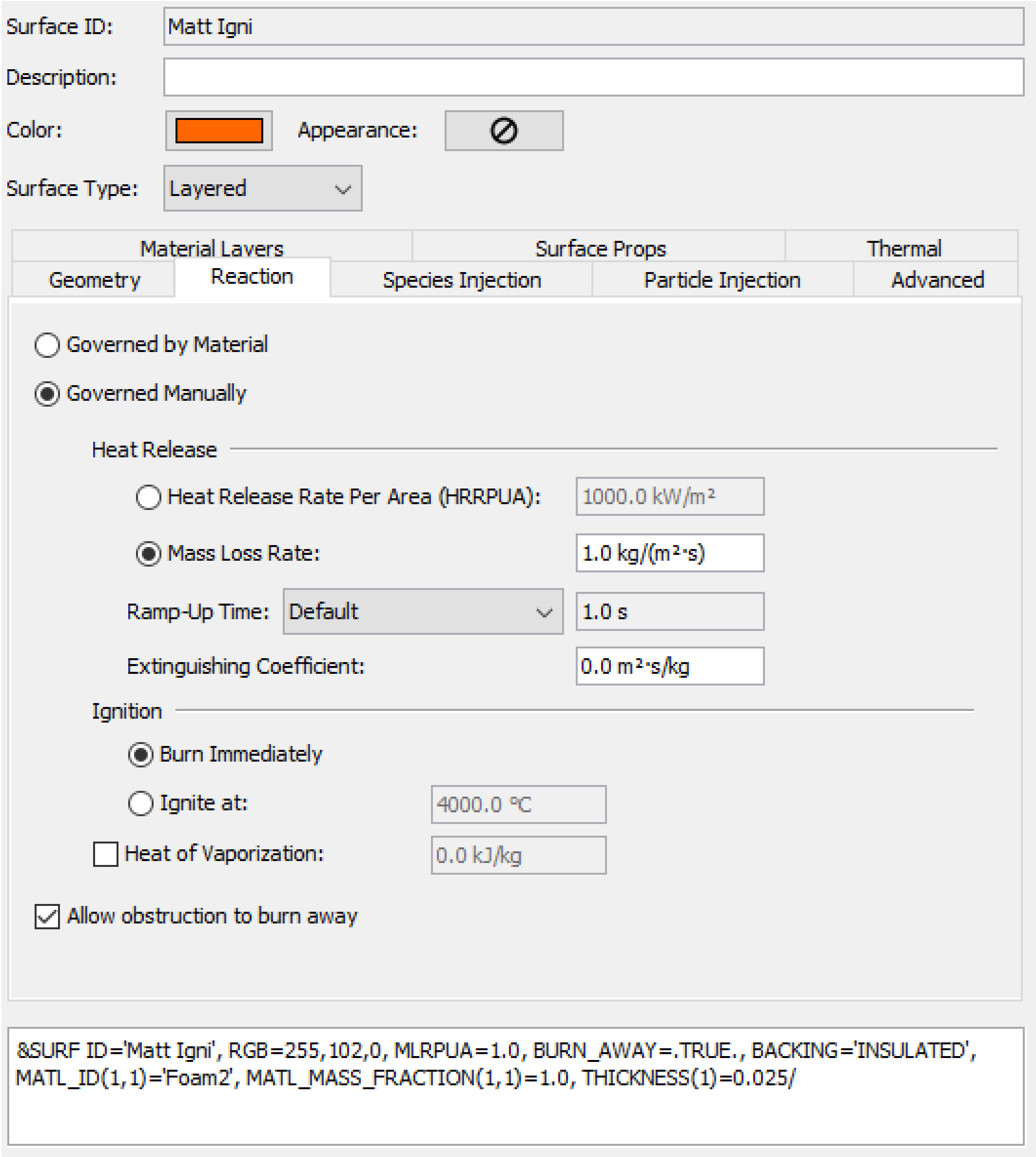
85200	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1			17.5	16.6		
0.8						
0						

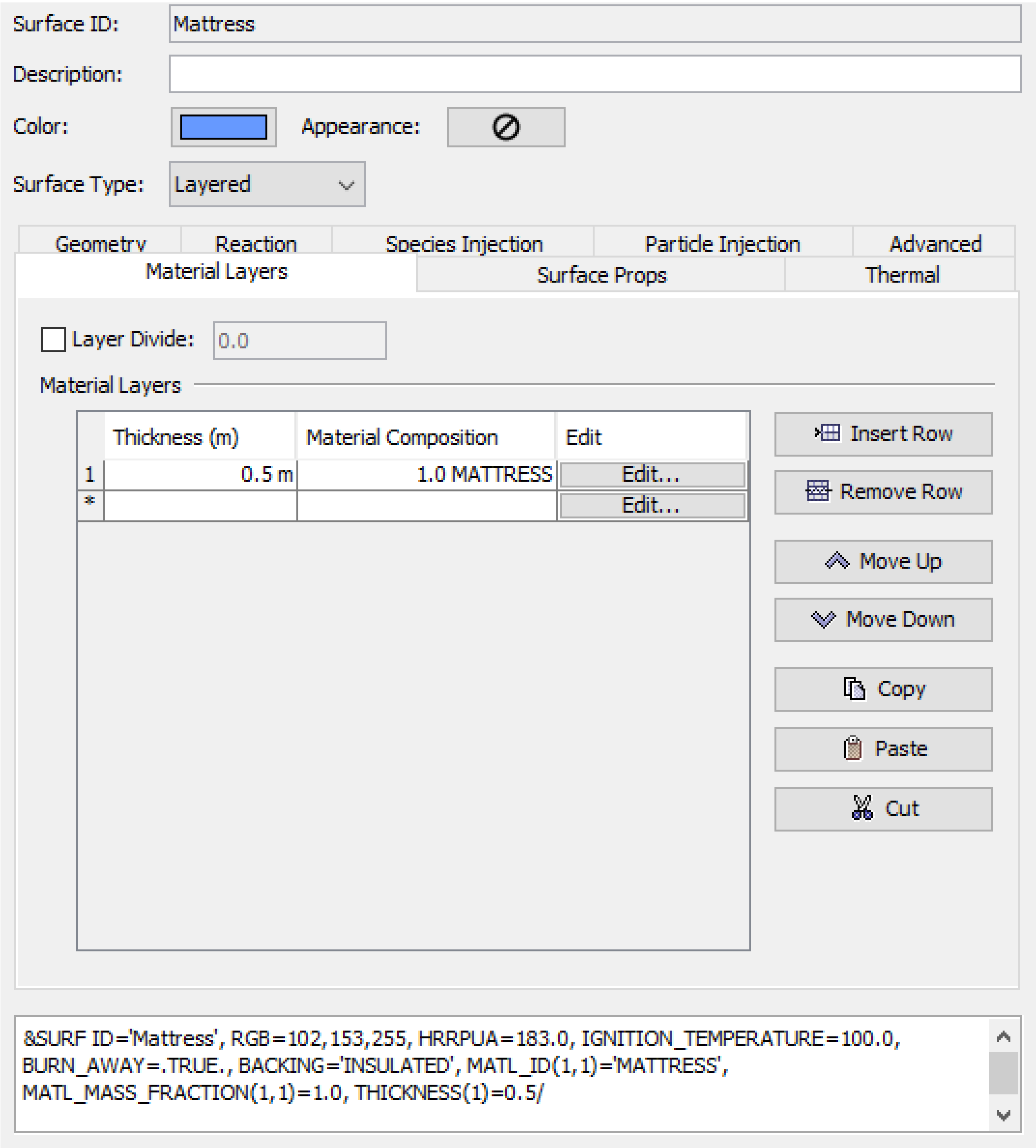
86400	0	1	1.6	2.4	3	4
3.2						
2.4						
2						
1.6						
1			16.7	24.12		
0.8						
0						

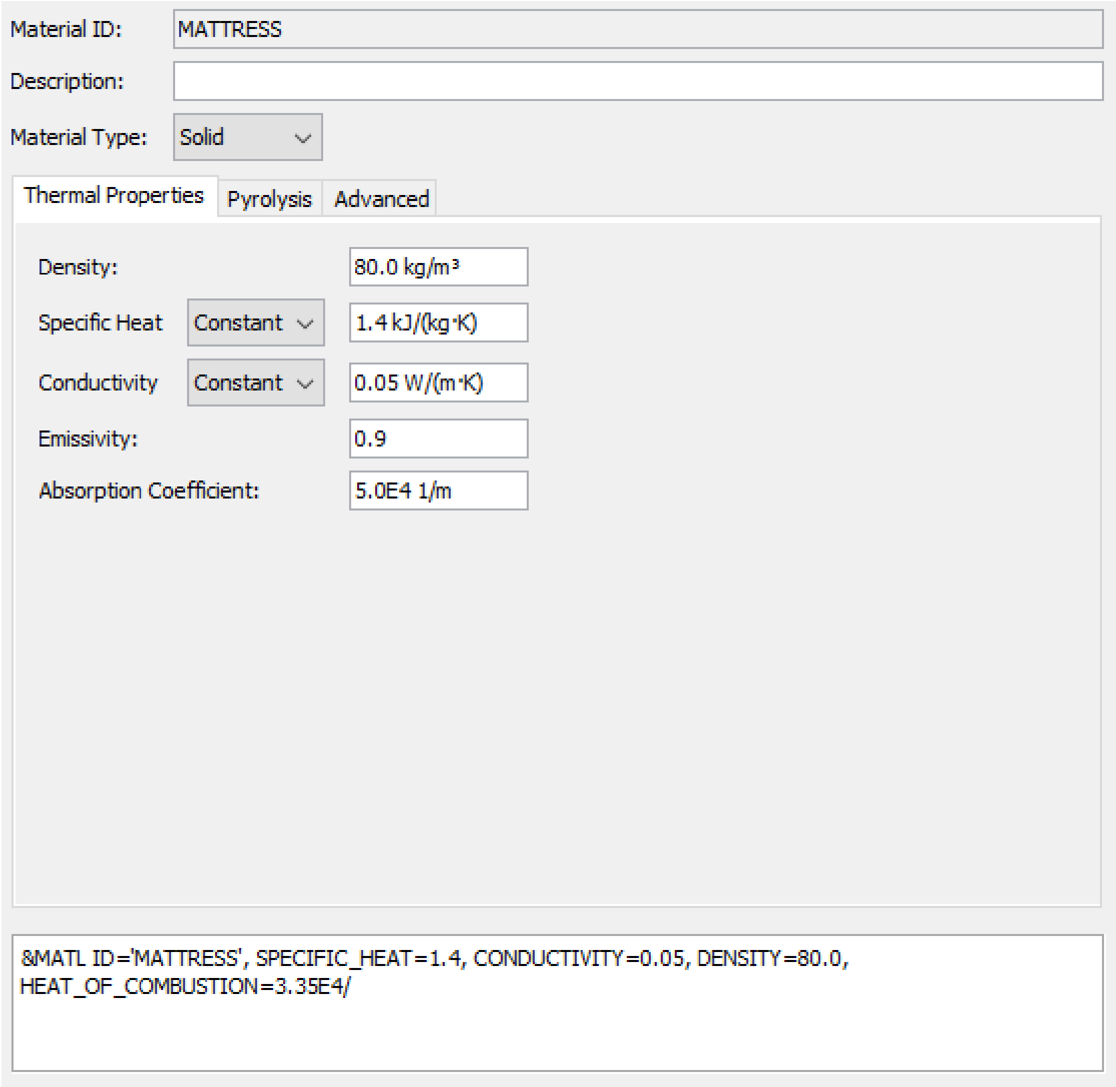
E APPENDIX C – CFD models

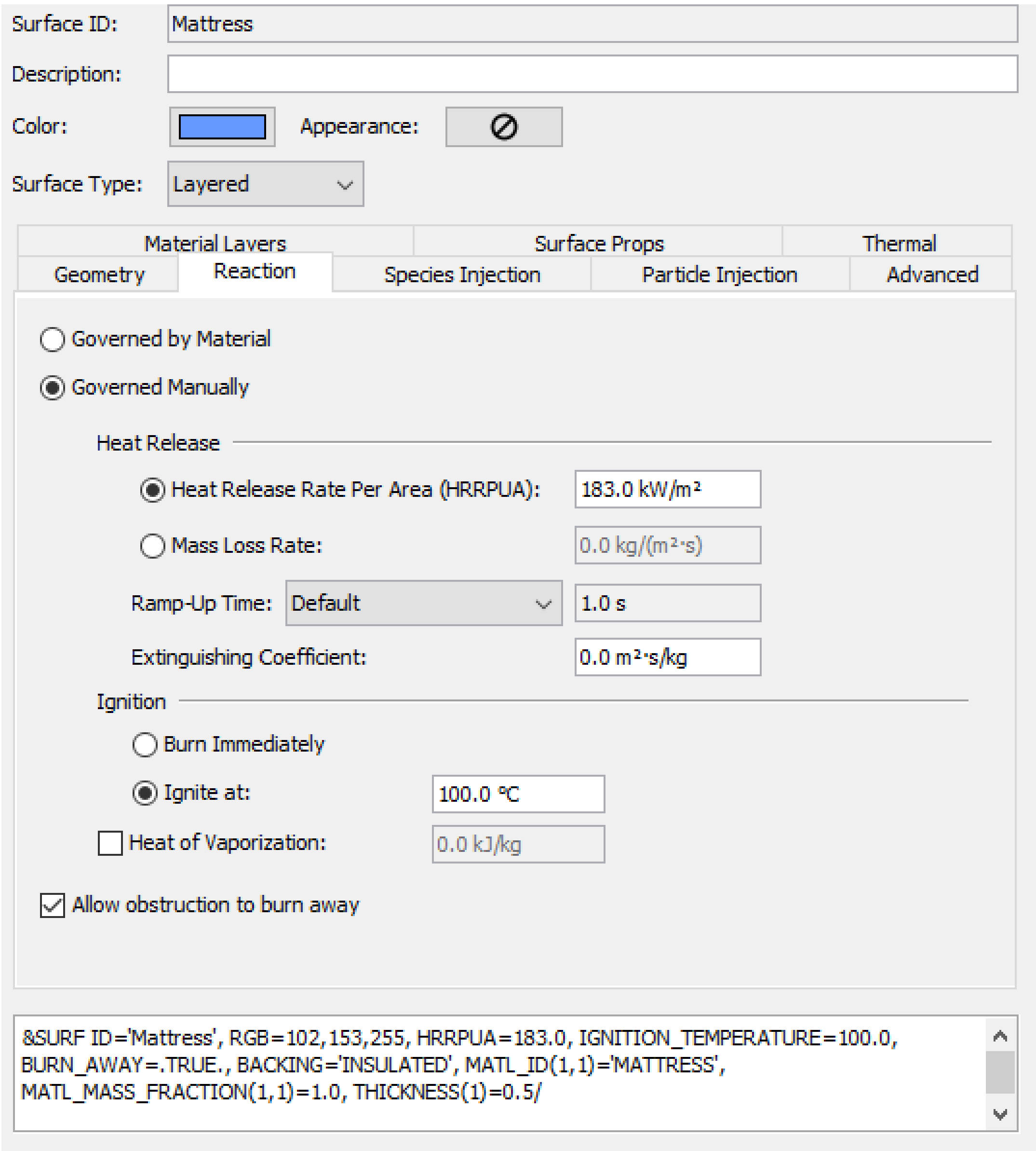


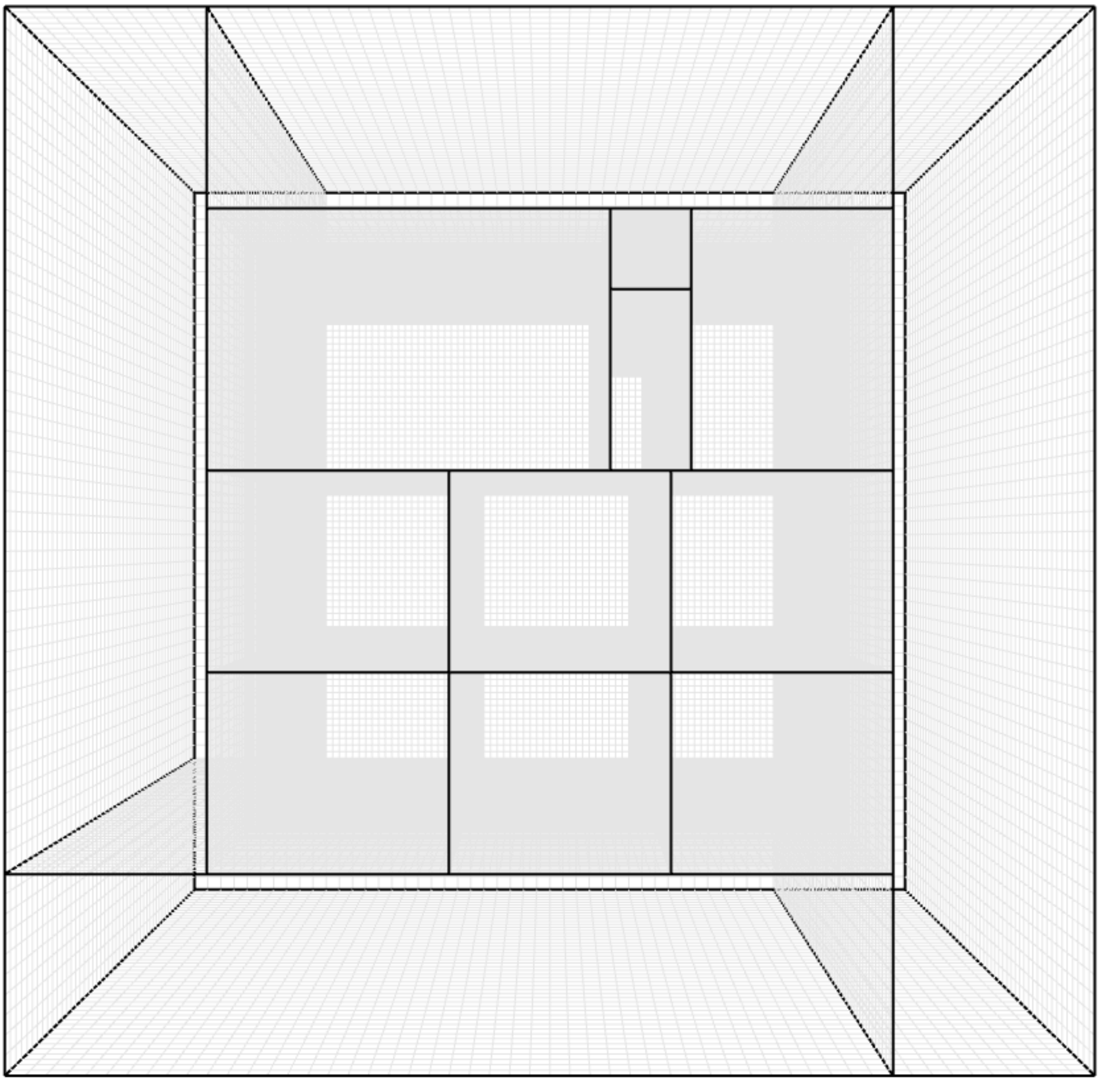

Material ID:
Foam2
Description:
Material Type:
Solid
Thermal Properties
Pyrolysis
Advanced
Density:
28.0 kg/m³
Specific Heat
Constant
1.7 kJ/(kg·K)
Conductivity
Constant
0.05 W/(m·K)
Emissivity:
0.9
Absorption Coefficient:
5.0E4 1/m
&MATL ID='Foam2', SPECIFIC_HEAT=1.7, CONDUCTIVITY=0.05, DENSITY=28.0,
HEAT_OF_COMBUSTION=2.54E4/

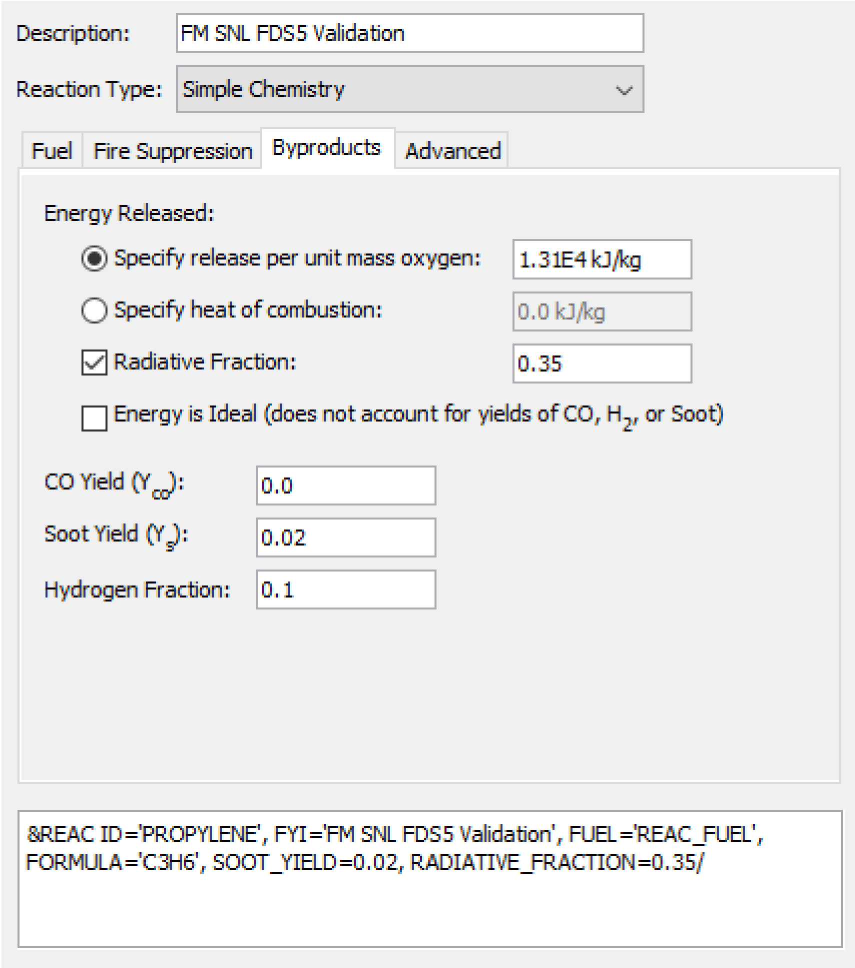

Surface ID:
Matt Igni
Description:
Color:
Appearance:
Surface Type:
Layered
Material Layers
Surface Props
Thermal
Geometry
Reaction
Species Injection
Particle Injection
Advanced
Governed by Material
Governed Manually
Heat Release
Heat Release Rate Per Area (HRRPUA):
1000.0 kW/m²
Mass Loss Rate:
1.0 kg/(m²·s)
Ramp-Up Time:
Default
1.0 s
Extinguishing Coefficient:
0.0 m²·s/kg
Ignition
Burn Immediately
Ignite at:
4000.0 °C
Heat of Vaporization:
0.0 kJ/kg
Allow obstruction to burn away
&SURF ID='Matt Igni', RGB=255,102,0, MLRPUA=1.0, BURN_AWAY=.TRUE., BACKING='INSULATED',
MATL_ID(1,1)='Foam2', MATL_MASS_FRACTION(1,1)=1.0, THICKNESS(1)=0.025/

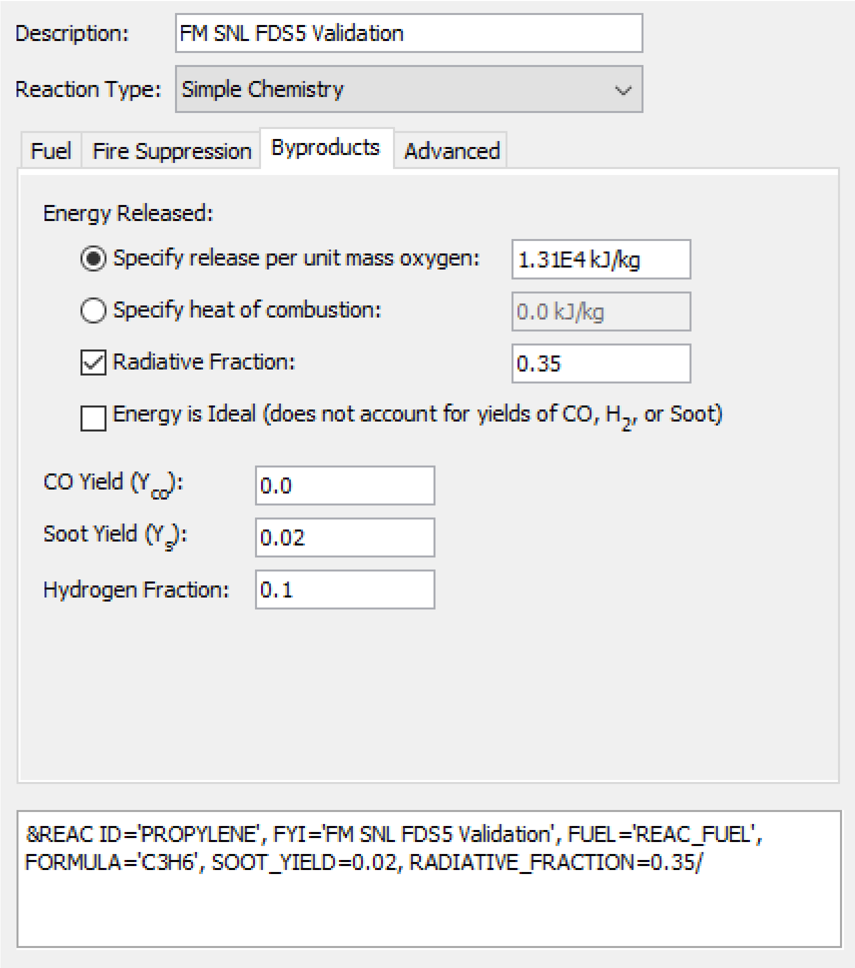

Surface ID:
Mattress
Description:
Color:
Appearance:
Surface Type:
Layered
Geometry
Reaction
Species Injection
Particle Injection
Advanced
Material Layers
Surface Props
Thermal
Layer Divide:
0.0
Material Layers
Thickness (m)
Material Composition
Edit
1
0.5 m
1.0 MATTRESS
Edit...
*
Edit...
Insert Row
Remove Row
Move Up
Move Down
Copy
Paste
Cut
&SURF ID='Mattress', RGB=102,153,255, HRRPUA=183.0, IGNITION_TEMPERATURE=100.0,
BURN_AWAY=.TRUE., BACKING='INSULATED', MATL_ID(1,1)='MATTRESS',
MATL_MASS_FRACTION(1,1)=1.0, THICKNESS(1)=0.5/

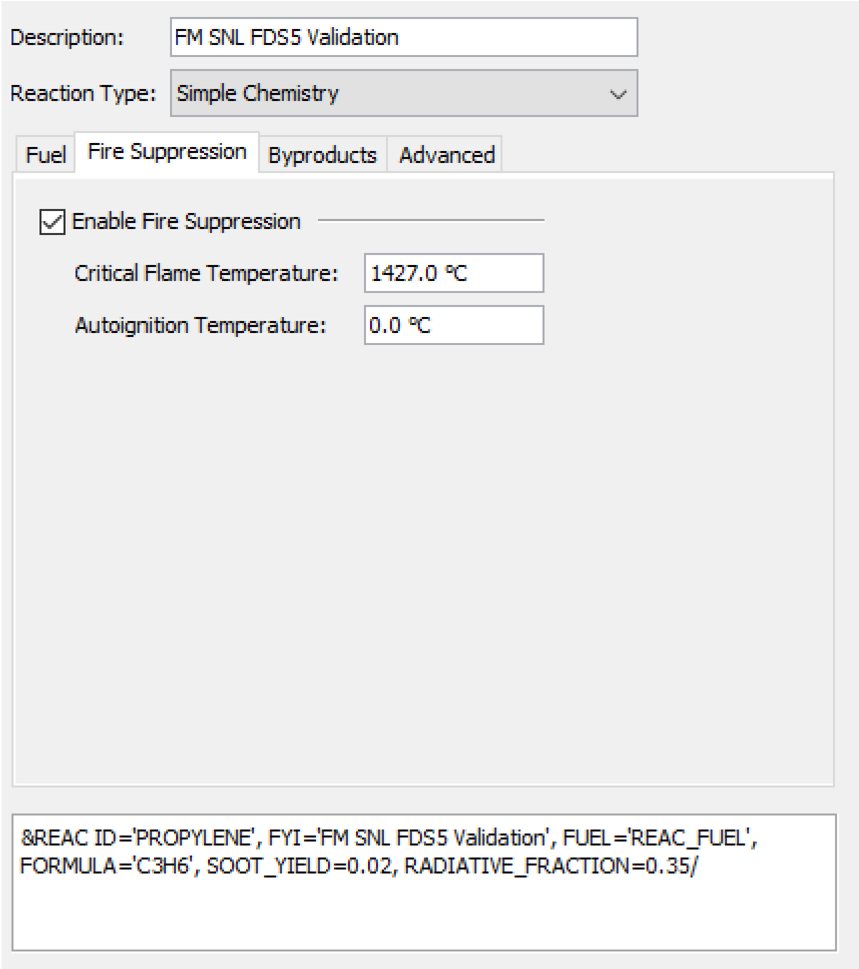

Material ID:
MATTRESS
Description:
Material Type:
Solid
Thermal Properties
Pyrolysis
Advanced
Density:
80.0 kg/m³
Specific Heat
Constant
1.4 kJ/(kg·K)
Conductivity
Constant
0.05 W/(m·K)
Emissivity:
0.9
Absorption Coefficient:
5.0E4 1/m
&MATL ID='MATTRESS', SPECIFIC_HEAT=1.4, CONDUCTIVITY=0.05, DENSITY=80.0,
HEAT_OF_COMBUSTION=3.35E4/

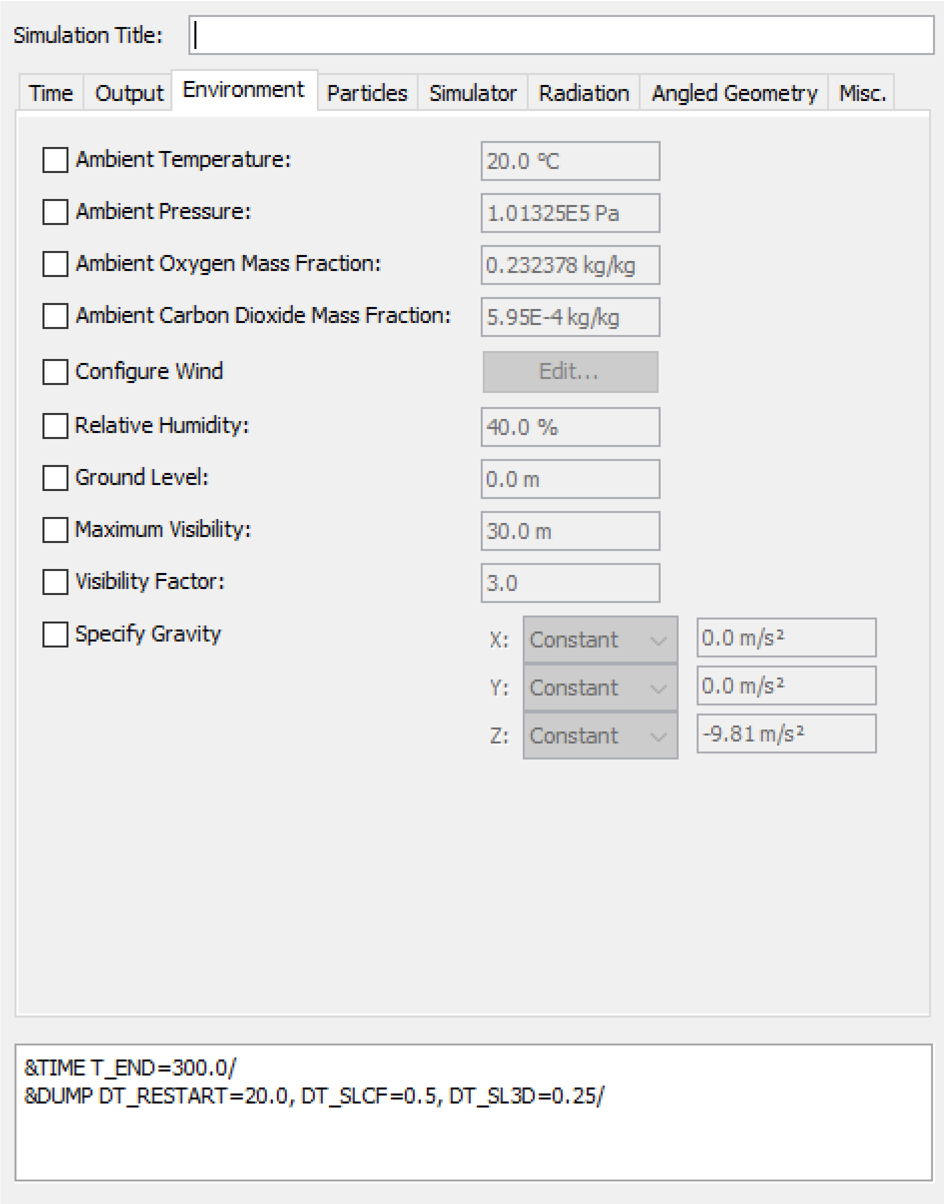

Surface ID:
Mattress
Description:
Color:
Appearance:
Surface Type:
Layered
Material Layers
Surface Props
Thermal
Geometry
Reaction
Species Injection
Particle Injection
Advanced
Governed by Material
Governed Manually
Heat Release
Heat Release Rate Per Area (HRRPUA):
183.0 kW/m²
Mass Loss Rate:
0.0 kg/(m²·s)
Ramp-Up Time:
Default
1.0 s
Extinguishing Coefficient:
0.0 m²·s/kg
Ignition
Burn Immediately
Ignite at:
100.0 °C
Heat of Vaporization:
0.0 kJ/kg
Allow obstruction to burn away
&SURF ID='Mattress', RGB=102,153,255, HRRPUA=183.0, IGNITION_TEMPERATURE=100.0,
BURN_AWAY=.TRUE., BACKING='INSULATED', MATL_ID(1,1)='MATTRESS',
MATL_MASS_FRACTION(1,1)=1.0, THICKNESS(1)=0.5/

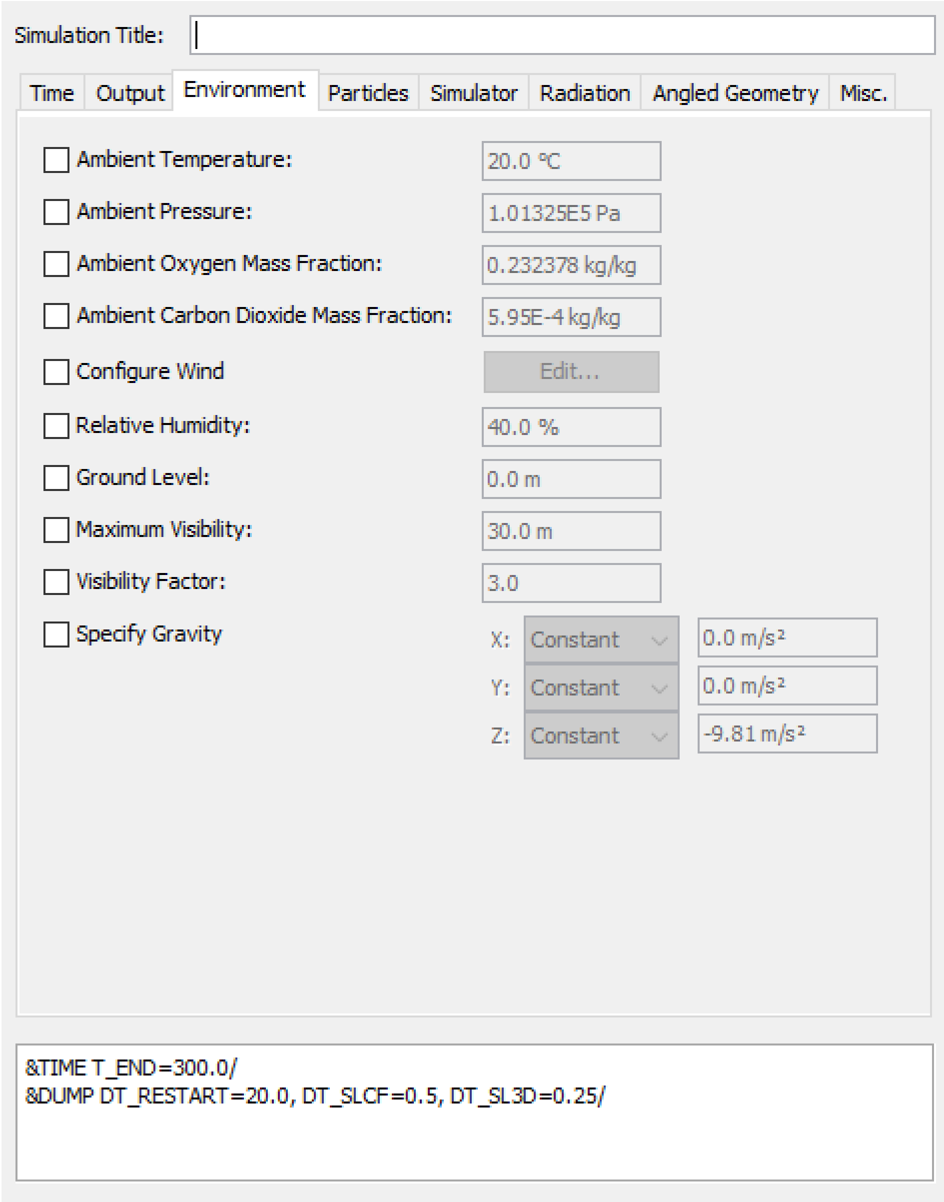


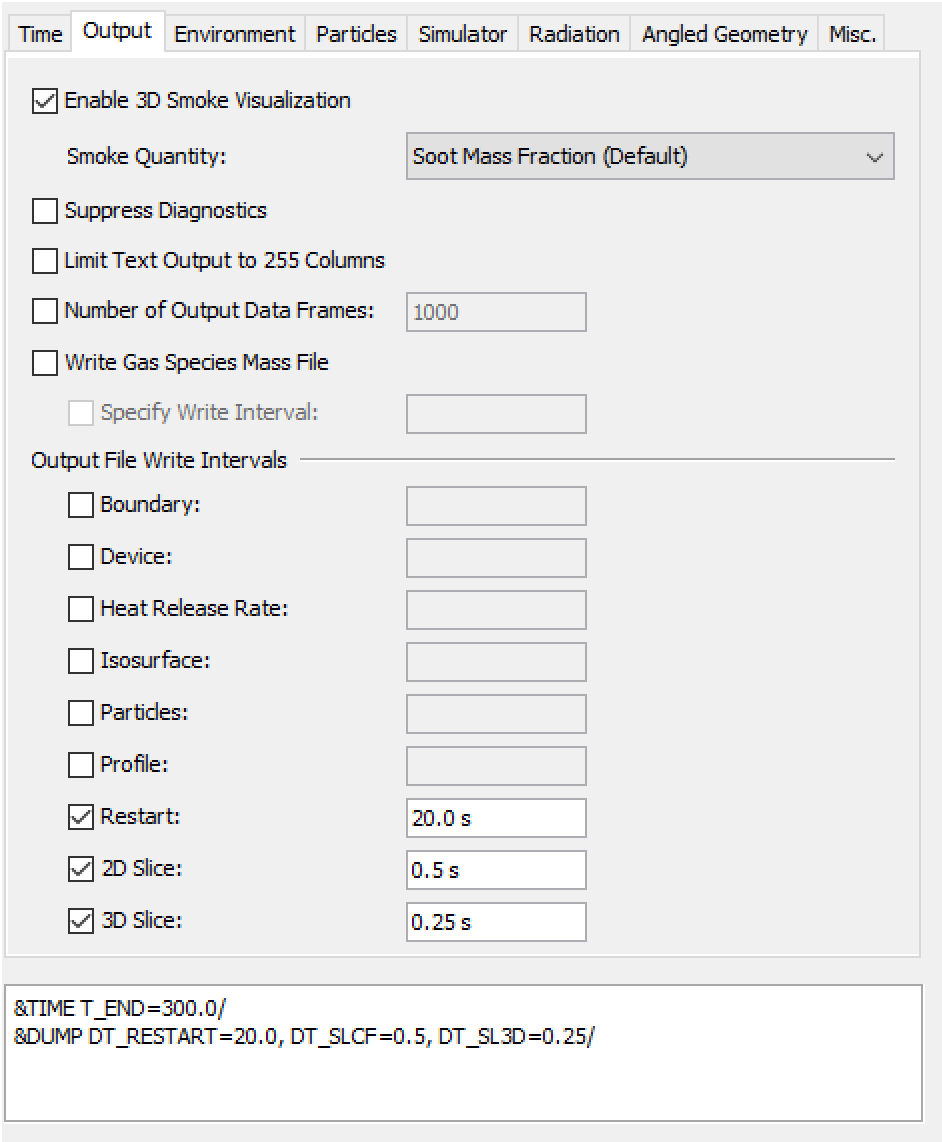

Description:
FM SNL FDS5 Validation
Reaction Type:
Simple Chemistry
Fuel
Fire Suppression
Byproducts
Advanced
Energy Released:
Specify release per unit mass oxygen:
1.31E4 kJ/kg
Specify heat of combustion:
0.0 kJ/kg
Radiative Fraction:
0.35
Energy is Ideal (does not account for yields of CO, H2, or Soot)
CO Yield (Yco):
0.0
Soot Yield (Ys):
0.02
Hydrogen Fraction:
0.1
&REAC ID='PROPYLENE', FYI='FM SNL FDS5 Validation', FUEL='REAC_FUEL',
FORMULA='C3H6', SOOT_YIELD=0.02, RADIATIVE_FRACTION=0.35/

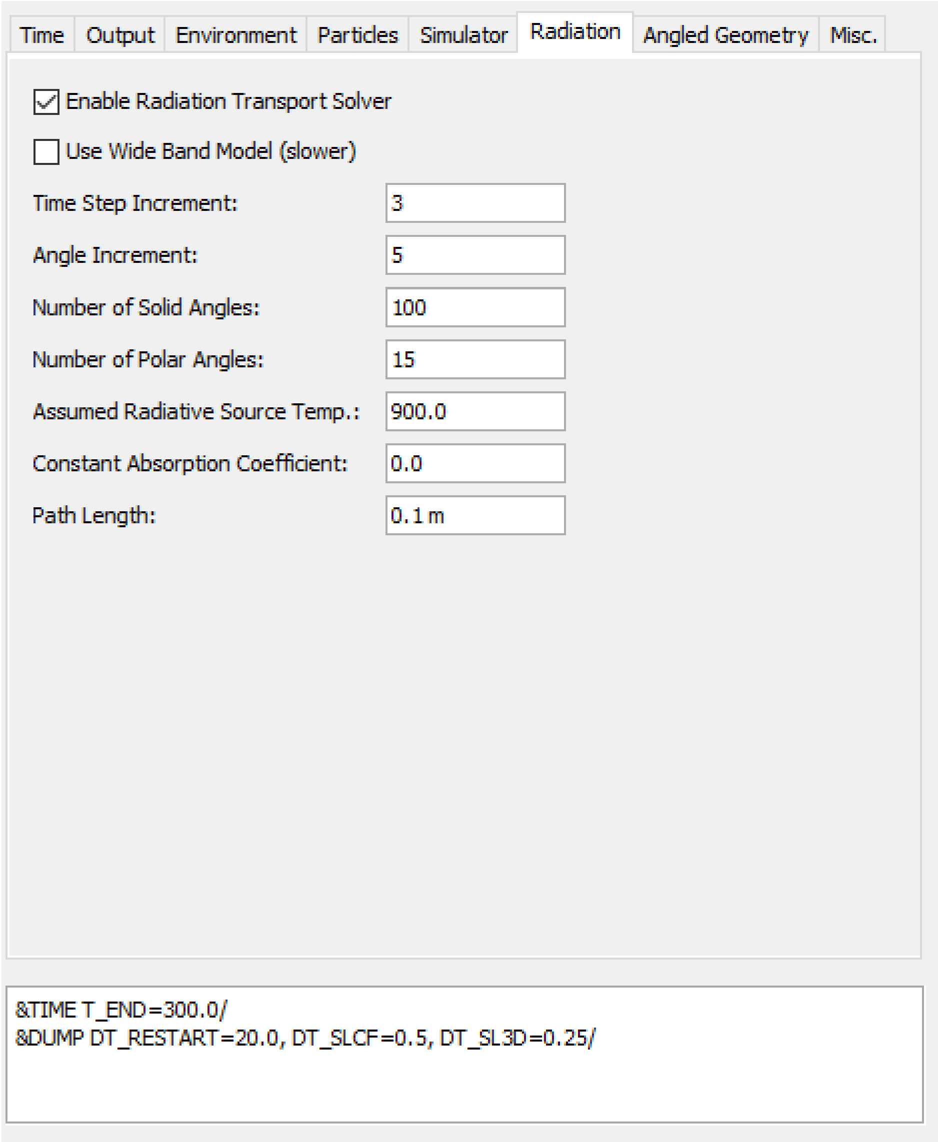

Description: FM SNL FDS5 Validation
Reaction Type: Simple Chemistry
Fuel
Fire Suppression
Byproducts
Advanced
Energy Released:
Specify release per unit mass oxygen: 1.31E4 kJ/kg
Specify heat of combustion: 0.0 kJ/kg
Radiative Fraction: 0.35
Energy is Ideal (does not account for yields of CO, H2, or Soot)
CO Yield (Yco): 0.0
Soot Yield (Ys): 0.02
Hydrogen Fraction: 0.1
&REAC ID='PROPYLENE', FYI='FM SNL FDS5 Validation', FUEL='REAC_FUEL',
FORMULA='C3H6', SOOT_YIELD=0.02, RADIATIVE_FRACTION=0.35/

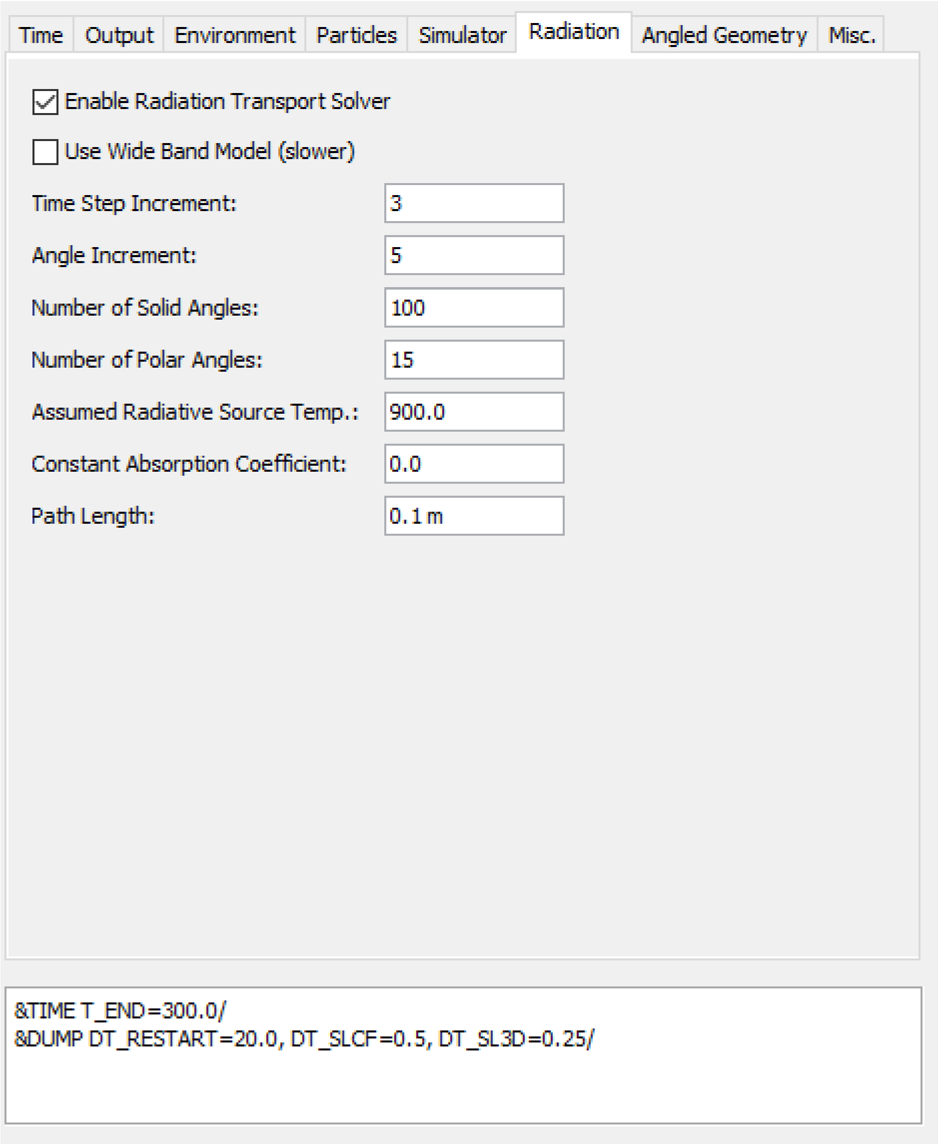

Description:
FM SNL FDS5 Validation
Reaction Type:
Simple Chemistry
Fuel
Fire Suppression
Byproducts
Advanced
Enable Fire Suppression
Critical Flame Temperature:
1427.0 °C
Autoignition Temperature:
0.0 °C
&REAC ID='PROPYLENE', FYI='FM SNL FDS5 Validation', FUEL='REAC_FUEL',
FORMULA='C3H6', SOOT_YIELD=0.02, RADIATIVE_FRACTION=0.35/

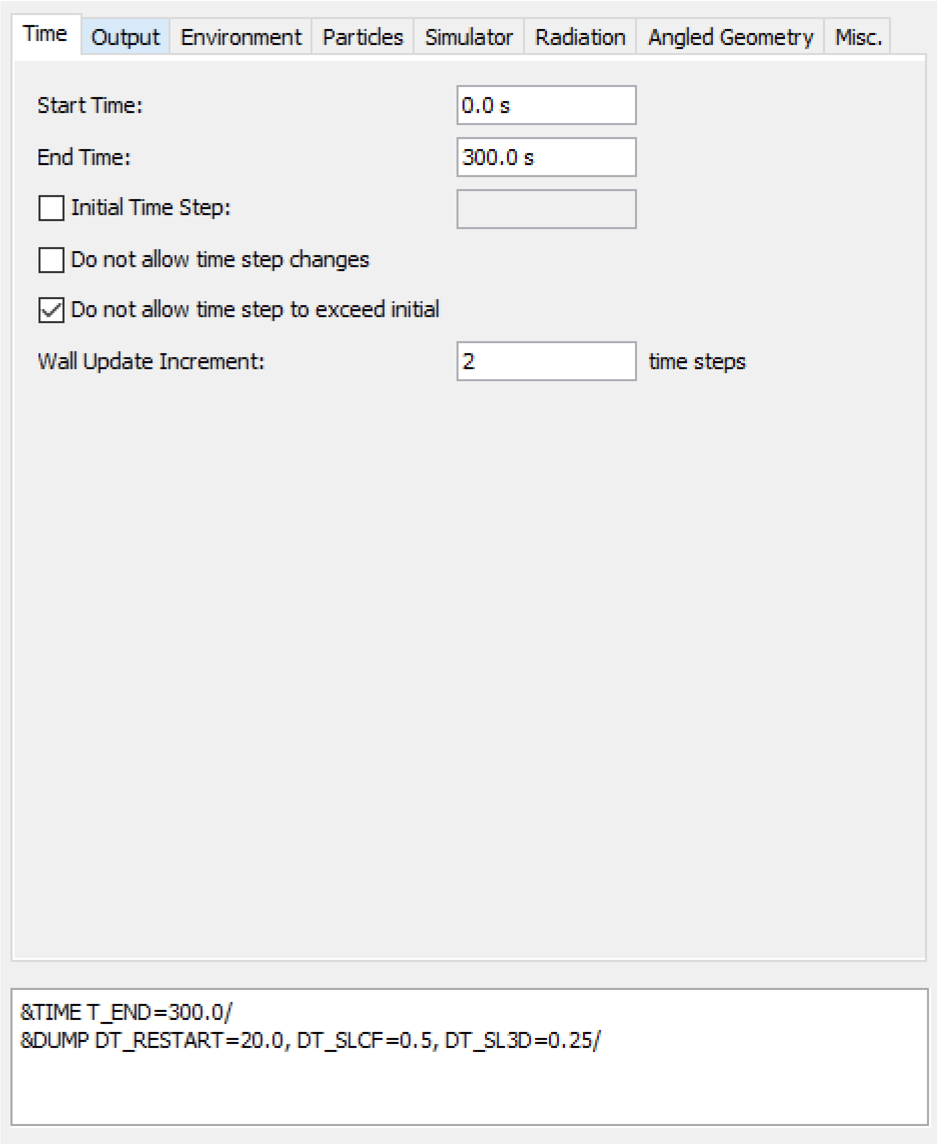

Simulation Title:
Time
Output
Environment
Particles
Simulator
Radiation
Angled Geometry
Misc.
Ambient Temperature:
20.0 °C
Ambient Pressure:
1.01325E5 Pa
Ambient Oxygen Mass Fraction:
0.232378 kg/kg
Ambient Carbon Dioxide Mass Fraction:
5.95E-4 kg/kg
Configure Wind
Edit...
Relative Humidity:
40.0 %
Ground Level:
0.0 m
Maximum Visibility:
30.0 m
Visibility Factor:
3.0
Specify Gravity
X: Constant
0.0 m/s²
Y: Constant
0.0 m/s²
Z: Constant
-9.81 m/s²
&TIME T_END=300.0/
&DUMP DT_RESTART=20.0, DT_SLCF=0.5, DT_SL3D=0.25/


Simulation Title:
Time
Output
Environment
Particles
Simulator
Radiation
Angled Geometry
Misc.
Ambient Temperature:
20.0 °C
Ambient Pressure:
1.01325E5 Pa
Ambient Oxygen Mass Fraction:
0.232378 kg/kg
Ambient Carbon Dioxide Mass Fraction:
5.95E-4 kg/kg
Configure Wind
Edit...
Relative Humidity:
40.0 %
Ground Level:
0.0 m
Maximum Visibility:
30.0 m
Visibility Factor:
3.0
Specify Gravity
X: Constant
0.0 m/s²
Y: Constant
0.0 m/s²
Z: Constant
-9.81 m/s²
&TIME T_END=300.0/
&DUMP DT_RESTART=20.0, DT_SLCF=0.5, DT_SL3D=0.25/


Time
Output
Environment
Particles
Simulator
Radiation
Angled Geometry
Misc.
Enable 3D Smoke Visualization
Smoke Quantity:
Soot Mass Fraction (Default)
Suppress Diagnostics
Limit Text Output to 255 Columns
Number of Output Data Frames:
1000
Write Gas Species Mass File
Specify Write Interval:
Output File Write Intervals
Boundary:
Device:
Heat Release Rate:
Isosurface:
Particles:
Profile:
Restart:
20.0 s
2D Slice:
0.5 s
3D Slice:
0.25 s
&TIME T_END=300.0/
&DUMP DT_RESTART=20.0, DT_SLCF=0.5, DT_SL3D=0.25/


Time
Output
Environment
Particles
Simulator
Radiation
Angled Geometry
Misc.
Enable Radiation Transport Solver
Use Wide Band Model (slower)
Time Step Increment: 3
Angle Increment: 5
Number of Solid Angles: 100
Number of Polar Angles: 15
Assumed Radiative Source Temp.: 900.0
Constant Absorption Coefficient: 0.0
Path Length: 0.1 m
&TIME T_END=300.0/
&DUMP DT_RESTART=20.0, DT_SLCF=0.5, DT_SL3D=0.25/


Time
Output
Environment
Particles
Simulator
Radiation
Angled Geometry
Misc.
Enable Radiation Transport Solver
Use Wide Band Model (slower)
Time Step Increment:
3
Angle Increment:
5
Number of Solid Angles:
100
Number of Polar Angles:
15
Assumed Radiative Source Temp.:
900.0
Constant Absorption Coefficient:
0.0
Path Length:
0.1 m
&TIME T_END=300.0/
&DUMP DT_RESTART=20.0, DT_SLCF=0.5, DT_SL3D=0.25/


Time
Output
Environment
Particles
Simulator
Radiation
Angled Geometry
Misc.
Start Time:
0.0 s
End Time:
300.0 s
Initial Time Step:
Do not allow time step changes
Do not allow time step to exceed initial
Wall Update Increment:
2
time steps
&TIME T_END=300.0/
&DUMP DT_RESTART=20.0, DT_SLCF=0.5, DT_SL3D=0.25/

APPENDIX D BRE critique of report supplied to WISH

Notes on WISH fire tests

Following meeting on 3 July, we agreed to review and comment on WISH fire test data once analysis and assumptions had been provided.

Report on second stage tests appears to largely dismiss findings from the first stage, so we have only commented to the second stage tests.

The WISH fire tests have not provided any information or analysis, which would require us to review the content of our current regulatory guidance.

Our guidance places controls on the maximum dimensions and piles, and requires a 6m separation distance between piles, the perimeter of the site, buildings and any other flammable/combustible materials. In addition, and to be used in combination with the 6m separation distance, we require a quarantine area to which an operator must move waste to as soon as possible or, at most, within 1 hour of a fire starting. The quarantine area is designed to provide additional separation and isolation of wastes, at the outbreak of a fire.

The 6m separation distance and quarantine area was taken from fire tests conducted on wastes by the Fire Research Station (now known as BRE Global), published research and guidance from other regulators.

We understood that the results, analysis and interpretation of the WISH fire tests were to be independently peer reviewed, but that this does not appear to have happened. The lack of independent peer review coupled with the omission of reference to relevant published research, other guidance and fire tests does limit the credibility of the interpretations placed on the WISH fire tests.

<u>General overarching comments in relation to the summary findings (page 2)</u>

1. How is the current understanding of thermal decomposition in polymers being considered in relation to charring, rate of fire growth and heat release rate? (Point 10 below)
2. Where is the surface temperature of the waste being measured – are you assuming that surface temp of the waste and flame temperature are the same? If not, then what assumptions are being made?

3. These tests all appear to be conducted using open flame piloted ignition. What variability in the results would be anticipated from a thermal radiation source?
4. A general observation would be that there are inconsistencies in whether reasonable case or worst case has been assumed. For example, the WISH guidance assumes that rubber and plastics all burn at 1200 °C, when other fire test results conducted by the Fire Safety Research Station showed tyres burning at 1000 °C. In addition, scientific papers studying thermal decomposition of plastics show that only polymers which decompose via end chain scission can achieve such high combustion temperatures. The majority of plastics do not thermally decompose via random chain scission, and therefore would be highly unlikely to combust at such high temperatures.

   However, the fire tests which underpin the WISH guidance assume the minimum heat flux required for ignition of a building as 12.6 kW/m^2, whereas studies by the Health and Safety Laboratory recommend using a minimum heat flux for ignition of a building covered in plastic or composite skinned materials as 10 kW/m^2. Therefore, we would question the benefit of differentiating between some types of waste material, and differentiating between separation distances for waste to waste storage vs waste to building storage.

<u>Conclusions in relation to burn temperatures</u>

Section 3 – wood tests

4. It states 'there were several fire tests using pre crushed wood. This was due to the consistency of the burning characteristic of wood and the relatively low pollution level that is produced'. The definition of pollution in the Environmental Permitting Regs includes 'harm to human health'. We know that waste wood fires emit extremely harmful combustion products, including the irritant acrolein. Please can you clarify what you mean by the statement above?
5. General observation - it is quite difficult to compare temp vs time graphs, when a range of different scales and ways of recording the information are used. We are not sure what figure 3 is trying to represent – without some form of explanation?
6. In the narrative beneath figure 6 it states, 'Peak temperatures of 850°c were recorded but these were very localised and short lived'. We believe that this could be a typo, and the temperature should be 950°C?

   It then goes on to say, 'The large scale test was ideal burning conditions with dry wood and medium breeze Peak temperatures of 1000°c were recorded'. The conclusions state 'the duration of the initial peaks are a function of the prevailing weather conditions….and in wet conditions the peak output will be extended but of a lower magnitude. In the observed ideal fire conditions the duration of the peak fire output is in the order of 20 minutes before the ash and char formation dominates the combustion processes.' The data on the graph shows wood in windy and wet conditions and appears to show a peak output for approx. 8 minutes. How has the conclusion that peak outputs are extended in wet conditions been arrived at?

7. Figure 7 and the narrative beneath – it is difficult to understand what is being conveyed. Please can this be re-phrased?
8. Figures 8 and 9 say 'gas temp' and appear to have no labels. What are the units? Heat flux in kW/m2 and a time in a date stamp? Do we have data on the moisture content of the pre-crush, fines and wood chip? What were the physical details of the pre-crush wood chip and the screened wood which were both found to burn with identical results?
9. Section 4 Other materials, there only appears to be one graph for shredded rubber (which is unlabelled). Is this all the data? How many tests were carried out on shredded rubber?

   We assume that the y axis is temperature in degrees. The highest constant temperature occurs at 800°C. In which case what additional data/information has been used to conclude that rubber burns at 1200 °C for the purposes of calculating the sliding scale separation distances?
10. The document states that 'baled plastic initially displayed the same behaviours. However, the intensity of the vortex in the gaps rapidly increased to a general fire vortex engulfing the whole mass of plastic. Temperatures of 1200°c were recorded however, it is likely that these were exceeded'. From our understanding, only Polyethylene (PE) in low and high density form have been burnt during the fire tests. Is this correct? If so, what is the basis of the assumption that all plastics would behave in a similar/identical way?

   Drysdale, Hirschler and Beyler and others have written extensively about the thermal decomposition of polymers, including a wide range of plastics. They explain that only polymers which undergo thermal decomposition by **random chain scission** could behave so aggressively when burnt.

   So, for the many different types of plastics that can be recycled or appear in waste loads, which undergo thermal decomposition via end chain scission, chain stripping or have cross-linking, these would behave in a much less aggressive way than PE. It is therefore important for us to understand why all plastics appear to have defined based on the behaviour of PE?

11. Assumptions appear to have been made about the burn temperature of various wastes and this in turn has been used to try and assign them into one of two categories – those that burn at 950°C and those that burn at 1200 °C. There appears to be a number of anomalies in these assumptions. For example, in point 6, the text highlighted in yellow indicates that in supportive conditions, wood burns at 1000°C for over 20 minutes.

The Home Office research into tyre fires concluded after several fire tests that tyres burn at 1000°C. Coupled with the issues described earlier in relation to assuming that the thermal decomposition of plastics behave in exactly the same way as PE, further highlights these discrepancies.

Our general observation would be to question the value of trying to differentiate wastes into two categories based on what appear to be inconsistent assumptions about burn temperatures?

Conclusions in relation to deep seated fires and the configuration of baled wastes in fire growth

11. Section 5 – deep seated ignition. This has been achieved using buried firelighters. Was this designed to replicate perhaps a foreign body in the waste which has caught fire? If so, can the limitations of these tests in relation to predicting the behaviour of self-combustion be described?

12. Figure 15 baled RDF test, in the narrative it states that 'The main driver for the fire spread was clearly the fluid dynamic flow between the gaps in the bales. Long linear gaps resulted is intense fire growth reminiscent of a fire vortex'. It's not clear how the graph supports this conclusion? This observation/conclusion also appears to conflict with the Hogland paper, which was provided in the original email.

We also think it is appropriate to draw attention to the conclusions in the published Hogland paper, which states 'In cylindrical bale storages, a natural draft of air through the gaps between the bales can increase flame spread, whereas air flow between rectangular bales is limited being more compactly stored. Moreover, another perspective which can be explored in the future is regarding the effect of trapped molten plastic [from the molten LDPE wrapper] between the adjacently stored rectangular bales on the flame spread rate.'

Hogland's research and published papers not only show that air flow between rectangular bales is limited and the creation of vortices unlikely, but they also show that the risk of fire spread is actually increased where bales wrapped in LDPE plastic are **interlaced**, since the molten LDPE will pool at the base of each bale significantly increasing the likelihood of fire spread. Hogland actually references storing bales in a way that allows the molten LDPE wrapper to flow away from the bales and to store them on some type of non-combustible 'pallet' or other means of raising the bales off the floor and thereby reducing the likelihood of fire spread from the molten plastic pool fire. We believe that these conclusions contradict the advice given in the WISH guidance to interlace bales when they are stacked.

13. In the report in then goes on to state 'A fourth test was conducted with the bale bricks laid to reduce the height of the vertical gaps. This was observed to reduce the intensity of the "tunnel fire" and generally reduce the fire growth however, the fire spread horizontally along the gaps. We couldn't see the evidence within the report to support this statement – please can we see it?

Conclusions in relation to minimum heat flux required for ignition

14. The report states 'No consideration has been given to the actual ignition temperatures or critical heat fluxes required to ignite individual material. This is a very specific characteristic of the stored materials and the operator will have to determine these figures from test results of their materials'. We completely agree with this conclusion, and therefore find it difficult to understand why the report then goes on to assume a value of 10 kW/m^2 for the heat flux for ignition for all waste materials and 12.6 kW/m^2 for all buildings?

The justification for assuming 10 kW/m^2 for waste is based on a published paper by Babrauskas on the ignition of wood. However, fire test data published by the Home Office in 1995, in relation to tyres demonstrated that minimum heat flux for ignition could be achieved at 9 kW/m^2. This supports our earlier comments about the apparent inconsistency in whether the assumptions being made are indeed worst case, reasonable case or some other perception?

In 2006, the Health and Safety Laboratory (HSL) reviewed ignition criteria for buildings [2], the report concluded that The Building Regulation guidance criterion of 12.6 kW/m^2 accurately represents the piloted ignition threshold of soft wood for continuous radiant exposures of 10-20 minutes. However, it would be inappropriate to use this criterion if the building was not clad in timber.

The published HSL report then goes on to state 'in Thomson and Drysdale, a critical ignition heat flux of 10 kW/m^2 is recommended for plastic and composite skinned building materials' which is the basis of cladding for many light industrial units. Please can we understand why 10 kW/m2 was not assumed as a worst case scenario?

The fundamental point which needs addressing, is that the generic assumptions which have been made in relation to minimum heat flux for ignition for both wastes and buildings, are neither worst case, nor do they follow the recommendations in relevant published literature.

Calculations and conclusions in relation to minimum separation distances between waste piles and buildings

[2] Burrell and Hare, Review of HSE Building Ignition Criteria HSL/2006/33 (2006)

15 Page 19 – the start of the calculations for separation distance. It appears that certain assumptions have been made about pile length and width and flame height. These don't appear to correlate with dimensions quoted in WISH guidance. We also can't see any evidence of their significance or why they have been adopted?

16 Page 20 is blank – was this intentional? We then have an extract from the WISH guidance, which describes 're-arranging the above base equation', but the base equation has not been set out

So, section 6.16 gives an equation without any explanation of the relevant parts? (we've therefore had to make the following assumptions of our own):

Ø is a configuration factor?

I_r intensity of normal radiation calculated using Lamberts cosine law? Using 45 or 90 degrees?

$\dot{\varepsilon}_f$ flame emissivity. Was this assumed =1? Or was a lower value used?

σ Stefan-Boltzmann constant (5.67 x 10 $^{-8}$ W/m^{2}K^4)?

T_f Temperature of flame? Were 950°C and 1200°C (converted to Kelvin) used?

17. It is unclear how this then relates to 6.17, and how the separation distance has been calculated?

It is also unclear how a single configuration factor considers emitters and receiver that are not directly opposite each other?

Have any other assumptions been made e.g., absorption or emission from molecules of water or carbon dioxide?

18. It is also unclear the relevance of 6.19, and how this has been considered in the calculations?

19. There are then several graphs in the report which refer to pile dimensions, which are different to the assumptions of pile dimensions given on page 19. The separation distances appear to be based on pile dimensions of 5m high and 22.5 – 23.4m long, whereas the WISH guidance proposes pile heights of 4m and piles up to 50m in length?

Heather Barker and John McCarthy

July 2017

APPENDIX E EXTRACT OF REPORT SUMMARISING STANDARDS COMMONLY USE IN THE WASTE MANAGEMENT SECTOR.

Introduction

This guide is an overview of a selection of standards commonly used or of relevance to the waste industry. Not all of the standards within deal directly with waste or waste sites but all contain information, specifications and criteria etc., which can be useful for dealing with fire safety on waste transfer and processing sites.

The aim of this guide is to simplify the process of using the given standards so that operators can quickly and easily know what a standard is about, what it is for and what parts of it might affect them. To help with this, there are two main sections to this guide: the first lists all the standards discussed here and summarises what each standard covers and how it is of relevance to waste sites. The second part of this guides contains, verbatim, all the excerpts from standards that might apply specifically to waste sites.

Scope

This guide only highlights a selection of key standards that might be of use to waste site operators. The list of included documents is not intended to be all-encompassing and other codes should always be consulted when required or more appropriate for the matter at hand.

There is no intention for this guide to give direction or advice on fire safety, to advise on the suitability of one standard over another or to be used as a complete reference to fire safety standards. This document is a brief overview of certain key fire safety codes and how they might be of relevance.

Relevant Standards

ACE Technical Risks: Energy from Waste – Fire Systems

The ACE Technical Risks Engineering Information Bulletin Guidance Document: Energy from Waste – Fire Systems Document.

Discusses general fire safety but with specific reference to the requirements of Energy from Waste sites and so covers topics such as waste site-specific fire separation recommendations and such.

This guidance document is no longer supported by ACE Group but can still be found in use regardless. A general document covering many aspects of fire safety systems in Energy from Waste sites, parts can be used with respect to waste processing and transfer sites. Please bear in mind that some of the standards referred to may be previous editions of current standards or superseded altogether by new documents.

BRE 187 2nd Edition (2014)

External fire spread – Building separation and boundary distances

General guidance document covering fire spread between the exteriors of buildings. Particularly of use during the design stage of building works.

This is a guidance document widely used throughout fire engineering for calculating whether external fire spread from a building elevation is a risk. Used alongside WASTE 28, BRE 187 can be used to determine whether a building is at risk of external fire spread from nearby waste piles or bale storage.

BRE 368

Design methodologies for smoke and heat exhaust ventilation

General guidance document for smoke and heat exhaust ventilation systems covering the design of such systems for use in large spaces. Has a fast/ultra-fast fire growth category that can be broadly applied to waste fires but is generally aimed at atria spaces and car parks rather than warehouse-type buildings and does not have any industrial occupancy groups.

Useful as a guidance document when designing a SHEV system but has no specific, relevant categories for waste sites.

BS 476-3:2004

Fire Tests on Building Materials and Structures – Classification and Method of Test for External Fire Exposure to Roofs

General standard covering tests for fire penetration of a roof by external fire and capacity for flame spread on the exterior surface of a roof. Defines fire test methods and criteria. Primarily useful for during the design stage of a building.

Nothing high hazard/risk factor or otherwise categorically specific. To be used as a general document as required for ascertaining the standard to which materials and roof systems have been tested when designing for building works and specifying roof construction and materials.

BS 476-4:1970

Fire Tests on Building Materials and Structures – Non-Combustibility Test for Materials

General standard covering the British Standard test for determining whether a building material can be classified as non-combustible. Defines the fire test method and test criteria.

Nothing high hazard/risk factor specific. To be used as a general document to support decision-making and discussion around building material choices when designing for building works and specifying material requirements and choices.

BS 476-6:2009

Fire Tests on Building Materials and Structures – Method of Test for Fire Propagation for Products

General standard covering the test methods for testing fire propagation. Usually used to test materials intended for use as internal wall and ceiling linings. Defines fire test method and criteria.

Nothing specific to high hazard/risk factor or other similar categories. Useful as a general document for clarity and supporting information when designing building works, specifying material requirements and making material selections.

BS 476-7:1997

Fire Tests on Building Materials and Structures – Method of Test to Determine the Classification of the Surface Spread of Flame of Products

General standard covering the fire test method and criteria for measuring lateral flame spread along the vertical surface of a material.

Nothing specific to high hazard/risk factor or similar categories. Recommended for use for clarification and supporting information when designing building works, specifying material requirements and selecting suitable materials for fire safety purposes.

BS 476-10:2009

Fire Tests on Building Materials and Structures – Guide to the Principles, Selection, Role and Application of Fire Testing and Their Outputs

General standard covering the basic principles of fire tests, the inputs and outputs of the BS 476 series of tests, the equivalent ISO and EN (International and European) tests. The standard also covers which tests suit which purpose, and how the output of each test defines what it can be used for and its role in the test suite.

This document is not specifically relevant to waste sites; however, the standard is broadly useful for helping with the understanding of which tests can be used to give which classifications, and what material characteristics are quantified by each test. This is helpful when designing building works as it allows for a better understanding of what should be given as the fire safety specifications for materials in order for them to provide the required performance.

BS 476-11:1982

Fire Tests on Building Materials and Structures – Method for Assessing the Heat Emission from Building Materials

General standard covering the test method for determining the heat emission from a material. Defines the test method and criteria.

Nothing high hazard/risk factor specific. To be used as a general document in support of designing building works, particularly when deciding on heat emission requirements and identifying suitable materials.

BS 476-12:1991

Fire Tests on Building Materials and Structures – Method of Test for Ignitability of Products by Direct Flame Impingement

General standard covering the British Standard test method and criteria for the ignitability of materials when in direct contact with flame. Usually referred to during the design stages of building works.

Nothing high hazard/risk factor specific, useful during the design stage of building works as a supporting document to help in determining suitable performance requirements and finding qualified materials for fire safety purposes.

BS 476-13:1987

Fire Tests on Building Materials and Structures – Methods of Measuring the Ignitability of Products Subjected to Thermal Irradiance

General standard covering the British Standard test method and criteria for the ignitability of materials when exposed to thermal irradiance.

Has nothing specific to high hazard/risk factor or similar purpose groups or categories. Useful for understanding test criteria and results to aid in specifying fire safety performance requirements and then selecting appropriate materials during the design stages of building works.

BS 476-20:1987

Fire Tests on Building Materials and Structures – Method for Determination of the Fire Resistance of Elements of Construction (General Principles)

General standard detailing the British Standard fire test method and criteria for quantifying the fire resistance of elements of construction.

General document with nothing specific to categories such as high hazard of high risk factor. Useful during design stages to support decisions regarding fire resistance requirements and then suitable materials.

BS 476-21:1987

Fire Tests on Building Materials and Structures – Methods for the Determination of Fire Resistance of Loadbearing Elements of Construction

General standard covering the test methods for the British Standard test to determine fire resistance for loadbearing parts of construction. Gives the requirements for specimen selection, and design as well as equipment, procedures, criteria and test conditions. Applies to beams, columns, floors, walls and flat roofs. To be used in conjunction with BS 476-20.

Nothing specific to categories such as high hazard or high risk factor. Most useful during the design stages of building works to give an understanding of the BS test, how it works, what it tests for and what elements can be tested. Helpful when specifying fire resistance requirements or selecting appropriately resistant materials.

BS 476-22:1987

Fire Tests on Building Materials and Structures – Methods for Determination of the Fire Resistance of Non-Loadbearing Elements of Construction

General standard detailing the British Standard test for measuring the fire resistance of elements of construction not intended to bear loads. Details the test methods, conditions and criteria. Used in conjunction with BS 476-20.

Nothing high hazard/risk factor specific. Most useful during the design stages of building works to give an understanding of the BS test, how it works, what it tests for and under what conditions. Helpful when specifying fire resistance requirements or selecting appropriately resistant materials.

BS 476-23:1997

Fire Tests on Building Materials and Structures – Methods for Determination of the Contribution of Components to the Fire Resistance of a Structure

General standard covering the British Standard fire test procedures for quantifying the contribution made by a component to the total fire resistance of a structure or assembly. Details specimen selection, design and construction, specimen edge conditions, test equipment, *procedures and criteria. Applies to suspended ceilings protecting steel beams as well as intumescent seals used with fire resisting, single-action, latched timber door assemblies. Used in conjunction with BS 476-20.*

Nothing specific to categories such as high hazard or high risk factor. Most useful during the design stages of building works to give an understanding of the BS test, how it works, what it tests for and what elements can be tested. Helpful when specifying fire resistance requirements or selecting appropriately resistant materials.

BS 476-24:1987

Fire Tests on Building Materials and Structures – Methods for Determination of the Fire Resistance of Ventilation Ducts (AKA: ISO 6944-1985 Fire Resistance Tests – Ventilation Ducts)

General standard covering the British/International Standard test method and criteria for when determining the resistance of ventilation ducts under given fire conditions. Details specimen selection, design and construction, test conditions, equipment, procedures and criteria.

General document that contains nothing high hazard/risk factor specific. Most useful during the design stages of works to aid with the specification of fire resistance requirements and with the selection of suitable products to meet said requirements.

BS 476-31.1:1983

Fire Tests on Building Materials and Structures – Methods for Measuring Smoke Penetration Through Doorsets and Shutter Assemblies – Method of Measurement Under Ambient Temperature Conditions

General standard detailing the British Standard test method and criteria for measuring smoke penetration through doorsets and vertical shutter assemblies. Measures smoke control performance, but not fire resistance performance.

Has nothing specific to high hazard/risk factor or similar categories. Most useful during the design stages of building works for clarifying what smoke control classifications mean, what safety requirements are needed, and which products fit those requirements.

BS 476-32:1989

Fire Tests on Building Materials and Structures – Guide to Full Scale Fire Tests Within Buildings

General standard providing guidance concerning the British Standard tests simulating building fires through full scale experiments. Details specimen selection, design and construction, test conditions, equipment, procedures and criteria.

Has nothing specific to high hazard/risk factor or similar categories. Most useful during the design stages of building works as clarification and supporting information to help with *determining fire safety requirements and suitably qualified products or commissioning test works in order to quantify the performance of a fire engineered solution.*

BS 476-33:1993

Fire Tests on Building Materials and Structures – Full-scale Room Test for Surface Products

General standard covering the British Standard full-scale room test. Details the test principles, method, conditions, equipment and criteria.

Nothing high hazard/risk factor specific, helpful as part of the design stages of building works as clarification and supporting information to help with determining fire safety requirements and suitably qualified products or commissioning test works in order to quantify the performance of a fire engineered solution.

BS 5306-0:2011

Fire Protection Installations and Equipment on Premises – Guide for Selection of Installed Systems and Other Fire Equipment

A mostly general document covering various types of firefighting media, such as water and foams, as well as various types of fixed system such as sprinklers or hydrant systems, the use and control of these systems and the identification fire hazard categories and selection of the optimal system to account for such hazards.

Has an appendix giving some clarification regarding suitable fire systems for different hazard categories. However, this appendix is quoted from BS EN 12845 and is thus not included here as that standard and its relevant excerpts are discussed below. Otherwise, is useful as an overview of the various fire suppression options available under the British Standards for fire protection.

BS 5306-1:2006

Code of Practise for Fire Extinguishing Installations and Equipment on Premises – Hose Reels and Foam Inlets

A general standard covering the design, installation and maintenance of hose reels and foam inlets.

Contains nothing regarding high hazard/risk factor categories. To be used when required as a general standard where such systems are proposed, under design or installed.

BS 5306-3:2017

Fire Extinguishing Installations and Equipment on Premises – Commissioning and Maintenance of Portable Fire Extinguishers – Code of Practice

A general standard covering the initial commissioning of portable fire extinguishers as well as their subsequent maintenance. Also covers dealing with obsolete extinguishers which no longer have standard maintenance schedules.

Contains nothing regarding high hazard/risk factor categories. To be used when required as a general standard where portable extinguishers are proposed or installed.

BS 5306-4:2001+A1(2012)

Fire Extinguishing Installations and Equipment on Premises – Specification for Carbon Dioxide Systems

A general standard dealing with the design, installation and maintenance of carbon dioxide suppression systems.

Contains nothing regarding high hazard/risk factor categories. To be used when required as a general standard where such systems are proposed, under design or installed.

BS 5306-5.1:1992

Fire Extinguishing Installations and Equipment on Premises – Specification for Halon 1301 Total Flooding Systems

A general standard covering the characteristics, design, installation and maintenance of halon 1301 total flooding fire suppression systems.

Contains nothing regarding high hazard/risk factor categories. To be used when required as a general standard where such systems are proposed, under design or installed.

BS 5306-5.2:1984

Fire Extinguishing Installations and Equipment on Premises – Specification for Halon 1211 Total Flooding Systems

A general standard covering the characteristics, design, installation and maintenance of halon 1211 total flooding fire suppression systems.

Contains nothing regarding high hazard/risk factor categories. To be used when required as a general standard where such systems are proposed, under design or installed.

BS 5306-8:2012

Fire Extinguishing Installations and Equipment on Premises – Selection and Positioning of Portable Fire Extinguishers – Code of Practice

A general standard covering suitability and positioning of portable fire extinguishers.

Contains nothing regarding high hazard/risk factor categories. To be used when required as a general standard where portable extinguishers are proposed or installed.

BS 5839-1:2017

Fire Detection and Fire Alarm Systems for Buildings – Code of Practice for Design, Installation, Commissioning and Maintenance of Systems in Non-domestic Premises

General standard detailing the planning, design, installation, commissioning and maintenance of fire detection and alarm systems.

Contains nothing regarding high hazard/risk factor categories. To be used when required as a general standard where fire alarm and detection systems are proposed, under design or installed.

BS 7974:2019

Application of Fire Safety Engineering Principles to the Design of Buildings.

Document covering the methods and applications of fire engineering for building design, a general fire safety code for all hazard types and risk factors, helpful for when fire engineered solutions are required.

Nothing high hazard/risk factor or otherwise categorically specific. To be used when required as a general standard for such systems.

BS 8110-2:1985

Code of Practice for Concrete for Special Circumstances.

While still mentioned on occasion, has been superseded by BS EN 1992-1-1:2004 below.

Refer to BS EN 1992-1-1:2004 instead.

BS 8489-1:2016

Fixed Fire Protection Systems – Industrial and Commercial Watermist Systems

Code covers water mist systems overall, under a range of hazard types. Covers most aspects of designing, installing and maintaining a water mist system, detailing the requirements of such a system and how to meet them. Very relevant where water mist systems are installed, under design or proposed. It should be noted that this standard is based on providing proof that the water mist system will work on a specific fire load density. The manufacture of the system will therefore be required to provide test evidence as specified in the standard. It is therefore recommended that this test data is provided at the enquiry stage of a project.

For most waste sites the High Hazard category excerpts will be of immediate interest. The rest of the document covers the either lower hazard or the general aspects of water mist systems.

BS 9990:2015

Non-Automated Fire-fighting Systems in Buildings – Code of Practice

A general standard giving guidance and recommendations on the design, installation, commissioning and maintenance of systems such as wet and dry fire-fighting mains, private hydrants and other water supplies and supply pumping. To be used in conjunction with parts BS 5306 parts 1, 3 and 8.

Nothing high hazard/risk factor or otherwise categorically specific. To be used when required as a general standard where such systems are required, proposed, under design or installed.

BS 9999

Fire Safety in the Design, Management and Use of Buildings – Code of Practice

General standard covering fire safety as a whole and applying to most non-residential buildings. Particularly useful during the design stages of any building works.

As waste sites will generally be categorised as risk profile A3 or A4 sites, only the excerpts dealing specifically with these profiles are included below.

This is primarily a code of practice that addresses life safety issues and elements of its recommendations may not be acceptable to insurers or the Environment Agency in particular with regard to the relaxation of structural fire resistance and the duration of the water supply for the suppression systems.

Note, regarding sections 6.2 – 6.4: where piled or stacked waste is over 50% plastic by volume, the fire growth rate should be classed as category 4, and the resulting risk factor then A4. Under BS 9999, an A4 risk factor is unacceptable unless moderated by a suppression system or sprinklers. See Table 4, particularly footnote A for further guidance.

BS EN 710:1997+A1(2010)

Safety Requirements for Foundry Moulding and Coremaking Machinery and Plant and Associated Equipment

Document covering the risks and management thereof relating to machinery and plant in foundries. Largely irrelevant except for the select reference included here.

Makes select references to the usage of plant in high-heat environments, as occurs when plant is used to remove burning waste from storage and transfer sheds. In particular, the risk of hydraulic fluid ignition (as shown below).

BS EN 1992-1-2:2004

Eurocode 1, Part 1-2: General Actions – Actions on Structures Exposed to Fire

Supersedes BS 8110-2:1985. Follows on from BS EN 1992-1-1 and parts 1 and 2 of BS EN 1991-1. General document covering the overall principles and rules regarding the effects of fire on concrete.

To be used when required as a general standard regarding concrete subjected to fire loads. The below section, and the rest of section 5.4, however, may be of particular use in the design of partition walls separating stockpiles or acting as thermal barriers.

BS EN 12845

Fixed Firefighting Systems – Automatic Sprinkler Systems – Design, Installation and Maintenance

General document covering automatic sprinkler systems, the requirements for these systems and how to meet those requirements. Very useful where sprinklers are proposed, under design or installed.

For the majority of sites, the High Hazard category will be the most appropriate, and those excerpts are included below. For non-hazard specific or lower hazard aspects, refer to the rest of the code.

BS EN 13501-1:2018

Fire Classification of Construction Products and Building Elements – Classification Using Data from Reaction to Fire Tests

A general document covering the method and criteria for categorising the reaction to fire of construction products.

Has no specific high hazard/risk factor content. Helpful as part of the design stages of building works as clarification and supporting information to help with determining fire safety requirements and suitably qualified products in order to achieve adequate fire reaction performance.

BS EN 13501-2:2016

Fire Classification of Construction Products and Building Elements – Classification Using Data from Fire Resistance Tests, Excluding Ventilation Services

A general document covering the method and criteria for categorising the reaction to fire of construction products.

Has no specific high hazard/risk factor content. Helpful as part of the design stages of building works as clarification and supporting information to help with determining fire safety requirements and suitably qualified products in order to achieve adequate fire reaction performance.

BS EN 14243-1

Materials Obtained from End of Life Tyres. General Definitions Related to the Methods for Determining Their Dimensions and Impurities.

Provides definitions for sample collection and preparation for when determining the dimensions and impurities of end of life tyre materials.

Useful for providing additional clarity when working with BS EN 14243.

BS EN 14243-2

Materials Obtained from End of Life Tyres. Granulates and Powders – Methods for Determining the Particle Size Distribution and Impurities, Including Free Steel and Free Textile Content.

Provides test methods for determining the particle size distribution and the impurities of granulates and powders derived from end of life tyres.

Allows for standardised testing, categorisation and description of end of life tyre materials.

BS EN 14243-3

Materials Obtained from End of Life Tyres. Shreds, Cuts and Chips – Methods for Determining Their Dimension(s) Including Protruding Filaments Dimensions

Provides test methods for determining the dimensions of shreds, cuts and chips derived from end of life tyres.

Allows for standardised testing, categorisation and description of end of life tyre materials.

BS EN 15357

Solid Recovered Fuels – Terminology, Definitions and Descriptions.

Standardised definitions of various terms relating to SRF.

Useful if needing additional clarity when using standards dealing with SRF.

BS EN 15359

Solid Recovered Fuels – Specifications and Classes

Gives standardised classifications and specifications for SRF and the principles for those classifications and specifications.

Useful for additional clarity as to what standards might consider SRF or not and how to classify SRF for use with other standards.

End-of-Life Vehicles Regulations 2003 + Amendments (2010)

The End-of-Life Vehicles (Amendment) Regulations 2003 No. 2635, 2010 No. 1094

Regulations dealing with the storage and disposal of end-of-life vehicles (ELVs).

General regulations not dealing with fire or waste sites specifically but does contain one clause dealing with fire which may be of use to waste sites dealing with ELVs.

FPP Guidance

Guidance – Fire Prevention Plans: environmental permits

(Retrieved 19/06/2019 from https://www.gov.uk/government/publications/fire-prevention-plans-environmental-permits/fire-prevention-plans-environmental-permits)

Guidance provided by the EA to help waste site operators achieve compliance with FPP requirements. Provides information about what the FPP requirements means in practical terms and advice on how to meet these requirements.

A targeted document aimed at helping waste operators manage fire risk and damage on site and compile a suitable FPP for compliance with EA requirements.

Guidance on BATRRT and Treatment of WEEE 2006

Guidance on Best Available Treatment, Recovery and Recycling Techniques (BATRRT) and Treatment of Waste Electrical and Electronic Equipment

Provides guidance on treating, recovering and recycling WEEE safely and in accordance with the WEEE Directive. A general document, there is some mention of fire precautions. Relevant to most waste site operators as many sites deal with WEEE to an extent.

Has little relating to fire safety directly, what content there is, is included below. Useful for reference on safety precautions.

NEN 6060

Dutch standard covering Fire Safety of Large Fire Compartments.

This standard isn't available in English, but for operators with interests in the Netherlands, this standard could be of use and operators should be aware of it.

Most waste transfer and processing sheds are classed as large compartments, and so this standard would apply.

NFPA 12:2018

Standard on Carbon Dioxide Extinguishing Systems

General standard covering the design, installation and maintenance of carbon dioxide suppression systems.

Nothing high hazard/risk factor or otherwise categorically specific. To be used when required as a general standard where such systems are proposed, under design or installed.

NFPA 13:2016

Standard for the Installation of Sprinkler Systems

General standard covering the design, installation and maintenance of automatic fire sprinkler systems. Does not cover water mist systems.

For the majority of sites, the High Hazard category will be the most appropriate, and those excerpts are included below. For non-hazard specific or lower hazard aspects, refer to the rest of the code.

NFPA 15:2017

Water Spray Fixed Systems for Fire Protection

General standard covering the design, installation and maintenance of water spray suppression systems.

Nothing high hazard/risk factor or otherwise categorically specific. To be used when required as a general standard where such systems are proposed, under design or installed.

NFPA 18:2017

Standard on Wetting Agents

General standard covering the usage of wetting agent in automatic water suppression systems. Covers the usage of foams.

Nothing high hazard/risk factor or otherwise categorically specific. To be used when required as a general standard for such systems. Often used in conjunction with NFPA 18A.

NFPA 18A:2017

Standard for Water Additives for Fire Control and Vapour Mitigation

General standard covering water additives and their usage in automatic water suppression systems. Covers the use of surfactants.

Largely contains nothing high hazard/risk factor or otherwise categorically specific bar a few select paragraphs. To be used when required as a general standard where water additives are proposed or in use. Often used in conjunction with NFPA 18.

NFPA 20:2019

Standard on Stationary Pumps for Fire Protection

General standard covering the design and installation of water supply pumps for fire protection systems.

Nothing high hazard/risk factor or otherwise categorically specific. To be used when required as a general standard for such systems.

NFPA 22:2018

Standard for Water Tanks for Private Fire Protection

General standard covering the design, installation and maintenance of water supply tanks for fire protection systems such as the supply tank for sprinkler systems.

Does not define hazard groups or make any reference to high hazard groups or risk factors etc. but makes a singular reference to hazards greater than Ordinary Hazard Group 2, as included below. Standard to be used as a general standard for such tanks but only where the following does not apply.

NFPA 25:2017

Standard for the Inspection, Testing and Maintenance of Water-Based Fire Protection Systems

Overall, a general standard applicable to sprinkler, standpipe, hose, fixed water spray, water mist and foam water systems as well as private fire hydrants. Covers the inspection, maintenance and testing of these systems and how to update these systems to account for changes in occupancy or processes etc. that impact the fire safety of a site.

Has no high hazard category defined but does make a few select mentions to special hazard systems and is also of use as a general standard that applies to most fire suppression and protection systems.

NFPA 80A:2017

Recommended Practice for Protection of Buildings from Exterior Fire Exposures

General guidance on preventing fire spread between building exteriors through use of suitable separation distances.

Makes no reference to high hazard groups or high risk factors but does account for varying severities of fire load. The severe fire load category may be more relevant to waste operators depending on site characteristics. The excerpts for sever fire loads are included below.

NFPA 750:2019

Standard on Water Mist Fire Protection Systems

General standard covering the design, installation and maintenance of water mist suppression systems.

The High Hazard category has been removed from this revision of the standard (as of 01/05.2019), and the lower hazard categories do not apply particularly well to waste transfer and processing, so this is now to be used when required as a general standard for such systems.

NFPA 850:2015

Recommended Practise for Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations

Standard covering fire protection systems for electric generating plants with specific reference to plants generating from alternative fuels including RDF and rubber tyres. Covers fire protection and fire suppression systems generally as well as specific measures for plants using RDF, rubber tyres or other alternative fuels.

Applies to a degree to many waste sites, even if just the fuel-specific sections. Useful, in particular as a standard more directly focussed on waste sites and applicable to general fire safety.