

Toxic Species and Particulate Emissions from Synthetic Polymer Fires

Miss Hasimawaty Binti Mat Kiah

Submitted in accordance with the requirements for the degree of
Doctor of Philosophy

The University of Leeds

School of Chemical and Process Engineering

March, 2020

The candidate confirms that the work submitted is her own, except where work which has formed part of jointly-authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

- 1) **Mat Kiah M.H.**, Mustafa B.G., Andrews G.E., Phylaktou H.N., Li H (2019). **PVC Sheathed Electrical Cable Fire Smoke Toxicity**, Proceedings of the Ninth International Seminar on Fire and Explosion Hazards, St. Petersburg, Russia (April, 2019).

(Included in Chapter 4)

All the experimental work, analysis of results and writing up of the publication were carried out by Miss Hasimawaty Binti Mat Kiah. Bintu Grema Mustafa participated in carrying out the experimental procedures as two students are required when undertaking experiments and I participated in her work relating to the toxic hazards of commercial wood products. Dr Herodotos Phylaktou, Professor Gordon Andrews and Dr Hu Li (particle number specialist) supervised the research work and proof-read the publication.

On-going and other joint publications are listed in Appendix A.

This copy has been supplied on the understanding that it is copyright material and that no quotation from the thesis may be published without proper acknowledgement.

The right of Miss Hasimawaty Binti Mat Kiah to be identified as Author of this work has been asserted by her in accordance with the Copyright, Designs and Patents Act 1988.

Acknowledgements

I would like to thank my supervisors, *Dr Herodotos Phylaktou, Professor Gordon Andrews and Dr Hu Li* for their continuous support, great supervision, kind advices, valuable ideas and positive discussions through this research work.

I also would like to thank the staff and friends under the same department who helped me direct and indirectly during my study. My special thanks for whom always there to assist me when needed go to: my research mate, *Bintu Grema Mustafa* and the SCAPE laboratory technicians, *Ed Woodhouse, David Instrell, Dr Adrian Cunliffe, Karine Alves Thorne, Gurdev Bhogal, Stuart Micklethwaite, Ryan Smith and Lucy Leonard*. I also want to extend my thanks to *Professor David Purser* for his idea sharing and advices when I was at my initial stage of my PhD study.

Also not forgetting, special thanks to *Kevin O'Neill, Neil Duddy and Gavin Andrews* for their generosity on supplying some of research test materials. *Kevin O'Neill* had supplied Siemens' Wind Turbine and other LSZH cables, *Neil Duddy* had supplied bunding materials which mostly were Polyethylene type of materials and *Gavin Andrews* from Leeds Solar company had supplied high voltage Solar Energy cables.

Great thanks to the *Malaysian Government (Ministry of Higher Education, Malaysia)* and *Universiti Teknologi Malaysia* for sponsoring my PhD study.

My extraordinary thanks to *my husband also known as my soulmate **Izham***, my lovely daughter ***Damia*** and my sweet son ***Daffa***. My deepest thanks, love and gratitude for *my parents and all family members* in Malaysia. This work would not have been completed without their borderless love and endless support throughout the PhD journey.

Abstract

Overall fire statistics and residential and industrial fires in which there have been large number of fatalities demonstrate that the cause of most deaths can be attributed to effects of toxic smoke produced in these fires. Despite this fact there are no national or international legal requirements to determine the toxic emissions from materials used in construction, electrical cabling or the wide range of polymer based products used in house construction and industry. Many polymers used commercially are fire retarded and the materials used for this can add to the toxicity. The only indirect control comes through some test requirements for product classification based on the volume of smoke production. However, this is not an adequate approach to the problem. Fire smoke contents can cause death directly or can impair escape so that people die indirectly from the effects of toxic gases, and in the first we need to identify and quantify these emissions for different materials and under different fire conditions. Currently, as a consequence of this lack of legal requirements, there is a dearth of data on toxic emissions from real industrial products under fire conditions.

This research was focused on toxic gas emissions under fire conditions from practical industrial polymeric materials: insulating foams, electrical cables, Polyethylene and Polystyrene goods together with some other polymeric materials: rubber, GRP, PVC pipes and clear Acrylic. All were either used by industry who gave samples for testing or were on sale in construction product retailers. Some of the goods were fire retarded and had HCl, HBr or HF in the product gases or had high ash content. These generally produced higher toxic emissions than non-fire retarded products.

Most of the work was carried out using the Leeds University modified Cone Calorimeter with raw gas sampling from a chimney above the cone outlet. A heated sample line, heated filter and heated sample pump with heated FTIR was the method of analysis used. All products were found to have significant toxic gas emissions, but the most important toxic gas depended on the material tested and was rarely CO. A data set of toxic emissions and toxic gas yields was produced which is greater than most data sources in the literature for synthetic polymer materials.

Part of this work was the modification of the Purser Furnace by adding raw hot gas sampling and eliminating the backflow of dilution air into the reaction tube. This took a long time to design and construct and was only available at the end of the research work where it was used with PE samples at lean and rich equivalence ratios.

A significant part of the work was the first use of this equipment for particle size analysis using the DMS 500 instrument. Ultra fine particles (<50nm) were present in all the fires and were a significant health hazard.

Table of Contents

Acknowledgements	iii
Abstract	iv
Table of Contents	v
List of Tables	xiii
List of Figures	xvi
Nomenclature and Symbols	xxvi
Chapter 1 Introduction	1
1.1 Fire Statistics	1
1.2 Notable Relevant Fires	5
1.2.1 Grenfell Tower	6
1.2.2 The Rose Park Nursing Home	6
1.2.3 Piper Alpha	7
1.2.4 Kings Cross Fire 1988	7
1.3 Particulates	10
1.4 Legislation.....	11
1.5 General Research Aims.....	12
Chapter 2 Literature Review	13
2.1 Toxic Gases and Particulate Emissions from Fires.....	13
2.1.1 Asphyxiant Gases	18
2.1.2 Irritant Gases	18
2.1.3 Particulates from Smoke	19
2.2 Causes of Fire Deaths	20
2.2.1 Smoke Inhalation	20
2.2.2 Burns (Heat Shock).....	22
2.2.3 Reduction of Oxygen Levels	23
2.3 Fire Stages.....	23
2.3.1 Smouldering Fires (Incipient)	24
2.3.2 Developing Fires (Well-ventilated Flame)	24
2.3.3 Ventilation Controlled Pre-Flashover Fire	25
2.3.4 Fully Developed Fires (Post-Flashover Phase).....	25
2.3.5 Decay Phase.....	25
2.4 Factors Influence the Emission of Toxic Gases from Fires	25
2.4.1 Equivalence Ratios of Fuel and Air Mixture	26

2.4.2	Variable Ventilation Conditions	27
2.4.3	Type of Test Materials	27
2.5	Review of Fire Toxicity Test Methods	29
2.5.1	Using the Purser Furnace System	29
2.5.2	Using the Cone Calorimeter Method.....	30
2.6	Specific Research Objectives	41
Chapter 3	Research Methodology	42
3.1	Cone Calorimeter	42
3.1.1	Test Procedure for the Cone Calorimeter Method	44
3.2	Purser Furnace	45
3.2.1	Principles of Operation.....	45
3.2.2	Problems of the Purser Furnace Method	47
3.2.3	Description of the Modified Purser Furnace Method	48
3.2.4	Test Procedure for the Purser Furnace Method.....	50
3.3	Analysers Used in Experimental Works	51
3.3.1	Fourier Transform Infrared Heated Gas Analyser (FTIR)...	51
3.3.2	Differential Mobility Spectrometer (DMS500)	56
3.3.3	Smoke Meter.....	59
3.3.4	Thermodenuder	60
3.4	Test Materials	62
3.4.1	Sample Preparation Before Test for the Cone Calorimeter	65
3.4.2	Sample Preparation for Pre and Post Analysis	66
3.5	Pre and Post Analysis Equipment.....	67
3.5.1	CHNS-O Analyser	68
3.5.2	Thermo-Gravimetric Analyser (TGA)	69
3.5.3	Bomb Calorimeter	71
3.5.4	Scanning Electron Microscopy (SEM).....	73
3.5.5	Gas Chromatography (GC-MS)	74
3.6	Calculations and Data Interpretations	74
3.6.1	Determination of Sample Chemical Formula.....	75
3.6.2	Air to Fuel Ratio (AFR) and Equivalence Ratio, Φ (ER)	76
3.6.3	Normalised Mass Loss (NML) and Mass Loss Rate (MLR).....	84
3.6.4	Heat Release Rate (HRR)	85

3.6.5 Gas Concentration, Total Toxicity and Major Gas Contribution	85
3.6.6 Emission Index for Pollutants or Toxic Gas Yields for Fire Toxicity.....	87
3.6.7 Particle Number and Mass Distributions, Particulate Yields and Cumulative Mass.....	89
3.6.8 Soot Mass from Filter Papers.....	90
3.6.9 Summarised Data for Proximate and Ultimate Analysis.....	91
Chapter 4 Electrical Cable Fires in the Cone Calorimeter	95
4.1 Introduction	95
4.2 General Combustion Properties of PVC and Other Types of Electrical Cable Fires	95
4.2.1 PVC Electrical Cable Fires.....	99
4.2.1.1 PVC Prysmian A Electrical Cable Fires	99
4.2.1.2 Other PVC Electrical Cable Fires.....	104
4.2.2 Non PVC Electrical Cable Fires	106
4.2.2.1 Solar Energy Cable Fires.....	106
4.2.2.2 Siemens' Wind Turbine Cable Fires.....	108
4.2.2.3 LSZH Electrical Cable Fires	109
4.2.2.4 Other Non-PVC Electrical Cable Fires	111
4.3 Toxicity from Various Types of Electrical Cable Fires	113
4.3.1 Gas Concentrations for PVC Prysmian A Cable Fires	113
4.3.2 Gas Concentrations for Other Electrical Cable Fires	119
4.3.3 Total Toxicity for PVC Prysmian A Cable Fires.....	129
4.3.4 Total toxicity for Other Electrical Cable Fires	132
4.3.5 Gas Yields for PVC Prysmian A Cable Fires	137
4.3.6 Gas Yields for Other Electrical Cable Fires.....	145
4.3.7 Major Gases Contribution for PVC Prysmian A Cable Fires.....	162
4.3.8 Major Gases Contribution for Other Electrical Cable Fires.....	176
4.4 Particle Number and Mass Distributions for Electrical Cable Fires.....	193
4.4.1 Particle Number Distributions for PVC Prysmian A Cable Fires at Various Heat Fluxes and Ventilation Rates.....	193
4.4.2 Particle Mass Distributions for PVC Prysmian A Cable Fires at Various Heat Fluxes and Ventilation Rates.....	199

4.4.3	Particle Size Distributions for Wind Turbine Cable Fires at Irradiation Level of 35 kW/m ² and Free Ventilation	209
4.4.4	Particle Size Distributions for Other LSZH Cable Fires at Irradiation Level of 35 kW/m ² and Free Ventilation	213
4.4.5	Particulate Yields for PVC Prysmian A Cable Fires at Various Heat Fluxes and Ventilation Rates.....	216
4.4.6	Particulate Yields for Siemens' Wind Turbine Cable Fires at Heat Flux of 35 kW/m ² and Free Ventilation	220
4.4.7	Particulate Yields for Other LSZH Cable Fires at Heat Flux of 35 kW/m ² and Free Ventilation.....	222
4.5	Findings and Conclusion from Electrical Cable Fire Tests	223
Chapter 5 Solid Foam Fires with Free Ventilation in the Cone Calorimeter Test.....		227
5.1	General Combustion Properties of Various Foam Fires.....	227
5.1.1	Mass Loss Rates, Equivalence Ratios and Heat Release Rates for PIR Foam Fires	228
5.1.2	Mass Loss Rates, Equivalence Ratios and Heat Release Rates for PU and PIR Foam Fires	230
5.2	Toxicity from PU and PIR Foam Fires.....	232
5.2.1	Gas Concentrations for PIR Foam Fires at Various Irradiation Levels with Free Ventilation	232
5.2.2	Gas Concentrations for PU and PIR Foam Fires at 35 kW/m ² Irradiation Level with Free Ventilation	234
5.2.3	Gas Yields for PIR Foam Fires at Various Irradiation Levels with Free Ventilation	237
5.2.4	Gas Yields for PU and PIR Foam Fires at 35 kW/m ² Irradiation Level with Free Ventilation.....	239
5.2.5	Total Toxicity for PIR Foam Fires at Various Irradiation Levels with Free Ventilation	242
5.2.6	Total toxicity for PU and PIR Foam Fires at 35 kW/m ² Irradiation Level with Free Ventilation.....	245
5.2.7	Major Gases Contribution for PIR Foam Fires at Various Irradiation Levels with Free Ventilation	246
5.2.8	Major Gases Contribution for PU and PIR Foam Fires at 35 kW/m ² Irradiation Level with Free Ventilation	250
5.3	Particle Size Distributions for PIR Foam Fires with Varied Irradiation Levels	258
5.3.1	Particle Number and Mass Distributions for PIR Foam Fires.....	258
5.3.2	Particulate Yields for PIR Foam Fires	265

5.4 Findings and Conclusion from Solid Foam Fire Tests.....	267
5.4.1 PIR Foam Fires at Various Irradiation Levels	267
5.4.2 PIR and PU Foam Fires at 35 kW/m ² with Free Ventilation	268
Chapter 6 Polyethylene Fires with Free Ventilation in the Cone Calorimeter Test.....	271
6.1 Introduction	271
6.2 General Combustion Properties for Different Types of Polyethylene Fires	272
6.2.1 Profile for Mass Reduction and Oxygen Changes	274
6.2.2 MLR and ER	275
6.2.3 Heat Release Rate (HRR) for Polyethylene Fires	276
6.3 Determination of Ignition Time and Temperature Profile for Polyethylene and GRP Fires with Pilot Ignition and Free Ventilation Condition	277
6.3.1 Ignition Time and Test Data for Polyethylene and GRP Fires.....	278
6.3.2 Surface Temperature for Polyethylene and GRP Burning Samples.....	280
6.4 Toxicity of Polyethylene Fires	283
6.4.1 Gas Concentration as a Function of Time.....	283
6.4.2 Gas Yields for Polyethylene Fires at 35 kW/m ² with Free Ventilation	287
6.4.3 Total Toxicity for Polyethylene Fires at 35 kW/m ² with Free Ventilation.....	296
6.4.4 Major Gases Contribution for Polyethylene Fires at 35 kW/m ² with Free Ventilation.....	297
6.5 Findings and Conclusion from Polyethylene Fire Tests	305
Chapter 7 Polystyrene Fires with Free Ventilation in the Cone Calorimeter Test.....	307
7.1 General Combustion Properties of Various Polystyrene Fires	307
7.1.1 Profile for Mass Reduction and Oxygen Changes	308
7.1.2 Correlations between MLR and ER.....	309
7.1.3 Heat Release Rate (HRR) Profiles for Polystyrene Fires.	310
7.2 Toxicity of Polystyrene Fires	311
7.2.1 Gas Concentration as a Function of Time.....	311
7.2.2 Gas Yields for Polystyrene Fires at 35 kW/m ² with Free Ventilation	315

7.2.3	Total Toxicity for Polystyrene Fires at 35 kW/m ² with Free Ventilation	321
7.2.4	Major Gases Contribution for Polystyrene Fires at 35 kW/m ² with Free Ventilation	322
7.3	Findings and Conclusion from Polystyrene Fire Tests	332
Chapter 8 Other Polymer Fires with Free Ventilation in the Cone Calorimeter Test.....		334
8.1	General Combustion Properties of Other Polymer Fires	334
8.1.1	Profile for Mass Reduction and Oxygen Changes	335
8.1.2	Correlations between MLR and ER.....	335
8.1.3	Heat Release Rate (HRR) Profiles.....	336
8.2	Toxicity of Other Polymer Fires.....	337
8.2.1	Gas Concentration as a Function of Time.....	337
8.2.2	Gas Yields	339
8.2.3	Total Toxicity.....	343
8.2.4	Major Gases Contribution	344
8.3	Particle Size Distributions from Other Polymer Fires	352
8.3.1	Particle Number and Mass Distributions for Rubber Butyl Sheet Fire	352
8.3.2	Particulate Yields for Rubber Butyl Sheet Fire	355
8.4	Findings and Conclusion from Other Polymer Fire Tests.....	356
Chapter 9 Development and Testing in the Purser Furnace		358
9.1	Improved Design of the New Purser Furnace System	358
9.1.1	The Purser Furnace Method for Fire Toxicity Measurements and Its Design Problems	358
9.1.2	The Redesigned Furnace for Toxic Gas and Particulate Measurements	362
9.2	Engineered Design	364
9.2.1	Insertion of Orifice Plate to Overcome Back Flow Problem	365
9.2.2	Mixing Improvement in the Measurement Chamber	365
9.2.3	Explosion Vent Installation.....	366
9.2.4	Direct Heated Gas and Diluted Samplings.....	366
9.3	Construction Works of the Modified Furnace System	366
9.3.1	Driving Mechanism System	367
9.3.1.1	Gear Ratio Calculations	368
9.3.1.2	Verification of Driving Speed.....	369

9.3.2 Quartz Tube	370
9.3.3 Tube Furnace.....	371
9.3.4 Mixing and Measurement Chamber	371
9.4 Commissioning and operation of New Purser Furnace System ..	373
9.5 Experimental Data	373
9.5.1 General Combustion Properties.....	375
9.5.2 Toxicity of Polyethylene Fires in the Cone Calorimeter and Purser Furnace Tests	377
9.5.2.1 Gas Concentration (Raw Gas Samples)	377
9.5.2.2 Gas Yields.....	380
9.5.2.3 Total Toxicity.....	385
9.5.2.4 Major Gases Contribution	386
9.5.3 Particle Mass from Polyethylene Fires in the Purser Furnace Test.....	390
9.5.4 Particle Size Distributions of Polyethylene Fires in the Purser Furnace Test	394
9.5.4.1 Particle Number and Mass Distributions	394
9.5.4.2 Particulate Yields	398
9.6 Findings and Conclusion from PE-Y Fire Tests in the Cone Calorimeter and Purser Furnace.....	400
Chapter 10 Conclusion and Recommendation.....	402
10.1 General Discussion of Significant of Findings	402
10.1.1 Main Findings.....	402
10.2 Conclusion	404
10.2.1 Restricted Ventilation Fire Tests in the Cone Calorimeter	404
10.2.2 Free-ventilated Fire Tests in the Cone Calorimeter	405
10.2.3 Fire Tests in the Purser Furnace System.....	409
10.2.4 Comparison of Results for Fire Tests in the Cone Calorimeter and Purser Furnace System.....	411
10.3 Recommendation.....	411
10.4 Future Works	412
10.4.1 Fire Tests with and without Thermodenuder attached to the Particle Sizer in the Cone Calorimeter and Purser Furnace System.....	412
10.4.2 More Fire Tests in the New Developed Purser Furnace System Burning Various Fuels.....	413

10.4.3 More Restricted Ventilation Fire Tests in the Cone Calorimeter Burning Various Polymers	413
List of References	415
List of Abbreviations	424
Appendix A Papers and Presentations	426
A.1 List of Papers and Publications	426
A.1.1 PVC Electrical Cable Fires	426
A.1.2 Solid Foam Fires	426
A.1.3 Other Submitted Abstracts	426
A.1.4 Other Joint Publications.....	426
A.2 List of Conferences and Presentations.....	427
Appendix B The Modified Cone Calorimeter	428
B.1 Standard Test Procedure and Check List.....	428
B.2 Pictures of Cone Calorimeter Tests.....	431
Appendix C The Modified Purser Furnace.....	432
C.1 Standard Test Procedure and Check List.....	432
C.2 Pictures of Purser Furnace Tests	434
Appendix D List of Fire Toxicity Tests	435
Appendix E Cumulative Mass of CO for Various Polymer Fires.....	439
Appendix F Assembly Drawings of the Modified Purser Furnace.....	443

List of Tables

Table 1.1 Trends in fire deaths in the countries of the World in 2012-2016 [2].	2
Table 1.2 Fire incident types in Great Britain from 2008 to September 2019 [1].	5
Table 1.3 List of fire incidents involved cladding materials.....	8
Table 2.1 Asphyxiant and irritant gases [22, 23].	13
Table 2.2 Toxic gases and their effects to human health.....	15
Table 2.3 Limit concentration for major toxic species [39-41].	22
Table 2.4 Composition of test materials containing nitrogen [63].	28
Table 2.5 List of references related to the previous fire toxicity studies.	31
Table 3.1 Calibrated irradiation level at certain Cone temperature.	44
Table 3.2 Calibration and wavelength range for each species measured by the FTIR [105-107].	53
Table 3.3 List of PVC electrical cables and their application in building.....	64
Table 3.4 List of non-PVC electrical cables and their application in building.....	64
Table 3.5 List of polymers and their application in building.....	65
Table 3.6 Chemical formula for various groups of polymers.....	68
Table 3.7 Stoichiometric A/F by mass for various Hydrocarbons.	78
Table 3.8 Antoine Constants for water.....	82
Table 3.9 Dial number points of the driver at certain Φ	83
Table 3.10 Air flowrates (IAF) in different units.....	85
Table 3.11 Proximate and ultimate analysis results for test materials.	92
Table 4.1 Thickness, sample mass and Copper mass for electrical cable samples.	96
Table 4.2 Test details for PVC Prysmian A electrical cable fires.....	97
Table 4.3 Test details for other PVC electrical cable fires at 35 kW/m ² of irradiation level under free ventilation condition.....	98
Table 4.4 Test details for non PVC electrical cable fires.	99
Table 4.5 (a) Maximum gas yields for electrical cable fires at various irradiation levels and ventilation rates.....	159
Table 4.5 (b) Mean gas yields for PVC Prysmian A electrical cable fires at various irradiation levels and ventilation rates.	160

Table 4.5 (c) Mean gas yields for other electrical cable fires at several irradiation levels and ventilation rates.	161
Table 4.6 First six major species for PVC Prysmian A electrical cable fires.	171
Table 4.7 First six major species for various electrical cable fires. ...	186
Table 5.1 Test details for PIR foam (Grenfell Tower) fires at various irradiation levels with free ventilation.	228
Table 5.2 Test details for PU and PIR foam (Grenfell Tower) fires at 35 kW/m² irradiation level with free ventilation.	228
Table 5.3 Maximum gas yields for solid foam fires at various irradiation levels with free ventilation.	244
Table 5.4 Mean gas yields for solid foam fires at various irradiation levels with free ventilation.	245
Table 5.5 First six major species for various solid foam fires.	254
Table 6.1 Test details for Polyethylene fires.	273
Table 6.2 Test details for PE-Y fires.	278
Table 6.3 Test details for PE-Blue fires.	279
Table 6.4 Test details for PE-Black fires.	279
Table 6.5 Test details for GRP-Blue fires.	280
Table 6.6 FTIR species that are in or well outside the calibration range.	284
Table 6.7 Maximum gas yields for Polyethylene fires at irradiation level of 35 kW/m² with free ventilation.	295
Table 6.8 Mean gas yields for Polyethylene fires at irradiation level of 35 kW/m² with free ventilation.	296
Table 6.9 First six major species for various Polyethylene fires.	302
Table 7.1 Test details for Polystyrene fires.	307
Table 7.2 Maximum gas yields for Polystyrene fires.	320
Table 7.3 Mean gas yields for Polystyrene fires.	320
Table 7.4 First six major species for various Polystyrene fires.	328
Table 8.1 Test details for other polymer fires.	335
Table 8.2 Maximum gas yields for other polymer fires.	342
Table 8.3 Mean gas yields for other polymer fires.	343
Table 8.4 First six major species for other polymer fires.	349
Table 9.1 Calibrated values for fuel feed rate at corresponding dial or point number.	370
Table 9.2 Calculated details and parameters prior to Purser Furnace tests.	374

Table 9.3 Test details for the Purser Furnace tests.	375
Table 9.4 Maximum gas yields for Polyethylene fires in the Cone Calorimeter and Purser Furnace tests.	384
Table 9.5 Mean gas yields for Polyethylene fires in the Cone Calorimeter and Purser Furnace tests.	385
Table 9.6 First six major species for PE-Y fires in the Cone Calorimeter and Purser Furnace.	388
Table 9.7 PM mass collected from filter paper in the Purser Furnace tests.	392
Table 9.8 Filter paper analysis by TGA for the Purser Furnace tests.	394

List of Figures

Figure 1.1 Fire distribution by (a) types in worldwide (2016) [2] and (b) causes of fire deaths in Great Britain for 2018/19 [4].....	3
Figure 1.2 Total fire-related fatalities, England; year ending September 2011 to year ending September 2019 [1]	4
Figure 2.1 Reaction path to formation Nitrogen based species from the reaction with the Nitrogen from the air in fires [24].....	14
Figure 2.2 Different development stages of a compartment fire [45]..	24
Figure 3.1 Configuration of the Cone Calorimeter with a chimney.	43
Figure 3.2 Configuration of the Cone Calorimeter for restricted ventilation test (with the air tight box).	43
Figure 3.3 The actual and schematic configuration of the Purser Furnace System.	50
Figure 3.4 FTIR and Oxygen analyser.	56
Figure 3.5 Example of spectrum recorded by the FTIR analyser.....	56
Figure 3.6 Particle sizer, the DMS500 [124, 125].	58
Figure 3.7 An online graph as shown by the DMS500 computer.....	59
Figure 3.8 Smoke meter equipment.	60
Figure 3.9 Filter paper in the electrically heat holder after collection of particles. The black circle indicates mainly soot particles. If the volatiles are high the circular spot is brown.....	60
Figure 3.10 Volatile remover, the Dekati Thermodenuder.	62
Figure 3.11 Electrical cable samples in sample holder.	66
Figure 3.12 Polymer samples in sample holder.	66
Figure 3.13 Cryomill used to grind samples.....	67
Figure 3.14 Crushing machine and ball mill PM100.....	67
Figure 3.15 Ground polymer samples in powder form.	68
Figure 3.16 Thermo EA2000.	69
Figure 3.17 Shimadzu TGA-50.	70
Figure 3.18 Bomb Calorimeter – Parr 6200.....	72
Figure 3.19 Samples formed by the presser.....	72
Figure 3.20 Photo of SEM Hitachi SU8230 FESEM.....	73
Figure 3.21 Spectrums and image from SEM analysis.	74
Figure 4.1 Combustion properties against time for PVC Prysmian A electrical cable fires at 25 kW/m ² with various air flow rates.....	101
Figure 4.2 Combustion properties against time for PVC Prysmian A electrical cable fires at 35 kW/m ² with various air flow rates.....	103

Figure 4.3 Combustion properties against time for PVC Prysmian A electrical cable fires at 50 kW/m² with various air flow rates.....	104
Figure 4.4 Combustion properties against time for other PVC electrical cable fires at 35 kW/m² with various air flow rates.....	106
Figure 4.5 Combustion properties against time for Solar Energy cable fires at 35 kW/m² with free ventilation.....	108
Figure 4.6 Combustion properties against time for Siemens' Wind Turbine cable fires at 35 kW/m² with free ventilation.	109
Figure 4.7 Combustion properties against time for LSZH electrical cable fires at different heat fluxes and ventilation rates.	111
Figure 4.8 Combustion properties against time for other tested electrical cable fires at 35 kW/m² with free ventilation.....	113
Figure 4.9 Gas concentrations as a function of time for PVC Prysmian A electrical cable fires at 25 kW/m² and various ventilation rates.	115
Figure 4.10 Gas concentrations as a function of time for PVC Prysmian A electrical cable fires at 35 kW/m² and various ventilation rates.	117
Figure 4.11 Gas concentrations as a function of time for PVC Prysmian A electrical cable fires at 50 kW/m² and various ventilation rates.	119
Figure 4.12 Concentration of gases as a function of time from other PVC electrical cable fires at 35 kW/m² and free ventilation.....	121
Figure 4.13 Concentration of gases as a function of time from Solar Energy cable fires at 35 kW/m² and free ventilation.	123
Figure 4.14 Concentration of gases as a function of time from Siemens' Wind Turbine cable fires at 35 kW/m² and free ventilation.....	125
Figure 4.15 Concentration of gases as a function of time from LSZH electrical cable fires under several test conditions.....	127
Figure 4.16 Concentration of gases as a function of time from other Non-PVC electrical cable fires at 35 kW/m² and free ventilation.	129
Figure 4.17 Total toxicities indices for PVC Prysmian A electrical cable fires at 25 kW/m² with various air flow rates.	130
Figure 4.18 Total toxicities for PVC Prysmian A electrical cable fires at 35 kW/m² with various air flow rates.....	131
Figure 4.19 Total toxicities for PVC Prysmian A electrical cable fires at 50 kW/m² with various air flow rates.....	132
Figure 4.20 Total toxicity for other PVC electrical cable fires at 35 kW/m² and free ventilation.	133

Figure 4.21 Total toxicity for Solar Energy cable fires at 35 kW/m ² and free ventilation.	134
Figure 4.22 Total toxicity for Siemens' Wind Turbine cable fires at 35 kW/m ² and free ventilation.	135
Figure 4.23 Total toxicity values (LC50, COSHH and AEGL-2) for LSZH electrical cable fires under several test conditions.	136
Figure 4.24 Total toxicity for other Non-PVC electrical cable fires at 35 kW/m ² and free ventilation.	137
Figure 4.25 Gas yields for PVC Prysmian A electrical cable fires at 25 kW/m ² and various ventilation conditions.	139
Figure 4.26 Combustion efficiency, η for PVC Prysmian A electrical cable fires at 25 kW/m ² and various ventilation conditions.	139
Figure 4.27 Gas yields for PVC Prysmian A electrical cable fires at 35 kW/m ² and various ventilation conditions.	141
Figure 4.28 Combustion efficiency, η for PVC Prysmian A electrical cable fires at 35 kW/m ² and various ventilation conditions.	142
Figure 4.29 Gas yields for PVC Prysmian A electrical cable fires at 50 kW/m ² and various ventilation conditions.	144
Figure 4.30 Combustion efficiency, η for PVC Prysmian A electrical cable fires at 50 kW/m ² and various ventilation conditions.	145
Figure 4.31 Gas yields for other PVC electrical cable fires at 35 kW/m ² and free ventilation.	147
Figure 4.32 Combustion efficiency, η for other PVC electrical cable fires at 35 kW/m ² and free ventilation.	147
Figure 4.33 Gas yields for Solar Energy cable fires at 35 kW/m ² and free ventilation.	149
Figure 4.34 Combustion efficiency, η for Solar Energy cable fires at 35 kW/m ² and free ventilation.	150
Figure 4.35 Gas yields for Siemens' Wind Turbine cable fires at 35 kW/m ² and free ventilation.	152
Figure 4.36 Combustion efficiency, η for Siemens' Wind Turbine cable fires at 35 kW/m ² and free ventilation.	152
Figure 4.37 Gas yields for LSZH electrical cable fires at different heat fluxes and ventilation rates.	155
Figure 4.38 Combustion efficiency, η for LSZH electrical cable fires at different heat fluxes and ventilation rates.	155
Figure 4.39 Gas yields for other Non-PVC electrical cable fires at 35 kW/m ² and free ventilation.	157
Figure 4.40 Combustion efficiency, η for other Non-PVC electrical cable fires at 35 kW/m ² and free ventilation.	158

Figure 4.41 Contribution of major toxic gases (based LC50 _{30min}) for PVC Prysmian A electrical cable fires at 25 kW/m ² with various air flow rates.....	162
Figure 4.42 Contribution of major toxic gases (based COSHH _{15min}) for PVC Prysmian A electrical cable fires at 25 kW/m ² with various air flow rates.....	163
Figure 4.43 Contribution of major toxic gases (based AEGL-2 _{10min}) for PVC Prysmian A electrical cable fires at 25 kW/m ² with various air flow rates.....	164
Figure 4.44 Contribution of major toxic gases (based LC50 _{30min}) for PVC Prysmian A electrical cable fires at 35 kW/m ² with various air flow rates.....	165
Figure 4.45 Contribution of major toxic gases (based COSHH _{15min}) for PVC Prysmian A electrical cable fires at 35 kW/m ² with various air flow rates.....	166
Figure 4.46 Contribution of major toxic gases (based AEGL-2 _{10min}) for PVC Prysmian A electrical cable fires at 35 kW/m ² with various air flow rates.....	167
Figure 4.47 Contribution of major toxic gases (based LC50 _{30min}) for PVC Prysmian A electrical cable fires at 50 kW/m ² with various air flow rates.....	168
Figure 4.48 Contribution of major toxic gases (based COSHH _{15min}) for PVC Prysmian A electrical cable fires at 50 kW/m ² with various air flow rates.....	169
Figure 4.49 Contribution of major toxic gases (based AEGL-2 _{10min}) for PVC Prysmian A electrical cable fires at 50 kW/m ² with various air flow rates.....	170
Figure 4.50 Major gases contribution (based LC50 _{30min} , COSHH _{15min} and AEGL-2 _{10min}) for other PVC electrical cable fires at 35 kW/m ² and free ventilation.....	177
Figure 4.51 Major gases contribution (based LC50 _{30min} , COSHH _{15min} and AEGL-2 _{10min}) for Solar Energy cable fires at 35 kW/m ² and free ventilation.....	179
Figure 4.52 Major gases contribution (based LC50 _{30min} , COSHH _{15min} and AEGL-2 _{10min}) for Siemens' Wind Turbine cable fires at 35 kW/m ² and free ventilation.....	181
Figure 4.53 Major gases contribution (based LC50 _{30min} , COSHH _{15min} and AEGL-2 _{10min}) for LSZH electrical cable fires at different heat fluxes and ventilation rates.....	184
Figure 4.54 Major gases contribution (based LC50 _{30min} , COSHH _{15min} and AEGL-2 _{10min}) for Non-PVC electrical cable fires at 35 kW/m ² and free ventilation.....	185

Figure 4.55 Particle number distributions from the burning of PVC Prysmian A cable at 25 kW/m ² and various air flow rates.....	195
Figure 4.56 Particle number distributions from the burning of PVC Prysmian A cable at 35 kW/m ² and various air flow rates.....	197
Figure 4.57 Particle number distributions from the burning of PVC Prysmian A cable at 50 kW/m ² and various air flow rates.....	199
Figure 4.58 Particle mass distributions from the burning of PVC Prysmian A cable at 25 kW/m ² and various air flow rates.....	200
Figure 4.59 Size distributions for 10 nm and 100 nm particles from PVC Prysmian A cable fires at 25 kW/m ² and various air flow rates.....	201
Figure 4.60 Particulate cumulative mass for PVC Prysmian A cable fires at 25 kW/m ² and various air flow rates.....	202
Figure 4.61 Particle mass distributions from the burning of PVC Prysmian A cable at 35 kW/m ² and various air flow rates.....	204
Figure 4.62 Size distributions for 10 nm and 100 nm particles from PVC Prysmian A cable fires at 35 kW/m ² and various air flow rates.....	205
Figure 4.63 Particulate cumulative mass for PVC Prysmian A cable fires at 35 kW/m ² and various air flow rates.....	206
Figure 4.64 Particle mass distributions from the burning of PVC Prysmian A cable at 50 kW/m ² and various air flow rates.....	207
Figure 4.65 Size distributions for 10 nm and 100 nm particles from PVC Prysmian A cable fires at 50 kW/m ² and various air flow rates.....	208
Figure 4.66 Particulate cumulative mass for PVC Prysmian A cable fires at 50 kW/m ² and various air flow rates.....	209
Figure 4.67 Particle number distributions from the burning of Wind Turbine cables at 35 kW/m ² and free ventilation.....	211
Figure 4.68 Particle mass distributions from the burning of Wind Turbine cables at 35 kW/m ² and free ventilation.....	212
Figure 4.69 Particulate cumulative mass from the burning of Wind Turbine cables at 35 kW/m ² and free ventilation.....	213
Figure 4.70 Particle number distributions from the burning of other LSZH cables at 35 kW/m ² and free ventilation.....	214
Figure 4.71 Particle mass distributions from the burning of other LSZH cables at 35 kW/m ² and free ventilation.....	215
Figure 4.72 Particulate cumulative mass from the burning of other LSZH cables at 35 kW/m ² and free ventilation.....	216
Figure 4.73 Particulate yields for PVC Prysmian A cable fires at 25 kW/m ² and various air flow rates.....	218

Figure 4.74 Particulate yields for PVC Prysmian A cable fires at 35 kW/m ² and various air flow rates.....	219
Figure 4.75 Particulate yields for PVC Prysmian A cable fires at 50 kW/m ² and various air flow rates.....	220
Figure 4.76 Particulate yields (number and mass) for Wind Turbine cable fires at 35 kW/m ² and free ventilation.	222
Figure 4.77 Particulate yields (number and mass) for other LSZH cable fires at 35 kW/m ² and free ventilation.	223
Figure 5.1 Combustion properties for Polyisocyanurate foam fires at various heat fluxes with free ventilation.....	230
Figure 5.2 Combustion properties for Polyurethane and Polyisocyanurate foam fires at 35 kW/m ² with free ventilation...	231
Figure 5.3 Concentration of toxic gases as a function of time for various PIR foam fires.	234
Figure 5.4 Concentration of toxic gases as a function of time for PU and PIR foam fires at 35 kW/m ² and free ventilation.....	236
Figure 5.5 Yield of gases as a function of time for various PIR foam fires.	238
Figure 5.6 Combustion efficiency, η as a function of time for various PIR foam fires.....	239
Figure 5.7 Yield of gases as a function of time for PU and PIR foam fires at 35 kW/m ² and free ventilation.	241
Figure 5.8 Combustion efficiency, η as a function of time for PU and PIR foam fires at 35 kW/m ² and free ventilation.	242
Figure 5.9 The LC50 _{30min} , COSHH _{15min} and AEGL-2 _{10min} total relative toxicity for various PIR foam fires.....	243
Figure 5.10 The LC50 _{30min} , COSHH _{15min} and AEGL-2 _{10min} total relative toxicity for PU and PIR foam fires at 35 kW/m ² and free ventilation.....	246
Figure 5.11 Contribution of major gases (based LC50 _{30min}) for various PIR foam fires.	247
Figure 5.12 Contribution of major gases (based COSHH _{15min}) for various PIR foam fires.	248
Figure 5.13 Contribution of major gases (based AEGL-2 _{10min}) for various PIR foam fires.	250
Figure 5.14 Contribution of major gases (based LC50 _{30min}) for PU and PIR foam fires at 35 kW/m ² and free ventilation.....	251
Figure 5.15 Contribution of major gases (based COSHH _{15min}) for PU and PIR foam fires at 35 kW/m ² and free ventilation.....	252
Figure 5.16 Contribution of major gases (based AEGL-2 _{10min}) for PU and PIR foam fires at 35 kW/m ² and free ventilation.....	253

Figure 5.17 Particle size (number) distribution for PIR foam fire at various heat fluxes and free ventilation.....	259
Figure 5.18 Particle size (mass) distribution for PIR foam fire at various heat fluxes and free ventilation.....	260
Figure 5.19 Number and mass distributions for 10 nm, 50 nm and 100 nm particles from PIR foam fire at various heat fluxes and free ventilation.	261
Figure 5.20 Particle size distributions in 3D Waterfall plot for PIR foam fire at various heat fluxes and free ventilation.	264
Figure 5.21 Cumulative mass as a function of particle size for PIR foam fire at various heat fluxes and free ventilation.	265
Figure 5.22 Particulate yields for PIR foam fire at various heat fluxes and free ventilation.	267
Figure 6.1 Types of bunds used in industry.	274
Figure 6.2 Normalised mass loss and oxygen changes against time for Polyethylene fires at 35 kW/m ² with free ventilation.....	275
Figure 6.3 MLR and ER against time for Polyethylene fires at 35 kW/m ² with free ventilation.	276
Figure 6.4 HRRs against time for Polyethylene fires at 35 kW/m ² with free ventilation.	277
Figure 6.5 Surface temperature profiles for Polyethylene and GRP fires at various heat fluxes and free ventilation.....	282
Figure 6.6 Infrared images for Polyethylene and GRP fires during the flaming condition, with the peak temperature indicated.....	283
Figure 6.7 Gas concentrations for Polyethylene fires at 35 kW/m ² with free ventilation.	287
Figure 6.8 Gas yields for Polyethylene fires at 35 kW/m ² with free ventilation.....	290
Figure 6.9 Combustion efficiency, η and gas yields as a function of equivalence ratio for Polyethylene fires at 35 kW/m ² with free ventilation.....	294
Figure 6.10 Total toxicity for Polyethylene fires at 35 kW/m ² with free ventilation.....	297
Figure 6.11 Contribution of major gases (based LC50 _{30min}) for Polyethylene fires at 35 kW/m ² with free ventilation.....	298
Figure 6.12 Contribution of major gases (based COSHH _{15min}) for Polyethylene fires at 35 kW/m ² with free ventilation.....	300
Figure 6.13 Contribution of major gases (based AEGL-2 _{10min}) for Polyethylene fires at 35 kW/m ² with free ventilation.....	301
Figure 7.1 Normalised mass loss profiles for Polystyrene fires.....	308

Figure 7.2 Oxygen changes during polystyrene fire tests.	309
Figure 7.3 Mass loss rate (MLR) as a function of time.	309
Figure 7.4 Equivalence ratio (ER) as a function of time.	310
Figure 7.5 Heat release rates for various Polystyrene fires at 35 kW/m ² of irradiation level and free ventilation condition.	311
Figure 7.6 Toxic gas concentrations as a function of time for various Polystyrene fires at 35 kW/m ² with free ventilation.	315
Figure 7.7 Gas yields for Polystyrene fires at 35 kW/m ² with free ventilation.	318
Figure 7.8 Combustion efficiency, η for Polystyrene fires at 35 kW/m ² with free ventilation.	319
Figure 7.9 Total toxicity LC50 for Polystyrene fires at 35 kW/m ² with free ventilation.	321
Figure 7.10 Total toxicity COSHH _{15min} for Polystyrene fires at 35 kW/m ² with free ventilation.	322
Figure 7.11 Total toxicity AEGL-2 for Polystyrene fires at 35 kW/m ² with free ventilation.	322
Figure 7.12 Contribution of major gases (based LC50 _{30min}) for Polystyrene fires at 35 kW/m ² with free ventilation.	324
Figure 7.13 Contribution of major gases (based COSHH _{15min}) for Polystyrene fires at 35 kW/m ² with free ventilation.	325
Figure 7.14 Contribution of major gases (based AEGL-2 _{10min}) for Polystyrene fires at 35 kW/m ² with free ventilation.	327
Figure 8.1 Mass loss and oxygen consumption profiles for other tested polymer fires at 35 kW/m ² with free ventilation.	335
Figure 8.2 MLR and ER for other tested polymer fires at 35 kW/m ² with free ventilation.	336
Figure 8.3 HRR profiles for other tested polymer fires at 35 kW/m ² with free ventilation.	337
Figure 8.4 Gas concentrations for other tested polymer fires at 35 kW/m ² with free ventilation.	339
Figure 8.5 Gas yields for other tested polymer fires at 35 kW/m ² with free ventilation.	341
Figure 8.6 Combustion efficiency, η for other tested polymer fires at 35 kW/m ² with free ventilation.	342
Figure 8.7 Total toxicities for other tested polymer fires at 35 kW/m ² with free ventilation.	344
Figure 8.8 Contribution of major gases (based LC50 _{30min}) for other tested polymer fires at 35 kW/m ² with free ventilation.	345

Figure 8.9 Contribution of major gases (based COSHH _{15min}) for other tested polymer fires at 35 kW/m ² with free ventilation.	346
Figure 8.10 Contribution of major gases (based AEGL-2 _{10min}) for other tested polymer fires at 35 kW/m ² with free ventilation.	348
Figure 8.11 Particle number and mass distributions for Rubber Butyl Sheet (RBS FB) fire at heat flux of 35 kW/m ² and free ventilation.	352
Figure 8.12 Particle number and mass distributions in 3D Waterfall plot for Rubber Butyl Sheet (RBS FB) fire at heat flux of 35 kW/m ² and free ventilation.	353
Figure 8.13 Size distributions for 10 nm, 50 nm and 100 nm particles for Rubber Butyl Sheet (RBS FB) fire at heat flux of 35 kW/m ² and free ventilation.	354
Figure 8.14 Particulate cumulative mass for Rubber Butyl Sheet (RBS FB) fire at heat flux of 35 kW/m ² and free ventilation.	355
Figure 8.15 Particulate yields (number and mass) for RBS FB fire at 35 kW/m ² and free ventilation.	356
Figure 9.1 (a) Diagram of the old version Purser Furnace System [104].	364
Figure 9.1 (b) Overall diagram of the new Purser Furnace System.	364
Figure 9.1 (c) Quartz tube ends were sealed using the end caps.	365
Figure 9.2 Driving motor, driving belt and driving controller.	368
Figure 9.3 Speed rate values as a function of travel time (a) and dial number (b).	369
Figure 9.4 Furnace Quartz tube.	370
Figure 9.5 Main section of the tube furnace.	371
Figure 9.6 Transparent chamber of the new furnace rig.	372
Figure 9.7 Before, during and after test observations.	373
Figure 9.8 Temperature profiles in the Purser Furnace tests: Test 1 is ER 2.0 and Test 2 is ER 0.8.	375
Figure 9.9 General combustion properties for PE-Y fires in the Cone Calorimeter and Purser Furnace at different fire conditions.	377
Figure 9.10 Concentration of gases for PE-Y fires in the Cone Calorimeter and Purser Furnace at different fire conditions.	380
Figure 9.11 Yield of gases for PE-Y fires in the Cone Calorimeter and Purser Furnace at different fire conditions.	382
Figure 9.12 Combustion efficiency, η for PE-Y fires in the Cone Calorimeter and Purser Furnace at different fire conditions.	383
Figure 9.13 Total toxicity for PE-Y fires in the Cone Calorimeter and Purser Furnace at different fire conditions.	386

Figure 9.14 Contribution of major toxic gases for the Purser Furnace tests at two different equivalence ratios.....	387
Figure 9.15 Filter paper samples collected from the Purser Furnace tests.	391
Figure 9.16 PM mass as a function of time for the Purser Furnace tests.	393
Figure 9.17 Soot yields as a function of time for the Purser Furnace tests.	393
Figure 9.18 Wet ash contents from filter paper analysis by the TGA for the Purser Furnace tests.	394
Figure 9.19 Particle number and mass distributions for PE-Y fires in the Purser Furnace at two different equivalence ratios.	395
Figure 9.20 Particle number and mass distributions in 3D Waterfall plot for PE-Y fires in the Purser Furnace at two different equivalence ratios.....	396
Figure 9.21 10 nm and 100 nm particle distributions for PE-Y fires in the Purser Furnace at two different equivalence ratios.	397
Figure 9.22 Particulate cumulative mass as a function of particle size for PE-Y fires in the Purser Furnace at two different equivalence ratios.....	398
Figure 9.23 Particulate yields (number and mass) for PE-Y fires in the Purser Furnace at two different equivalence ratios.	399

Nomenclature and Symbols

CO	Carbon monoxide
CO ₂	Carbon dioxide
HCN	Hydrogen cyanide
HBr	Hydrogen bromide
HCl	Hydrogen chloride
HF	Hydrogen fluoride
N ₂	Nitrogen
O ₂	Oxygen
SO ₂	Sulphur dioxide
Φ	Equivalence ratio
%	Percent
°C	Unit temperature – degree Celsius
kW	Unit energy – kilowatt
m ²	Unit area – meters square
g/g	Yield unit – gram/gram
ppm	Part per million
s	Unit time – seconds
dm ³	Unit volume – cubic decimetre
m ³	Unit volume – cubic metre
min	Unit time – minutes
mm	Unit length – millimetre
nm	Unit length – nanometre
g	Unit mass – gram
L	Unit volume – litre
vol.	Volume
wt.	Weight
η	Combustion efficiency

Chapter 1

Introduction

Fire toxicity is one of the main causes of death and injury in fires in buildings. Statistics in the UK [1] show that toxic smoke inhalation accounts for about 60% of the total deaths in fires. However, currently there are no regulations that require the toxic emissions from the burning of building to be determined and taken into account. This project tests the fire toxicity of various polymeric materials used in the construction and contents of buildings. Other than gas toxicity, small particle size also a significant fire hazard. This hazard had been studied and measured from a small range of size (5nm).

1.1 Fire Statistics

As reported by the recent World Fire Statistics 2018 [2] and reproduced in Table 1.1, in consideration of 53 countries, India gave the highest number in fire deaths from year 2012 to 2016 with the fire death average number per year of 20,668. Russia gave the highest number of fire deaths for year 2016 which was about 50 percent (8,749 deaths) of the total world fire deaths (17,310 deaths), followed by USA with 3,390 deaths and Ukraine with 1,872 deaths. Meanwhile the total fire deaths in Great Britain in 2016 was 367 deaths and in Malaysia was 142 deaths with average number per year 344 and 122 deaths. Figure 1.1 (a) shows the total number of world fires categorised by type of environment in which the fires took place – the biggest fraction, 35.5 percent involved structure fires, 22.1 percent involved grass and forest fires, 13.5 percent involved vehicle fires, highlighting the importance of structural fires. Structural fires are the most hazardous to human life as it is where the highest concentration of people.

In the last few decades, the development in the fire safety research has led to the growth of fire toxicological studies. Before that, the well-known fire hazards were limited to thermal hazards only [3]. Fire statistics now show that the main cause of fire deaths is by smoke inhalation, not by heat burns.

In Great Britain the cause of death in fires has been attributed mainly the effects of smoke typically 40% due to “smoke” and another 20% due to the combination of “smoke and heat” with only 20% attributed to “heat” alone (the balance being “unspecified” or “other”). The 2013/14 statistics [8] are typical of these with three

main categories being 41, 20 and 20 % respectively. The most recent (2018/19) breakdown [9], is shown in Fig. 1.1 (b).

Table 1.1 Trends in fire deaths in the countries of the World in 2012-2016 [2].

№	Country	Population, thous. inh.	Number of fire deaths					Average number per		
			2012	2013	2014	2015	2016	year	100,000 inh.	100 fires
			2012	2013	2014	2015	2016	в год	на 100 тыс.чел.	на 100 пожаров
Страна	Население, тыс. чел.	Число погибших					Среднее число			
Staat	Einwohner in 1.000	Anzahl der Brandtoten					Mittelwert			
		2012	2013	2014	2015	2016	je Jahr	je 100.000 Einw.	je 100 Brände	
1	India	1 267 500	23 281	22 177	19 513	17 700	-	20 668	1.6	-
2	USA	323 128	2 855	3 420	3 275	3 280	3390	3 244	1.0	0.2
3	Bangladesh	154 331	210	161	70	68	-	127	0.1	0.7
4	Russia	146 270	11 652	10 601	10 138	9 405	8749	10 109	6.9	6.7
5	Japan	128 130	1 721	1 625	1 678	1 563	-	1 647	1.3	3.8
6	Vietnam	93 000	78	45	90	62	98	75	0.1	3.0
7	Germany	82 218	384	439	372	367	-	391	0.5	0.2
8	Thailand	70 498	20	110	-	-	-	65	0.1	-
9	France	66 628	362	321	280	335	289	317	0.5	0.1
10	Great Britain	63 796	380	350	322	325	-	344	0.5	0.2
11	Italy	61 000	258	196	141	222	295	222	0.4	0.1
12	Myanmar	51 496	184	83	60	-	-	109	0.2	7.2
13	Spain	47 079	170	132	162	143	175	156	0.3	0.1
14	Ukraine	42 673	2 751	2 494	2 246	1 948	1872	2 262	5.3	3.2
15	Poland	38 454	564	515	493	512	-	521	1.4	0.3
16	Canada	35 544	149	141	150	-	-	147	0.4	0.4
17	Malaysia	31 800	98	72	139	158	142	122	0.4	0.3
18	Nepal	30 430	77	59	67	-	-	68	0.2	6.8
19	Taiwan	23 089	142	92	124	117	169	129	0.6	8.0
20	Romania	20 121	222	-	-	646	258	375	1.9	1.2
21	Kazakhstan	17 500	518	455	401	386	371	426	2.4	2.9
22	Netherlands	16 979	-	-	75	81	42	66	0.4	0.1
23	Greece	10 788	49	33	-	-	-	41	0.4	0.1
24	Belgium	10 700	70	48	-	-	-	59	0.6	0.3
25	Czech Republic	10 579	125	111	114	115	124	118	1.1	0.6
26	Sweden	9 851	103	96	-	110	-	103	1.0	0.4
27	Hungary	9 830	140	112	94	108	114	114	1.2	0.5
28	Jordan	9 700	42	35	35	52	28	38	0.4	0.1
29	Belarus	9 505	927	783	737	578	538	713	7.5	5.7
30	Austria	8 544	30	20	-	-	-	25	0.3	0.1
31	Israel	8 300	-	-	-	-	19	19	0.2	0.2
32	Serbia	7 187	-	62	73	-	-	68	0.9	0.1
33	Bulgaria	7 154	53	106	103	109	-	93	1.3	0.3
34	Singapore	5 800	1	4	-	-	1	2	0.0	0.0
35	Denmark	5 710	65	70	84	68	52	68	1.2	0.5
36	Kyrgyzstan	5 522	90	80	80	48	80	76	1.4	1.9
37	Finland	5 463	77	58	86	74	82	75	1.4	0.6
38	Slovakia	5 412	44	-	-	-	-	44	0.8	0.3
39	Norway	5 109	40	62	54	-	-	52	1.0	0.7
40	New Zealand	4 596	-	-	-	13	19	16	0.3	0.2
41	Croatia	4 290	36	-	21	24	22	26	0.6	0.3
42	Moldova	3 553	150	120	118	107	-	124	3.5	2.5
43	Kuwait	3 415	21	17	19	38	50	29	0.8	1.5
44	Mongolia	3 120	75	53	61	59	60	62	2.0	1.6
45	Armenia	3 017	-	-	-	-	32	32	1.1	0.6
46	Lithuania	2 889	150	160	125	125	101	132	4.6	1.1
47	Slovenia	2 064	8	0	0	3	-	3	0.1	0.0
48	Qatar	1 975	22	4	18	18	1	13	0.6	1.0
49	Latvia	1 969	99	104	94	88	95	96	4.9	0.9
50	Estonia	1 315	54	47	54	50	39	49	3.7	0.9
51	Cyprus	858	2	5	-	-	-	4	0.4	0.0
52	Brunei	430	1	0	7	4	3	3	0.7	7.4
53	Liechtenstein	37	0	0	0	0	-	0	0.0	0.0
	Total/Итого/Gesamt	2 980 306	48 550	45 678	41 773	39 109	17 310	43 883	1.5	1.3

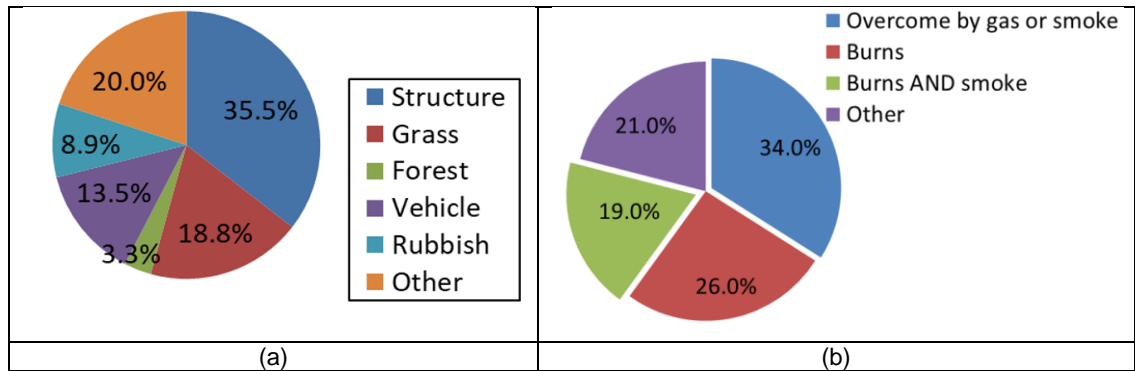


Figure 1.1 Fire distribution by (a) types in worldwide (2016) [2] and (b) causes of fire deaths in Great Britain for 2018/19 [4].

The causes of fire-related deaths are fairly stable across recent years, except for 2017/18 where the ‘other’ category was higher (27% compared with a usual range of between 10–20%) due to the Grenfell Tower fire - a large proportion of the fatalities are recorded as ‘unspecified’ while the public inquiry is still ongoing [9].

Smoke produced in fires normally contains toxic gases, vapour and various sizes of particulates. While the fire deaths are mainly attributed to the effects of smoke in terms of visibility and toxicity and most of previous fire toxicity studies are found to be focused more on the determination of toxic potency of fire effluents based on gas-phase products compared to particle-phase products. The effect of particulates has only recently started receiving attention. There are currently only a limited number of studies [5-7] which focus on the determination of particulate size from fires. As awareness on the health and environmental impact from particles generated in fires has increased, it is vital to conduct research in order to investigate the particulates emissions from the combustion of different materials and their effects on human health other than to be only focused on the toxic gases emission from the fire. This work will present data on both gaseous and particulate yields.

The latest Fire Rescue and Incident Statistics in England for year ending September 2019 [1] as in Figure 1.2, it showed a decrease of 31 percent of fire deaths which gave 248 fire deaths compared with year 2017 which gave 362 fire deaths including 72 from the Grenfell Tower fire. From the data, most of fire deaths involve fires in dwellings and other buildings compared to other locations such as road vehicles and other outdoor. This statistic has raised a critical concern to researchers when knowing that between these fire locations, even number of fires occurred are much lower for building fires than for chimney, road

vehicle and other outdoor fires but it has contributed to a high number of the total fire deaths. This consideration has become one of the reasons why the present work focussing on investigating the toxic gases and particulate emissions from building material fires. Table 1.2 shows a statistic of fire incident number by type comparing the year ending September 2019 with the year ending September 2018, five years previously in 2013/14 and ten years previously (where available) in 2008/09 in Great Britain. Fire related fatalities in dwellings had shown an increase of 9% in 2019 compared to 2018.

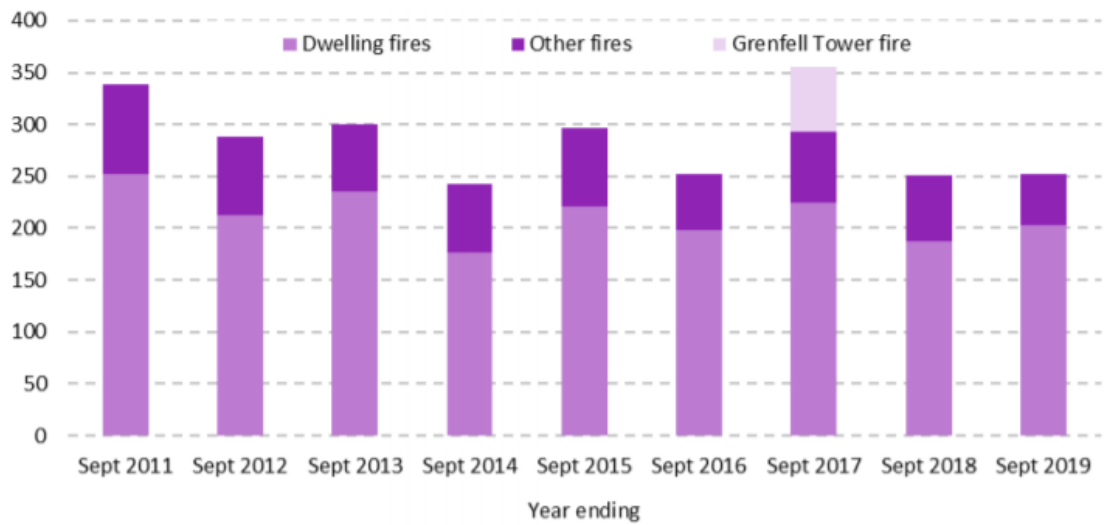


Figure 1.2 Total fire-related fatalities, England; year ending September 2011 to year ending September 2019 [1]

Table 1.2 Fire incident types in Great Britain from 2008 to September 2019 [1].

Incident type	Year ending September 2019 compared with		
	Year ending September 2018	2013/14	2008/09
554,269 all incidents	584,408 -5% ↓	526,812 +5% ↑	717,805 -23% ↓
163,039 fires	182,013 -10% ↓	171,349 -5% ↓	249,237 -35% ↓
69,534 primary fires	74,730 -7% ↓	73,230 -5% ↓	104,348 -33% ↓
28,655 dwelling fires	30,740 -7% ↓	31,910 -10% ↓	38,584 -26% ↓
25,755 accidental dwelling fires	27,569 -7% ↓	28,613 -10% ↓	32,428 -21% ↓
90,236 secondary fires	103,360 -13% ↓	92,132 -2% ↓	136,744 -34% ↓
228,309 fire false alarms	231,856 -2% ↓	224,119 +2% ↑	312,914 -27% ↓
162,921 non-fire incidents	170,539 -4% ↓	131,344 +24% ↑	155,654 +5% ↑
18,619 medical incidents	25,630 -27% ↓	13,649 +36% ↑	.. ¹
252 fire-related fatalities	251 =	278 -9% ↓	323 -22% ↓
203 fire-related fatalities in dwellings	187 +9% ↑	217 -6% ↓	255 -20% ↓
6,980 non-fatal casualties	7,107 -2% ↓	7,819 -11% ↓	9,227 -24% ↓
3,083 non-fatal casualties requiring hospital treatment	3,131 -2% ↓	3,453 -11% ↓	5,030 -39% ↓
5,164 non-fatal casualties in dwellings	5,284 -2% ↓	6,118 -16% ↓	7,455 -31% ↓

1.2 Notable Relevant Fires

Below is a brief summary of some well known fires in which the toxicity of the fire products was the main contributor to the mass fatalities of these fires. A list of other fires relevant to this project, involving cladding materials is also given in Table 1.3.

1.2.1 Grenfell Tower

Grenfell Tower fire happened on June 14, 2017 and took away 72 lives including one victim who died in the hospital seven months after the incident and around 70 injured [8]. As generally reported, the fire on this 24-storey residential tower block was started by a malfunctioning fridge-freezer on the fourth floor which then spread rapidly up the building's exterior, bringing fire and smoke to all the residential floors. This fire incident is one example of cladding materials based fire cases. Zinc cladding was initially considered as cladding materials for the building construction of the Grenfell Tower in 2015 but due to cost saving purpose, cladding materials like Reynobond PE and aluminium with plastic filling were finally used. There are many buildings constructed with using flammable cladding materials and many more will be in future if no further objection by rules as safety guidance. In Dubai UAE, more 70% skyscrapers were constructed with flammable cladding materials which was mainly PE. In example, Burj Kalifa Hotel fire started with an explosion and this building were constructed with 100% PE as panel cores of the cladding part. There were many fire cases around the world that involved cladding materials and some examples were listed in Table 1.3.

Whilst currently the cause of death of the 72 people in the building is currently "unspecified" (as discussed above) one of the objectives of the Public Inquiry is the determination of the cause of death. The phase 1 report from the fire Toxicology expert witness Prof. Purser [9] reported that blood toxicology from a limited number of victims (15) showed high concentrations of carboxyl haemoglobin consistent with CO poisoning. He also states that these measurements and and 999 call transcripts indicate that people who died in their flats were overcome by asphyxiant gases (CO and HCN) and died before their bodies were burned. He also identified the building cladding, PVC windows and contents of the apartments as contributors to the fatal toxic emissions.

1.2.2 The Rose Park Nursing Home

In 2004, a fire at a residential care home, the Rosepark Care Home, located in Lanarkshire, Scotland resulted in 14 deaths of elderly residents and another four residents injured [10, 11]. Fire safety procedures at this care home were found to be inadequate and deficient. As reported, the staff waited nine minutes before they contacted the fire service [11]. From the accident investigation and reconstruction tests with detailed toxic species concentration measurements [12] concluded that the elderly population of 18 residents were exposed to the same

mix of fire effluents but at different levels of severity depending upon their location. Ten persons in open rooms were exposed to high concentrations, resulting in death at the fire scene within ~8–9 min of the start of the fire. Persons in more protected locations were found alive after much longer exposure times although they some of these subsequently died due to their exposure.

1.2.3 Piper Alpha

A very high number of deaths (at least 165 died) caused by the Piper Alpha initial explosion and subsequent fires at North Sea oil platform, near Aberdeen in July 1988 [13]. This incident involved pool and liquid and gas jet fires in multi-level buildings. The cause of the incident was a leak of condensate due to failures of the permit to work system which resulted in a small explosion and subsequent hydrocarbon fires which eventually destroyed the whole platform [14]. Of the diseased, a large number (109) died from smoke inhalation most of them while sheltering in the designated accommodation modules.

1.2.4 Kings Cross Fire 1988

31 died in this fire accident at the Kings Cross Railway Station which was started by smokers' matches falling through the gap at the edge of the escalator [15]. The dirt and grease accumulated over months was the fuel ignited by the falling match below the escalator. A flashover through the ticket hall resulting from the pyrolysis of multilayers of paint is thought to have contributed to the dense toxic smoke that was associated with the fire the public inquiry that followed concluded that the toxic smoke contributed to the deaths and recommended the removal of materials known to produce toxic fumes.

Table 1.3 List of fire incidents involved cladding materials.

No.	Incident	Location	Date of Event	Number of Deaths	Number of Injuries	Cause of Fires	Information
1	EPF Building	Jalan Gasing, PJ, Selangor Malaysia, 6 storey building	13.02.2018 (14:15)	-	-	On the 1st floor due to renovation works at the back of the building	PE cladding
2	Grenfell Tower	North Kensington, London England, 24 storey flat	14.06.2017 (00:54)	72 (2 died in the hospital)	>70	Fridge-freezer faulty on 4th floor	Cladding materials used in the building were PE filler, PIR foam insulation, PU seal for joints and PVC windows
3	The Marina Torch Tower	Dubai UAE, 79 storey building	04.08.2017 (01:00)	-	-	Not known (Suspected caused by a thrown cigarette butt and it landed on a plant at a balcony)	During restorative works
4	The Marina Torch Tower	Dubai UAE, 79 storey building	21.02.2015 (02:00)	-	7 (due to smoke inhalation)	Fire started on the 50th floor	
5	Burj Khalifa Hotel	Dubai UAE, 63 storey building	31.12.2015 (New Year's Eve)	-	-	An explosion in the 39th floor	Fire started with an explosion. Flammable cladding materials (100% PE as panel cores)
6	Tamweel Residential Tower	Jumeirah Dubai UAE, 34 storey building	18.11.2012	-	-	A cigarette butt thrown into a bin	
7	Sharjah Residential Tower (Tiger 3 Building in Al Taawun)	Sharjah Dubai UAE, 40 storey building	04.03.2018 (07:03)	-	7	Flames allegedly started from a kitchen in an apartment on the 8th floor of the building. From investigation, fire might have started from the air-conditioning unit on the 1st floor.	
8	Al Buteenah Apartment	Al Buteenah, Sharjah Dubai UAE	12.02.2018 (01:12)	5 (due to suffocation)	-		
9	Al Manama Supermarket	Sharjah Dubai UAE	14.04.2017	2 (died of suffocation)	5		
10	Nasser Tower	King Faisal Street, Sharjah Dubai UAE, 32 storey building	01.10.2015	-	-		
11	Hafeet Tower 2 (10 Apartments)	Al Tawun, Sharjah Dubai UAE	22.04.2013	-	-	Fire broke out on the 20th floor.	
12	10 Apartments	Al Qasimiya, Sharjah Dubai UAE, 10 storey building	12.03.2013	-	-	A blaze gut 10 apartments on the 1st floor.	

13	Al Tayer Tower	Al Nahda Park, Sharjah Dubai UAE, 40 storey building	28.04.2012				
14	Al Baker Tower 4	Al Tawun Mall, Sharjah Dubai UAE	25.01.2012				The fire was caused by a lit cigarette that was thrown off the balcony from an upper floor and landed on the balcony on the 1st floor.
15	A High-rise Residential Tower	Al Nahda, Sharjah Dubai UAE	08.11.2011		6		
16	Al Wahda Street Apartment	Sharjah Dubai UAE	08.03.2011				Fire caused by an electric short circuit.
17	Bu Tinah Fire	Bu Tinah, Sharjah Dubai UAE, 14 storey building	06.07.2010				
18	Al Buhaira Corniche Apartment	Sharjah Dubai UAE	04.01.2009	-			Fire started from a kitchen and gutted the apartment on the 13th floor.
19	Abdullah Khouri Building	Jamal Abdul Nasser Street, Sharjah Dubai UAE	28.10.2008	2			Fire on the 4th floor.
20	Al Ta'awun Residential Building	Sharjah Dubai UAE	26.05.2008	-			The fire started on the 1st storey and extended to apartments up to the 7th floor.
21	Al Tahira Tower	Al Nahda, Sharjah Dubai UAE	21.07.2007	1	3		Fire breaks out in an apartment at the 8th floor.
22	Majaz 2 Residential Tower	Sharjah Dubai UAE	09.04.2007				Fire tore through four floors.
23	Al Yasmeen Apartment	Sharjah Dubai UAE	25.01.2007				
24	Dana Tower	Buhairah Corniche, Sharjah Dubai UAE, 47 storey building	09.01.2007				
25	Baku Residence Building	Baku Azerbaijan, 16-level residence building	19.05.2015	15 (toxic smoke inhalation)	63		Flammable Styrofoam facing had been installed on exterior of buildings. Flammable materials used in facade renovation.
26	Sanghai Fire	Shanghai China, 28 storey high-rise building	15.11.2010 (14:15)	58	>70		Fire started with construction materials and spread throughout the building.
27	The Beijing Television Cultural Center Fire	Beijing China	09.02.2009 (20:27)	1 (a fire-fighter)	7		A nearby unauthorised fireworks (Chinese New Year Celebration) display caused the fire. The building was built far less steel than conventional skyscrapers.

1.3 Particulates

Beyond the gaseous toxic emissions fires also emit large amounts of respirable particulates of various sizes which may harm the occupants and fire-fighters in different ways giving either a short term effect or a long term effect. Compared to ultra-fine particles, large particles usually will give a short term or immediate effect to the people who are exposed to them during the fire by causing irritancy to their eyes and skins which will reduce their capability to escape. As a long term effect, generation of nanoparticles (especially particle size below than 50 nm) from the combustion process may cause cancer disease to the people who has exposed to them when being absorbed through the blood line [16, 17].

The main aspects of particle toxicity relate to where they deposit in the respiratory tract, which depends on particle size, and their toxicity, which depends partly on their chemical composition and partly on their physical characteristics. In general large inhalable particles ~100-15 microns diameter, deposit in the upper respiratory tract and airways, If they carry toxic chemicals they cause acute airway inflammation, or following long term exposure (eg smoke from air pollution or tobacco) chronic obstructive lung disease and lung cancer. Smaller particles ~0.5-5 microns diameter penetrate into the alveolar region of the lung and can cause acute lung inflammation and oedema a few hours after exposure during a fire, which can be fatal. Ultrafine and nanoparticles may cause acute lung inflammation or emphysema but also cross into the blood stream where they can cause several effects depending on their chemistry and physical characteristics. These effects include polymer fume fever, cardiovascular disease (including heart attacks), and carcinogenicity.

Smaller particles can penetrate into the blood system easier than larger particles. These nanoparticles may act as transporters of absorbed and adsorbed toxic compounds (VOC or aerosols) into the lungs the blood stream and vital organs. Polycyclic aromatic hydrocarbons (PAH) such as Benzene and Naphthalene are the example of toxic compounds that may cause the cancer disease to the humans when they breathe in these particles during the fire. In 2014, there was a fire death case which was due to cancer disease where three fire fighters died on the same day after 13 years giving service as responders in the fire incident of the World Trade Centre, USA because of their direct exposure to the toxic species and particulates [17]. It is very important to do further investigations on the particle size and particle distribution from fires in order to be able to control

and prevent this kind of hazard from harming the people who are directly exposed.

Measurement of particulate yields and characterisation of particle size distribution is an important objective of this project.

1.4 Legislation

Most of fire deaths are generally involved in building fires. Building fire cases have involved various kinds of building structures such domestic or private home fires, high rise living accommodation fires, commercial and industrial building fires, public place building fires and also care centre fires.

There are various types of combustible materials used in building construction. Wood is the most common building material which is widely used compared to other materials like polymers. Due to an increase in demand for synthetic materials, cost savings with an advanced industrial production process, these synthetic materials have become a favourable option by the contractors and the end users. Even furniture, tools and small appliances are widely made by the synthetic materials.

Combustible building construction materials mostly used is wood, only 20 percent usage involved other materials which are mainly polymers. Polymer fires may produce gases which are more toxic than the wood fires depending to the type of polymer burnt, in example Polyisocyanurate (PIR) based materials will produce Hydrogen cyanide (HCN) which is toxic even at low concentration level. PVC based materials will produce irritant gases that can cause irritancy effects when burned which may impair the people who exposed to it from escape during the fire event. As for today, there is no regulation yet found to stop of using PVC or other harmful polymers in buildings.

The British standards for toxicity provide a guidance for the escape/safety of occupants where there is stated that there must be enough time to reach a place of safety without any harm [18-20]. From the existing standards, regarding the toxicity, only smoke obscuration is mentioned and the illustration of smoke alarms [18]. Smoke spread from the origin, hot gas layer and smoke optical density are the main parameters related to the application of fire safety engineering [19]. Although there are tenability limits defined in terms of exposure to toxic and irritants fire gases there is legal requirement to control the use of such materials based on their toxic yields in fire. The only control that may

translate to an indirect control of toxicity is the visibility requirement for safe escape and by controls of reaction-to-fire properties of products [20].

1.5 General Research Aims

In overall, the present work mainly aims to highlight and investigate the toxicity dangers of various electrical cables and polymers sold commercially for buildings using two different test methods, an existing modified Cone Calorimeter and a new developed Purser Furnace System with attachment to several external analysers such as Fourier Transform Infrared Spectroscopy (FTIR), Oxygen Analyser, Particle Sizer (DMS500) and Smoke Meter. The FTIR and Oxygen analyser were used to measure the toxic gases. For measurement of the particulate sizes, a particle size equipment called the Cambustion DMS500 was used. Smoke meter was also used to measure soot mass collected on the placed filter papers. Series of fire tests were conducted under different realistic fire conditions from well to under-ventilated fires. More than 40 polymers were burned and tested including the electrical cables. General research objectives are as follow:

- a) Develop a methodology for the analysis of toxic gases and particulates in the Cone Calorimeter and the steady state tube furnace.
- b) Design, construct and commissioning the new developed Purser Furnace System.
- c) Provide data of combustion and fire toxicity properties such as heat release rate, equivalence ratio, mass loss rate, toxic gas concentration, total toxicity, major gas contribution, gas and particulate yields and particle size and number distributions from polymer fires.
- d) Compare the results from both Cone Calorimeter and Purser Furnace methods.

List of References

1. *Fire & rescue incident statistics, England, year ending September 2019*. 2019.
2. *CTIF Centre of Fire Statistics-World Fire Statistics*:. 2018.
3. Alarifi, A., H.N. Phylaktou, and G.E. Andrews, *What Kills People in a Fire? Heat or Smoke?* 2016.
4. *National Statistics-Fire Statistics: Great Britain April 2013 to March 2014*. 2014.
5. Hertzberg, T., et al., *Particles and isocyanates from fires*. 2003: SP Swedish National Testing and Research Institute, Fire Technology.
6. Goo, J., *Study on the real-time size distribution of smoke particles for each fire stage by using a steady-state tube furnace method*. *Fire Safety Journal*, 2015. **78**: p. 96-101.
7. Lingard, J.J., et al., *Observations of urban airborne particle number concentrations during rush-hour conditions: analysis of the number based size distributions and modal parameters*. *Journal of Environmental Monitoring*, 2006. **8**(12): p. 1203-1218.
8. BBC. *Grenfell Tower: What happened*. 2019 [cited 2020 01.09.2020].
9. Purser, D.A., *Effects of exposure of Grenfell occupants to toxic fire products— Causes of incapacitation and death. Phase 1 Report: General description of hazards excluding comprehensive references to individual occupants*. 2018.
10. Moore, J. and V. Hrymak, *Fire Safety in 17 Irish Nursing Homes*. 2012.
11. BBC. *BBC News 2011: Rosepark care home deaths 'preventable' inquiry finds*. 2011.
12. Purser, D.A., *Effects of pre-fire age and health status on vulnerability to incapacitation and death from exposure to carbon monoxide and smoke irritants in Rosepark fire incident victims*. *Fire and Materials*, 2017.
13. Miller, K., *Piper Alpha and the Cullen Report*. *Indus. LJ*, 1991. **20**: p. 176.
14. Cullen, L.W.D., *The public inquiry into the Piper Alpha disaster*. *Drilling Contractor;(United States)*, 1993. **49**(4).
15. Fennel, D., *Investigation into the King's Cross Underground Fire*, in *Fennel Report*. 1988.
16. *How air pollution can cause cancer*. 2016.
17. *CBS News - FDNY: 9/11 illness kills 3 retired firefighters in one day*. 2014.
18. *The Building Regulations 2010 - Fire Safety (Approved Document B)*, H. Government, Editor. 2019: England.
19. *BS 7974:2001 - Application of fire safety engineering principles to the design of buildings. Code of practice. (2001)*. 2012.
20. *BS 9999:2017 - Fire safety in the design, management and use of buildings. Code of practice. (2017)*. 2017.
21. Kaczorek, K., A.A. Stec, and T.R. Hull, *Carbon monoxide generation in fires: effect of temperature on halogenated and aromatic fuels*. *Fire Safety Science*, 2011. **10**: p. 253-263.

22. Fraser, T.M., *Toxic Chemicals in the Workplace: A Manager's Guide to Recognition Evaluation Control*. 1996: Gulf Publishing Company.
23. Tan, K.-H. and T.-L. Wang, *Asphyxiants: simple and chemical*. *Ann Disaster Med Vol*, 2005. **4**: p. 1.
24. Michael A.T. Marro, M.A.P., J. Houston Miller, *Strategy for the simplification of nitric oxide chemistry in a laminar methane/air diffusion flamelet*. *Combustion and Flame*, 1997. **111**(3): p. Pages 208-221.
25. Stec, A. and T.R. Hull, *Fire toxicity and its assessment*. Fire retardancy of polymeric materials, Second edn. CRC Press, Boca Raton, FL, 2010: p. 453-477.
26. Stec, A.A., *Fire Toxicity and its Measurement*. 2007, The University of Bolton.
27. Mehlman, M., *Health Effects and Toxicity of Phosgene: Scientific Review*. *Defence Science Journal*, 2014. **37**(2): p. 269-279.
28. Faroon, O., et al., *Acrolein health effects*. *Toxicology and industrial health*, 2008. **24**(7): p. 447-490.
29. Organization, W.H., *Exposure to benzene: a major public health concern*. Geneva: WHO Document Production Services, 2010.
30. Pierini, C., *A Health-Destroying Toxin We Can't Avoid And Must Detoxify*.
31. Bruce, R.M., J. Santodonato, and M.W. Neal, *Summary review of the health effects associated with phenol*. *Toxicology and Industrial Health*, 1987. **3**(4): p. 535-568.
32. Sakurai, H., et al., *Health effects of acrylonitrile in acrylic fibre factories*. *British journal of industrial medicine*, 1978. **35**(3): p. 219-225.
33. Stec, A.A., et al., *The effect of temperature and ventilation condition on the toxic product yields from burning polymers*. *Fire and Materials*, 2008. **32**(1): p. 49-60.
34. Purser, D. *The application of exposure concentration and dose to evaluation of the effects of irritants as components of fire hazard*. in *Interflam, conference proceedings*. 2007.
35. Purser, D., *Behavioural impairment in smoke environments*. *Toxicology*, 1996. **115**(1-3): p. 25-40.
36. Stec, A.A., et al., *Comparison of toxic product yields from bench-scale to ISO room*. *Fire Safety Journal*, 2009. **44**(1): p. 62-70.
37. Stec, A.A. and T.R. Hull, *Assessment of the fire toxicity of building insulation materials*. *Energy and Buildings*, 2011. **43**(2-3): p. 498-506.
38. *Fire Statistics United Kingdom 2007*, Department for Communities and Local Government, London, August 2009, and preceding volumes. 2009.
39. *BS ISO 13344:2015 - Estimation of the lethal toxic potency of fire effluents*. (2016). 2016.
40. HSE. (2018). *EH40/2005 Workplace exposure limits*. 3rd ed. UK: TSO, part of Williams Lea Tag. 2018.
41. EPA, Environmental Protection Agency. (2018). *Compiled Acute Exposure Guideline Values (AEGVs)*. 2018.

42. Purser, D.A., *Toxic product yields and hazard assessment for fully enclosed design fires*. *Polymer International*, 2000. **49**(10): p. 1232-1255.
43. Purser, D.A., *Review of human response to thermal radiation, HSE contract research report No. 97/1996: S. M. Hockey and P. J. Rew. HSE Books, PO Box 1999, Sudbury, Suffolk CO10 6FS, UK 1996, 49 pp., £15.00 net, ISBN 0 7176 1083 7, paperback*. *Fire Safety Journal*, 1997. **28**(3): p. 290-291.
44. Forbes. *This Is How A Volcano's Pyroclastic Flow Will Kill You*. 2017 [cited 2020 01.09.2020].
45. Hartin, E., *Fire development and fire behavior indicators*. FireHouse. Accessed August, 2008. **10**.
46. Purser, D., *Influence of fire retardants on toxic and environmental hazards from fires*. *Fire retardancy of polymers: new strategies and mechanisms*. Royal Society of Chemistry, 2009: p. 381-404.
47. Hull, T.R., et al., *Factors affecting the combustion toxicity of polymeric materials*. *Polymer Degradation and Stability*, 2007. **92**(12): p. 2239-2246.
48. Hull, T.R. and K.T. Paul, *Bench-scale assessment of combustion toxicity—A critical analysis of current protocols*. *Fire Safety Journal*, 2007. **42**(5): p. 340-365.
49. Stec, A.A., T.R. Hull, and K. Lebek, *Characterisation of the steady state tube furnace (ISO TS 19700) for fire toxicity assessment*. *Polymer Degradation and Stability*, 2008. **93**(11): p. 2058-2065.
50. Stec, A.A., et al., *A comparison of toxic product yields obtained from five laboratories using the steady state tube furnace (ISO TS 19700)*. *Fire Safety Science*, 2008. **9**: p. 653-664.
51. Stec, A.A. and J. Rhodes, *Bench scale generation of smoke particulates and hydrocarbons from burning polymers*. *Fire Safety Science*, 2011. **10**: p. 629-639.
52. Stec, A.A. and J. Rhodes, *Smoke and hydrocarbon yields from fire retarded polymer nanocomposites*. *Polymer Degradation and Stability*, 2011. **96**(3): p. 295-300.
53. Hull, T.R., et al., *Combustion toxicity of fire retarded EVA*. *Polymer Degradation and Stability*, 2002. **77**(2): p. 235-242.
54. Hull, R.T., A.A. Stec, and J. Robinson. *Development of Standards for Assessment of Fire Effluent Toxicity and their Application to Cable Installations*. 2008.
55. Hull, T.R., et al., *Comparison of toxic product yields of burning cables in bench and large-scale experiments*. *Fire Safety Journal*, 2008. **43**(2): p. 140-150.
56. Carman, J.M., et al., *Experimental parameters affecting the performance of the Purser furnace: a laboratory-scale experiment for a range of controlled real fire conditions*. *Polymer International*, 2000. **49**(10): p. 1256-1258.
57. Chan, S., *An Exhaust Emissions Based Air–Fuel Ratio Calculation for Internal Combustion Engines*. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 1996. **210**(3): p. 273-280.

58. Chan, S. and J. Zhu, *Sensitivity analysis of an exhaust-emissions-based air: fuel ratio model for gasoline engines*. Journal of the Institute of Energy, 1996. **69**(480): p. 144-154.
59. Chan, S. and J. Zhu, *Exhaust Emission Based Air-Fuel Ratio Model (I): Literature Reviews and Modelling*. 1996, SAE Technical Paper.
60. Chan, S. and J. Zhu, *Exhaust Emission Based Air-Fuel Ratio Model (II): Divergence Analysis and Emission Estimations*. 1996, SAE Technical Paper.
61. Chan, S. and J. Zhu, *Divergence analysis of an emissions-based air—fuel ratio model and exhaust oxygen estimation*. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 1997. **211**(2): p. 137-144.
62. Purser, D.A., *Recent developments in understanding the toxicity of PTFE thermal decomposition products*. Fire and Materials, 1992. **16**(2): p. 67-75.
63. Purser, D. and J. Purser, *HCN yields and fate of fuel nitrogen for materials under different combustion conditions in the ISO 19700 tube furnace and large-scale fires*. Fire Safety Science, 2008. **9**: p. 1117-1128.
64. Blomqvist, P., et al., *Detailed determination of smoke gas contents using a small-scale controlled equivalence ratio tube furnace method*. Fire and Materials, 2007. **31**(8): p. 495-521.
65. Hirschler, M.M. and D.A. Purser, *Irritancy of the smoke (non-flaming mode) from materials used for coating wire and cable products, both in the presence and absence of halogens in their chemical composition*. Fire and Materials, 1993. **17**(1): p. 7-20.
66. Hull, T.R., K. Lebek, and J.E. Robinson, *Acidity, Toxicity And European Cable Classification*. 2006.
67. Hull, T.R., J.M. Carman, and D.A. Purser, *Prediction of CO evolution from small-scale polymer fires*. Polymer International, 2000. **49**(10): p. 1259-1265.
68. Purser, D.A., *Modelling Toxic and Physical Hazard in Fire*. Fire Safety Science, 1989. **2**: p. 391-400.
69. Purser, D.A., P. Grimshaw, and K.R. Berrill, *Intoxication by cyanide in fires: a study in monkeys using polyacrylonitrile*. Archives of Environmental Health: An International Journal, 1984. **39**(6): p. 394-400.
70. Purser, D.A., *A bioassay model for testing the incapacitating effects of exposure to combustion product atmospheres using cynomolgus monkeys*. Journal of fire Sciences, 1984. **2**(1): p. 20-36.
71. Purser, D. and P. Grimshaw, *The incapacitative effects of exposure to the thermal decomposition products of polyurethane foams*. Fire and Materials, 1984. **8**(1): p. 10-16.
72. Purser, D. and W. Woolley, *Biological effects of combustion atmospheres*. J. Fire Sci, 1982. **1**: p. 118-144.
73. Purser, D.A. and K.R. Berrill, *Effects of carbon monoxide on behavior in monkeys in relation to human fire hazard*. Archives of Environmental Health: An International Journal, 1983. **38**(5): p. 308-315.

74. Purser, D.A. and M.S. Rose, *The toxicity and renal handling of paraquat in cynomolgus monkeys*. Toxicology, 1979. **15**(1): p. 31-41.
75. Purser, D., *Validation of additive models for lethal toxicity of fire effluent mixtures*. Polymer Degradation and Stability, 2012. **97**(12): p. 2552-2561.
76. Stec, A.A., et al., *Analysis of toxic effluents released from PVC carpet under different fire conditions*. Chemosphere, 2013. **90**(1): p. 65-71.
77. Mahalingam, A., et al., *Numerical investigation of tube furnace toxicity measurement method (ISO 19700)*. Fire and Materials, 2012. **36**(1): p. 17-30.
78. Babrauskas, V., *Effective measurement techniques for heat, smoke, and toxic fire gases*. Fire Safety Journal, 1991. **17**(1): p. 13-26.
79. Babrauskas, V., et al., *Toxic potency measurement for fire hazard analysis*. Fire technology, 1991. **28**(2): p. 163-167.
80. Marquis, D.M., et al., *Usage of controlled-atmosphere cone calorimeter to provide input data for toxicity modelling*. Proceeding in the 12th. International Fire and Material., San Francisco, 2011.
81. Parker, W.J., *Calculations of the heat release rate by oxygen consumption for various applications*. Journal of fire Sciences, 1984. **2**(5): p. 380-395.
82. Stec, A.A. and T.R. Hull. *Assessment of fire toxicity from polymer nanocomposites*. in *Conference information: 11th Meeting on fire retardant polymers, Bolton, UK, Fire retardancy of polymers: new strategies and mechanisms*. 2009.
83. Babrauskas, V., *Development of the cone calorimeter—a bench-scale heat release rate apparatus based on oxygen consumption*. Fire and Materials, 1984. **8**(2): p. 81-95.
84. Babrauskas, V. and G. Mulholland, *Smoke and soot data determinations in the cone calorimeter*, in *Mathematical Modeling of Fires*. 1988, ASTM International.
85. Babrauskas, V. and W.J. Parker, *Ignitability measurements with the cone calorimeter*. Fire and Materials, 1987. **11**(1): p. 31-43.
86. 5660-1, B.I., *Cone Calorimeter Standard: Reaction-to-fire tests — Heat release, smoke production and mass loss rate*. 2015.
87. Babrauskas, V., *Toxic hazard from fires: a simple assessment method*. Fire Safety Journal, 1993. **20**(1): p. 1-14.
88. Pei, B., G.-y. Song, and C. Lu, *The Application of Cone Calorimeter on the Study of Burning Performance of Liquorices*. Procedia Engineering, 2014. **71**: p. 291-295.
89. Hull, T.R. and A.A. Stec, *Polymers and fire*. Fire retardancy of polymers—new strategies and mechanisms, ed. TR Hull and BK Kandola, The Royal Society of Chemistry, Cambridge, 2009: p. 8.
90. Stec, A.A., et al., *Quantification of fire gases by FTIR: Experimental characterisation of calibration systems*. Fire Safety Journal, 2011. **46**(5): p. 225-233.
91. Babrauskas, V., et al., *Toxic potency measurement for fire hazard analysis*. Fire technology, 1992. **28**(2): p. 163-167.
92. Babrauskas, V., et al., *A cone calorimeter for controlled-atmosphere studies*. Fire and Materials, 1992. **16**(1): p. 37-43.

93. Babrauskas, V., et al., *The phi meter: A simple, fuel-independent instrument for monitoring combustion equivalence ratio*. Review of scientific instruments, 1994. **65**(7): p. 2367-2375.
94. Babrauskas, V., *Fire safety improvements in the combustion toxicity area: is there a role for LC50 tests?* Fire and Materials, 2000. **24**(2): p. 113-119.
95. Babrauskas, V. and R.D. Peacock, *Heat release rate: the single most important variable in fire hazard*. Fire Safety Journal, 1992. **18**(3): p. 255-272.
96. Guillaume, E., D.M. Marquis, and C. Chivas, *Experience plan for controlled-atmosphere cone calorimeter by Doehlert method*. Fire and Materials, 2013. **37**(2): p. 171-176.
97. Guillaume, E., et al., *Effect of gas cell pressure in FTIR analysis of fire effluents*. Fire and Materials, 2015. **39**(7): p. 675-684.
98. Guillaume, E., D. Marquis, and L. Saragoza, *Calibration of flow rate in cone calorimeter tests*. Fire and Materials, 2014. **38**(2): p. 194-203.
99. Guillaume, E., C. Chivas, and A. Sainrat, *Regulatory issues and flame retardant usage in upholstered furniture in Europe*. Fire & Building Safety in the Single European Market. School of Engineering and Electronics, University of Edinburgh, 2008: p. 3.
100. Irshad, A., Andrews, G.E., Phylaktou, H.N. and Gibbs, B.M. *Development of the Controlled Atmosphere Cone Calorimeter to Simulate Compartment Fires*. in *Proc. Ninth Int. Sem.on Fire and Explosion Hazards (ISFEH9)*. 2019. Saint Petersburg, Russia: Published by Saint-Petersburg Polytechnic University Press.
101. 19700, I.T., *Controlled equivalence ratio method for the determination of hazardous components of fire effluents*. 2007.
102. Purser, J., et al., *Repeatability and reproducibility of the ISO/TS 19700 steady state tube furnace*. Fire Safety Journal, 2013. **55**: p. 22-34.
103. *DIN 53436-1 - Generation of Thermal Decomposition Products from Materials for Their Analytic - Toxicological Testing*. 2015.
104. 19700, I., *Controlled equivalence ratio method for the determination of hazardous components of fire effluents - The steady state tube furnace*. 2013.
105. Alarifi, A.A., *Compartment Fire Toxicity: Measurements and Aspects of Modelling*, in *School of Chemical and Process Engineering*. 2016, University of Leeds: Leeds, UK.
106. Irshad, A., *Gasification Burning of Biomass*, in *School of Chemical and Process Engineering*. 2017, University of Leeds: Leeds, UK.
107. Mustafa, B.G., *Toxic Species and Particulate Emissions from Wood and Pool Fires*, in *School of Chemical and Process Engineering*. 2019, University of Leeds: Leeds, UK.
108. Aljumaiah, O.A.O., *Combustion products from ventilation controlled fires: toxicity assessment and modelling*. 2012, The University of Leeds.
109. Andrews, G., et al., *FTIR investigations of toxic gases in air starved enclosed fires*. Fire Safety Science, 2005. **8**: p. 1035-1046.

110. Hakkarainen, T., et al., *Smoke gas analysis by Fourier transform infrared spectroscopy*. VTT Building Technology, Final report of the SAFIR project, 1999.
111. Speitel, L.C., *Fourier transform infrared analysis of combustion gases*. Journal of fire sciences, 2002. **20**(5): p. 349-371.
112. Abdulaziz A. Alarifi, H.N.P.a.G.E.A. *Toxic Gas Analysis from Compartment Fires using Heated Raw Gas Sampling with Heated FTIR 50+ Species Gas Analysis*. in *Proc. of the First International Fire Safety Symposium*. 2015. Coimbra, Portugal.
113. Abdulaziz A. Alarifi, H.N.P.a.G.E.A. *Heated Raw Gas Sampling with Heated FTIR Analysis of Toxic Effluents from Small and Large Scale Fire Tests*. in *Proceedings of the IAFSS, 10th Asia-Oceania Symposium on Fire Science and Technology, 10th AOSFST*. 2015. Tsukuba, Japan.
114. Alarifi, A., Andrews, G. E., Witty, L., & Phylaktou, H. N. *Ignition and toxicity of selected aircraft interior materials using the cone calorimeter and FTIR analysis*. in *In Conference Proceedings, Interflam2013*. 2013. Royal Holloway College - University of London. UK: Interscience Communications Ltd.
115. Aljumaiah, O., Andrews, G.E., Alqahtani, A.M., Husain, B.F., Singh, P. and Phylaktou, H.N. *Air Starved Acrylic Curtain Fire Toxic Gases using an FTIR*. in *Sixth International Seminar on Fire and Explosion Hazards*. 2010. University of Leeds, UK.
116. Andrews, G.E., Boulter, S., Burell, G., Cox, M., Daham, B, Li, H. and Phylaktou, H.N., *Toxic Gas Measurements Using FTIR for Combustion of COH Materials in Air Starved Enclosed Fires*, in *The European Combustion Institute Meeting, Chania, Crete, April, 2007*. 2007.
117. Andrews, G.E., et al., *Aircraft Blanket Ignition and Toxic Emission in Simulated Aircraft Cabin Fires Using the Cone Calorimeter*. *Fire and Materials* 2015, 2015: p. 734-748.
118. Mat Kiah, M.H., Mustafa, B.G., Andrews, G.E., Phylaktou, H.N. and Li, H. *PVC Sheathed Electrical Cable Fire Smoke Toxicity*. in *Proc. Ninth Int. Sem.on Fire and Explosion Hazards (ISFEH9)*. 2019. Saint Petersburg, Russia: Published by Saint-Petersburg Polytechnic University Press.
119. Mustafa, B.G., Mat Kiah, M.H., Andrews, G.E., Phylaktou, H.N. and Li, H. *Smoke Particle Size Distributions in Pine Wood Fires*. in *Proc. Ninth Int. Sem.on Fire and Explosion Hazards (ISFEH9)*. 2019. Saint Petersburg, Russia: Published by Saint-Petersburg Polytechnic University Press.
120. 19702, I., *Toxicity testing of fire effluents - Guidance for analysis of gases and vapours in fire effluents using FTIR gas analysis*. 2006.
121. 19701, B.I., *Methods for sampling and analysis of fire effluents*. 2013: International Organization for Standardization: Geneva.
122. Fardell, P. and E. Guillaume, *Sampling and measurement of toxic fire effluent*. *Flammability testing of materials used in construction, transport and mining (ISBN 978-1-85573-935-2)* This authoritative text reviews flammability tests for buildings and their contents,

- including wood products, cladding, sandwich panels, floor and ceiling materials, upholstered furniture and mattresses, cables and electrical appliances. It also covers, 2010: p. 385.
123. Ltd., C., *User Manual - DMS500 Fast Particulate Spectrometer with Heated Sample Line High Ratio Diluter*. 2011: United Kingdom.
 124. Reavell, K., Hands, T., and Collings, N., *A Fast Response Particulate Spectrometer for Combustion Aerosols 2002-01-2714*. 2002.
 125. Kittelson, D., Tim Hands, Chris Nickolaus, Nick Collings, Ville Niemelä, and Martyn Twigg, *Mass Correlation of Engine Emissions with Spectral Instruments*, JSAE paper number 20045462. 2004.
 126. Held, A., et al., *Aerosol size distributions measured in urban, rural and high-alpine air with an electrical low pressure impactor (ELPI)*. Atmospheric Environment, 2008. **42**(36): p. 8502-8512.
 127. Coudray, N., et al., *Density measurement of fine aerosol fractions from wood combustion sources using ELPI distributions and image processing techniques*. Fuel, 2009. **88**(5): p. 947-954.
 128. Liang, B., et al., *Comparison of PM emissions from a gasoline direct injected (GDI) vehicle and a port fuel injected (PFI) vehicle measured by electrical low pressure impactor (ELPI) with two fuels: Gasoline and M15 methanol gasoline*. Journal of Aerosol Science, 2013. **57**: p. 22-31.
 129. Elmer, P., *Thermogravimetric analysis (TGA) a beginner's guide*. United States of America: Perkin Elmer, 2010.
 130. D.T. Gottuk, R.J.R., *Effect of combustion conditions on species production*, in *SFPE handbook of fire protection engineering*. 1995, Quincy, Mass. : National Fire Protection Association ; Boston, Mass. : Society of Fire Protection Engineers. p. p. 2-64 – 2-84.
 131. Schaschke, C., *Antoine equation*. In *A Dictionary of Chemical Engineering*, 2014.
 132. Huggett, C., *Estimation of rate of heat release by means of oxygen consumption measurements*. Fire and Materials, 1980. **4**(2): p. 61-65.
 133. M., J., *Calorimetry*. In: Hurley M.J. et al. (eds) *SFPE Handbook of Fire Protection Engineering*. 2016, Springer, New York, NY.
 134. Abdul-Khalek, I., D. Kittelson, and F. Brear, *The Influence of Dilution Conditions on Diesel Exhaust Particle Size Distribution Measurements*. 1999, SAE International.
 135. Alarifi, A.A., et al., *Ignition and Toxicity Evaluation of Selected Aircraft Interior Materials Using the Cone Calorimeter and FTIR Analysis*. InterFlam2013, 2013: p. 37-48.
 136. Purser, D., A. Stec, and T. Hull, *Effects of the material and fire conditions on toxic product yields*. Fire toxicity. Cambridge, UK.: Woodhead Publishing Limited, 2010: p. 515-38.
 137. Lewin, M. and E.D. Weil, *2 - Mechanisms and modes of action in flame retardancy of polymers*, in *Fire Retardant Materials*, A.R. Horrocks and D. Price, Editors. 2001, Woodhead Publishing. p. 31-68.
 138. Price, D., G. Anthony, and P. Carty, *1 - Introduction: polymer combustion, condensed phase pyrolysis and smoke formation*, in *Fire*

- Retardant Materials*, A.R. Horrocks and D. Price, Editors. 2001, Woodhead Publishing. p. 1-30.
139. Purser, D.A., *Toxic Combustion Product Yields as a Function of Equivalence Ratio and Flame Retardants in Under-Ventilated Fires: Bench-Large-Scale Comparisons*. *Polymers*, 2016. **8**: p. 1-23.
 140. Wade, A.P.R.a.C.A., *Branz Study Report 185: Soot Yield Values for Modelling Purposes - Residential Occupancies*. 2008, Branz.
 141. Guillaume, E., *Effects of Fire on People: Bibliography Summary - July 2006*. 2006, Laboratoire National de Metrologie et d'Essais (LNE): Paris, France.
 142. Tewarson, A., *Generation of Heat and Chemical Compounds in Fires*, in *SFPE Handbook of Fire Protection Engineering*. 1988, National Fire Protection Association: Quincy, MA, USA.

- 3) Bintu G. Mustafa, Miss H. Mat Kiah, Juma Al-Nahdi, Gordon E. Andrews, Herodotos N. Phylaktou, Hu Li (2019). Toxic Emissions from Processed Wood in Cone Calorimeter Tests. Submitted to Fire and Materials (under review).
- 4) B.G. Mustafa, M.H. Mat Kiah, A. Irshad, G.E. Andrews, H.N. Phylaktou, H. Li and B.M. Gibbs (2019). Rich Biomass Combustion: Gaseous and Particle Number Emissions, Fuel (July, 2019).
- 5) Mustafa B.G., Mat Kiah M.H., Andrews G.E., Phylaktou H.N., Li H (2019). Smoke particle size distribution in pine wood fires, Proceedings of the Ninth International Seminar on Fire and Explosion Hazards, St. Petersburg, Russia (April, 2019).

A.2 List of Conferences and Presentations

- 1) ISFEH9 2019 – St. Petersburg, Russia, April 21-26, 2019, PVC Sheathed Electrical Cable Fire Smoke Toxicity, (Oral).
- 2) ISFEH9 2019 – St. Petersburg, Russia, April 21-26, 2019, Toxic Gases from PU and PIR Foam Fires (Poster).
- 3) Fired-UP 2018 – University of Edinburgh, United Kingdom, May 17-18, 2018, Toxicity of electrical cable fires under restricted and free ventilations in the Cone Calorimeter (Oral).
- 4) Cambridge Particle Meeting 2017 – University of Cambridge, United Kingdom, June 23, 2017.
 - a) Particle size distribution as a function of time during pine wood combustion on a cone calorimeter (Oral, presented by Dr Hu Li).
 - b) Particle size emissions from PVC electrical cable fires (Poster).
- 5) MySECON2017 2017 – University of Manchester, United Kingdom, May 12, 2017. Toxic species and particle size distribution from PVC cable fires (Poster).