TO DEVELOP A MODEL TO PREDICT THE CARBON EMISSIONS FROM FIRES IN THE BUILT ENVIRONMENT.

A dissertation submitted to the

University of Central Lancashire

in partial fulfilment of the requirements for the degree of

Master of Philosophy

in

Fire Safety Engineering

by

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November 2018

Abstract

The effects of Climate Change or Global Warming on our planet, but more directly on the human species has been long discussed and always controversial. This paper adds to that discussion in so far as it adds the Greenhouse Gas emissions from fires in our communities to the already accumulated data from most other activities and industries that affect our climate.

Whilst a lot of research has been carried out into Greenhouse Gases and their effects on the climate, and the potential economic and political consequences which inevitably creates controversy, only very limited research has been carried out on the effects of fires, in spite of the fact that Fire and Rescue Services in England dealt with 167 150 fires (1) in the year 2017/8, representing 30% of the total emergency calls, and that is only the number reported to, and attended by the Fire and Rescue Services.

The only reporting mechanism for the number and type of fires is by the Fire and Rescue crews attending them for the UK Government Statistics, using the Incident Recording System, a menu led tool that requires information about the type of incident and the amount of damage, as well as cause, location and method of extinguishment. Therefore, the model developed as a result of this work uses this data as the basis for the calculations. Whilst other ideas were considered at the beginning of this study it was clear from an early stage that the only data collection mechanism was and will continue to be the Incident Recording System, and the model had to complement that.

The effect of Carbon Dioxide as a Greenhouse Gas is considered pre-eminent of all of the Greenhouse Gases because of its abundance and longevity in the atmosphere. In 2013, the Intergovernmental Panel on Climate Change issued a global climate assessment (2) in which they described Carbon Dioxide as the most influential human influenced climate driver. That

is the rationale for this study to focus only on the Carbon Dioxide fraction of the smoke produced by fires.

The main conclusion of this work is to acknowledge that whilst fire has a devastating impact of people's lives and their communities, and that fires pollute the atmosphere locally as well as globally, such as Chernobyl in 1986, one of the most devastating example of this in living memory, the Australian bush fire in 2009 killing 180 and injuring around 500 people, the Kuwaiti oil fires after the Gulf War in 1991, the consequences of fire in terms of climate change, especially when compared to those other emitting activities and industries, might be regarded as negligible. In fact, the results of this study show that fires in the UK contribute approximately 140 000 tonnes of Carbon Dioxide emissions. To put that into context, the United States Geological Survey Volcano Hazards Programme estimates that the world's volcanoes, both on land and undersea, generate 200 million tonnes annually (42), and the BBC recently reported global Carbon Dioxide emissions from wildfires were over 30 billion tonnes in 2017(44). Closer to home, charcoal fired barbeques in the UK potentially generate more than double the emissions from fires (43).

The study focused on fires that, between them, account for almost half of the totals attended by Fire and Rescue Services, especially those serving major metropolitan cities. It also considered two major fire incidents, the fuel storage depot at Buncefield, Hertfordshire, and a Refuse Derived Fuel storage fire in Salford, Greater Manchester, to demonstrate the adaptability of the model proposed. It does, however, acknowledge that the results of the study represent an order of magnitude result rather than an accurate reflection of the problem, because of the inherent assumptions and parameters used throughout the study, from data gathering to Carbon loading factors for the fires.

By calculating the Carbon content of those things involved in fires, whether they be wheelie bins, cars, domestic dwellings and even industrial facilities, this study has developed a model that can predict the Carbon Dioxide emissions using current data gathering systems.

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Acknowledgements

I would like to acknowledge the following;

Dr. Paul Currie for his support and encouragement for seeing this project through to its submission, especially after picking up the role of mentor and academic supervisor part way through this project.

Dr. Andrei Chamchine for his guidance and enthusiasm in the early stages of this project.

Members of staff from the University of Central Lancashire who were always happy to help with any administrative issues, especially Clare Altham for her patience.

Members of Greater Manchester Fire and Rescue Service Data Management Team who provided the Incident Recording System data and were able to apply the Carbon Factors to that data to produce the carbon emission results from the model, most notably Chris Leech, the Team Manager.

Friends and colleagues from Greater Manchester Fire and Rescue Service who were always happy to offer technical advice and be critical friends, especially during the early stages of the model development.

My family for their support and humour, and patience during the times when I was juggling the demands of a new role in Greater Manchester Fire and Rescue Service with the demands of this project.

Thank you to all of you.

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1 INTRODUCTION

1.1 Background

This project was born out of an offer of between Greater Manchester Fire and Rescue Service and the University of Central Lancashire in 2010.

Greater Manchester Fire and Rescue Service and the University of Central Lancashire have a long history of collaboration; UCLAN hosted several of GMFRS Fire Safety Officers on the BSc Fire Engineering Degree, they provided Fire Investigation training for some of the Fire Safety Enforcement Officers, and supported further research and study, most notably Dr Jim Marsden, whose work on Carbon Emissions, Fire and the Environment, Understanding Carbon Footprints, will be referred to later.

The offer was to support GMFRS employees through research into an area previously not described. Whilst the impact of most sectors have been widely researched and reported, such as agriculture, transport, construction and energy production for example, research into the emissions from fire was largely restricted to wildfires and, other than the work done by Dr Marsden, very little had been done to assess fires within our built environment. So much so that early on in the investigation for this study, the only relevant information related to a Carbon Calculator based on Dr Marsden's work, mentioned above. It was possibly because of the relationship between GMFRS, UCLAN and Dr Marsden that this project was born.

1.2 Aims and Objectives

The main aim of this work is to provide a means to understand and evaluate the impact of fire emissions on our built environment. Importantly, the definition of a fire in the context of this work is those fires which are reported to, and are dealt with by, the Fire and Rescue Services.

In working towards this principle aim there were further challenges; for example, it had to be within the academic reach of the author and the likely end users of this model, firefighters. Therefore, the need for the understanding of relevant subjects like Chemistry, Mathematics and Physics was real, and required considerable patience. The objective was to make every attempt to keep the science, and therefore the model, tractable.

Next, there needed to be a robust and resilient means of reporting fire data. Currently there is only one method by which fire data is collected and analysed, the Incident Recording System and, whilst it has evolved from a paper-based Fire Report to an electronic menu led system, no other routine fire investigation process exists. The Fire and Rescue Services are obliged to gather fire data for statistical evaluation only and are not required to investigate beyond that level. The fact that some Fire and Rescue Services use professional and qualified Fire Investigators to determine the origin, cause and development of fires, is primarily to support police investigations into arson and related deaths and injuries. Operational firefighters are not currently trained as Fire Investigators, nor are Fire Investigators mobilised to investigate every fire. The data gathered at an incident is effectively the best estimate of the damage caused, because it is the only estimate, and this was the foundation of the work.

The approach focused both on what the model was expected to achieve whilst designing it within the parameters set by technologies and available resources. For example, unless there was a compelling reason for it there was little likelihood of laboratory funding. Equally, to ask GMFRS to re-design the data management system was not going to be possible. Therefore, the methodology for this had to be defined by personal scientific understanding, the existing data processing and largely theoretical.

Therefore, the following objectives were identified and will be met throughout the course of this study in order to achieve the principal aim of developing the model to understand and evaluate the impact of fire on the built environment;

- Simplicity; within the academic grasp of the author and accessible to the likely practitioners, the Fire and Rescue Services tasked with gathering and analysing the data.
- Using existing data gathering techniques.
- Working within a limited budget in terms of resources and available technologies.

1.3 Outline Structure

This thesis will describe the context within which it is relevant; why Carbon emissions are the focus of the work and the issue of climate change as a result of Global Warming. It will describe the efforts to quantify and resolve Carbon Emissions in other sectors and industries. It will introduce the reader to the current system of gathering and recording fire statistics within the United Kingdom Fire Service, and how it is used to determine public safety strategies and also its limitations. It will briefly and simplistically describe the principles of Organic Chemistry that were used to develop the model.

This thesis will go on to describe the types of fires chosen to demonstrate the model and why they were chosen, after which it will set out the theoretical model using these examples and how it was possible to create a simple change to the way the statistical data is presented in order to produce Carbon Emission results. This part of the paper will also underline the limitations of the model and the results it predicts.

It will then use the results to describe the impact on a local, national and even global scale, and demonstrate that it can also be used for single, extraordinary fire events. These results will be compared to work done in other Carbon emitting sectors to draw a comparison and then recommendations for future action, including the strategic approach to firefighting.

The paper will be set out as follows;

Chapter 1. Introduction

The background of this piece of research and the collaboration between the University of Central Lancashire to Greater Manchester Fire and Rescue Service.

Chapter 2. Literature Review

The context in which this study is set and the long history of research into Climate Change and it's, often controversial consequences for global politics.

Chapter 3. Methodology

Understanding the nature of combustion, compartment fires and their development and decay, how Carbon Dioxide is produced as a result of the combustion process, why some approaches were identified and discounted and how the chosen method was adopted.

Chapter 4. Chemistry and Model Development

Introducing the science of combustion and its products, or smoke as most people understand it. Also, the basics of Stoichiometry and balanced chemical reactions, chemical formulae and why some materials produce Carbon Dioxide whereas others don't. The use of molecular weights to determine the proportion by weight of Carbon in a molecule and validation of that approach to develop the model.

Chapter 5. Applying the Model

This is the point at which the theory becomes practice, in so far as the chemistry in the previous chapter is used to describe and quantify the Carbon emissions from a number of different fires, referred to as "volume fires" as they constitute a significant workload for the Fire and Rescue Services but are relatively straightforward in terms of investigating the damage and therefore the data gathered is realistic.

Chapter 6. Large Scale and Unique Incidents

Two case studies are looked at that represent large scale and significant incidents; one is the Oil Storage Facility at Buncefield in Hertfordshire in 2005 that had national coverage, and the second is a Refuse Derived Fuel storage facility in Salford, Greater Manchester. These two incidents demonstrate the value of the model for those incidents that might not be included as "volume fires" and might not be predictable but nonetheless have significant atmospheric impact in terms of their Carbon emissions.

Chapter 7. Results

All of the data from the fires is analysed and extrapolated to produce emissions results for both Greater Manchester and England and these results are compared and contrasted with the sectors responsible for the majority of the Carbon emissions.

Chapter 8. Conclusions

Conclusions based on the results of the research are formed with recommendations for future research given.

1.4 Value of the Research

To date the only piece of research into the effects of Carbon emissions from fires within the built environment is the work done by Dr. Jim Marsden (3), former Fire Engineering Officer with Greater Manchester Fire and Rescue Service in his paper Green Thinking and his presentation to the Fire and Rescue Service's Chief Fire Officers Association Fire and the Environment, Understanding Carbon Footprints, which will be discussed in more detail in the Literature Review that follows.

This research will explain how to calculate the Carbon emissions from fires delivers a template for large and unique fire events and ultimately puts the total Carbon emissions from those fires into context with other activities and industries, such as energy production, transport, agriculture, to inform future strategies to reduce those emissions. Without this research, those emissions would remain unknown.

2 LITERATURE REVIEW

2.1 Introduction

The Literature Review will introduce the reader to the history surrounding Climate Change and Global Warming, the impact of the human species on the planet, the controversies that surround the ongoing debate and what challenges the global community faces and what it is prepared to do to manage the potential consequences.

Much of this debate is in the public arena and has become politicised, with different factions in different countries arguing for and against the whole concept of Global Warming/Climate Change, whether it is a phenomenon influenced by us, whether it exists at all, the economic impact on the undeveloped countries vying for parity with the developed world.

Even when governments acknowledge the problem and resolve to address it, there are arguments and opinions with regard efficient and cost-effective solutions, the use of emerging technologies versus existing and historically hazardous solutions, whether there should be investment in new research to develop non-polluting, green technologies and even where they can be built in order not to blight the existing landscapes.

Ultimately, knowing whether or not an industry or activity is polluting and potentially contributing to emissions believed responsible for Global Warming/Climate Change has to be the starting point, and this paper sets out to do exactly that for fires.

2.2 History

The relevance of any model to predict Carbon emissions from fires in the built environment must been seen in the context of studies into Climate Change/Global Warming, and that can only be fully understood by acknowledging the history of the research into it.

It is possible the most significant example of climate change in the Earth's history was as a result of the meteor strike. Called the "Alvarez Hypothesis" it presents evidence that a meteorite struck the earth around 66 million years ago with over a billion times the energy of the atomic bombs dropped on Japan, causing a catastrophic impact on the climate, with large temperature drops, Tsunami, firestorms and persist dust clouds blocking out the sun (18). Whilst there are references to understanding terrestrial impacts on local climates attributed to Theophrastus, a student of Aristotle, recorded research into climate science begins in earnest in 1788, when James Hutton published his book Theory of the Earth (4) in which he described past glacial activity in places too warm for glaciers in modern times. This was the first steps in acknowledging that global climates had changed.

The 1883 eruption of Krakatoa in Indonesia was also credited with chaotic climate conditions which persisted for up to 5 years, including an increase in cloud cover which reflected the sun's rays resulting in the global temperature dropping.

In 1827, Fourier described the "greenhouse effect" in his article Memoire au les Temperatures du Globe Terestre et des Espaces Planetaire (5). In 1856, Eunice Newton Foote had her paper about the Circumstances affecting the heat of the Sun's Rays (6) presented to the American Association for the Advancement of Science, in which she describes how Carbonic Gas Acid (Carbon Dioxide) increases the warming effect of the sun's rays.

Then in 1896 Svente Arrhenius (7) publishes an article in which he describes human induced climate change, going on to say that halving Carbon Dioxide levels would lead to an ice age, whereas doubling it would lead to a temperature increase of between 5 to 6 ^{o} Centigrade.

At the turn of the Twentieth Century and with more sophisticated methods, scientists connected Geological strata and tree rings with Climate Change. Solar Climate connections were made in the 1920s and 1930s, as scientists concluded solar variations and sunspots were the cause of climate change. However, this theory was largely rejected by the end of the 1930s.

By the 1950s with improved instrumentation scientists found increasing evidence that it was indeed Carbon Dioxide that was the pre-eminent factor in atmospheric warming, with some projecting a 25% rise by the year 2000, with radical consequences for the climate. In 1960 Charles David Keeling presented the Keeling Curve (8), a graphic representation of rising Carbon Dioxide levels based on continuous readings since 1950 at the Mauna Loa Observatory in Hawaii. In 1968 Stanford University Professor Paul R. Ehrlich (9) wrote "we cannot predict what the overall climatic results will be of our using the atmosphere as a garbage dump." An acknowledgement that the problem was of our own making and the potential political and economic consequences it could deliver.

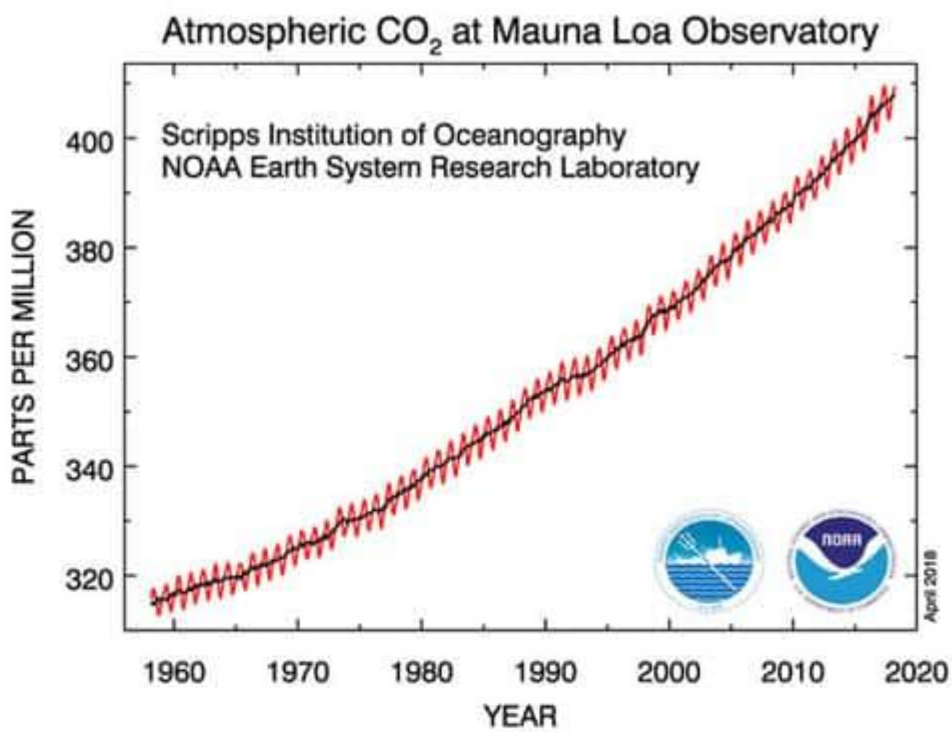


Figure 1 - The Keeling Curve. Charles David Keeling's graphic representation of rising Carbon Dioxide levels.

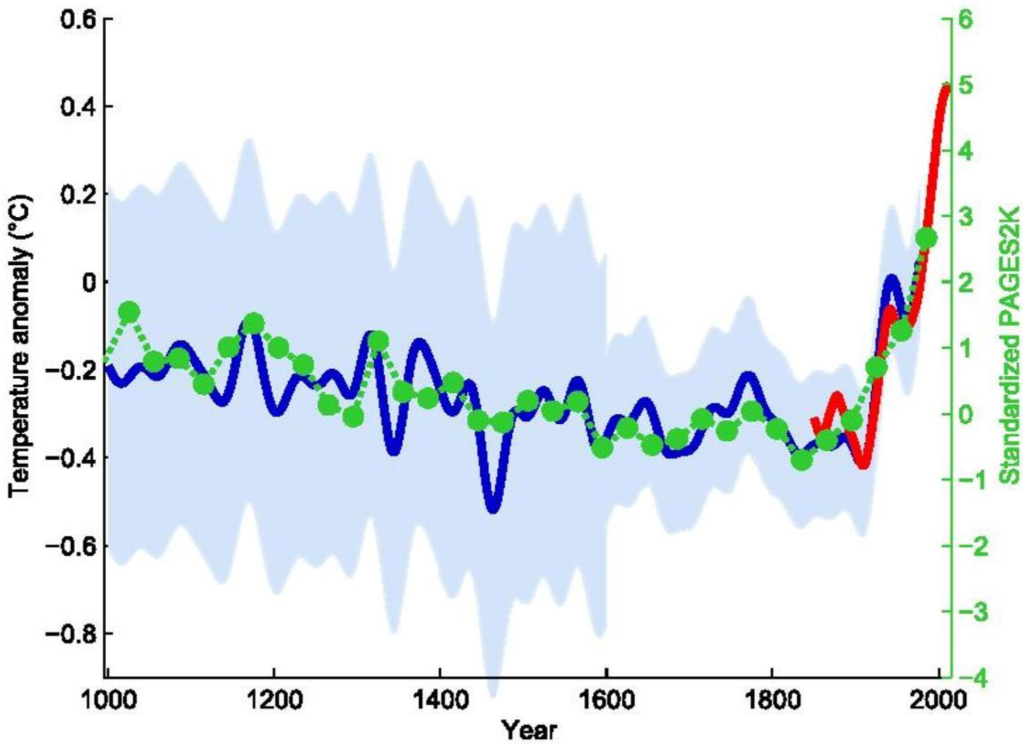


Figure 2 - The Hockey Stick Graph.

Climatologist Jerry Mahlman coined the term to describe the pattern of the global temperature record for the last millennium based on reconstructions by Mann, Bradley and Hughes; 1999, Northern Hemisphere Temperatures during the last millennium; Inferences, uncertainties and limitations. Geophysical Research Letters, 26 (6). It shows a relatively slow rate of cooling with a rapid warming in the twentieth century.

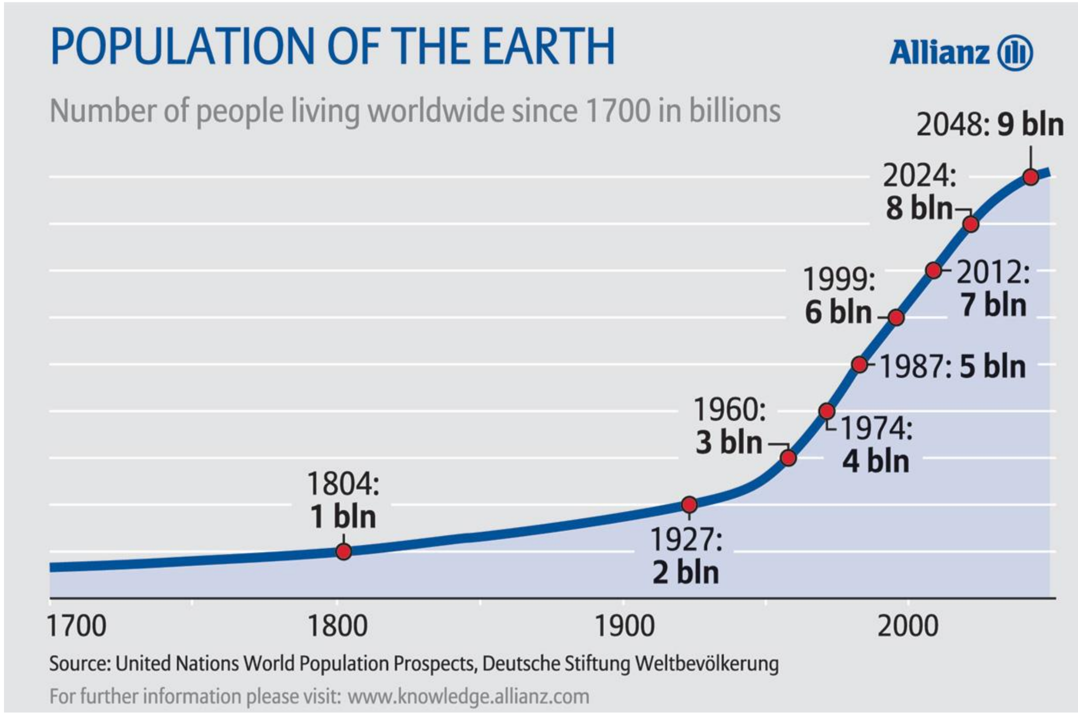


Figure 3 - The historic and projected population growth rate, with a rapid increase in population in the twentieth century.

2.3 The issue becomes controversial and global

NATO created a research hub in 1969 to deal with issues such as Acid Rain and the Greenhouse Effect, a potential precursor to the Intergovernmental Panel for Climate Change. During the period 1965 to 1979, a survey of the scientific literature found 7 articles predicting climate cooling versus 44 predicting climate warming (10), inevitably the latter were more widely discussed but it demonstrated there was not absolute consensus within the scientific community. Inevitably, this caused confusion and scepticism amongst the general public and when Newsweek magazine published an article by Peter Gwynne (11) about the evidence of global cooling being so strong that "meteorologists were having a hard time keeping up with it" followed by an almost immediate retraction the public could be forgiven.

In February 1979 the World Climate Conference, organised by the World Meteorological Organisation in Geneva (12) made an "Appeal to Nations" to "take full advantage of man's present knowledge of climate, take steps to improve significantly that knowledge, and foresee and prevent potential man made changes to climate that might be adverse to the well-being of humanity."

In 1982, ice cores drilled in Greenland demonstrated that dramatic climate changes could be seen in a human lifetime and work on Chlorofluorocarbons suggested that CFCs along with Methane and Carbon Dioxide would see global warming arrive in half the predicted time scale (13). In 1988 the World Meteorological Organisation and the United Nations Environment Programme established the Intergovernmental Panel for Climate Change, its remit to survey and peer review existing literature to provide an objective and balanced view (14). The IPCC produces an assessment report every 5 to 6 years.

In 2006, the film "An Inconvenient Truth" was released to document the campaign by former Vice President of the United States of America Al Gore, winning two Academy Awards for best documentary and is widely acknowledged as raising public awareness, including its controversial inclusion in school curriculums (39).

2.4 Kyoto

The Kyoto Protocol is probably the most well known and most often cited two words associated with the international climate change debate, but it is only a stepping stone along the path, albeit a significant one. In 1992, the United Nations Framework Convention on Climate Change was signed by 197 countries, including all member states of the United Nations and the European Union. Its objective is to "stabilise greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (15). The sets non-binding limits on emissions and has no enforcement powers but creates specific treaties or "protocols" to define how the Framework Convention objectives can be met. In 1997 the Kyoto Protocol was adopted, but not by everyone.

Kyoto applies to the six greenhouse gases; Carbon Dioxide, Methane, Nitrous Oxide, Hydrofluorocarbons, Perfluorocarbons and Sulphur Hexafluoride, and Water Vapour. It also acknowledges the responsibilities and abilities of countries to combat climate change. In other words, since the developed countries are largely responsible for the problem, they are largely responsible for fixing it. Following ratification by the minimum of 55 signatories, Kyoto came into force in 2005. The protocol set time periods for the signatories to comply with the targets set for them; the first reporting period was 2008 to 2012 and second round targets, known as the Doha Amendment, were established for 2012 to 2020. In 2015, the Paris Agreement set targets for 2020 and beyond.

2.5 Common goals

Although the Kyoto Protocol was signed by 197 countries, the United States of America refused to ratify it on the basis that it had an energy crisis and it would suffer disproportionately compared to emerging economies. The USA has further declared it will withdraw from the Paris Agreement. Canada withdrew from the Kyoto Protocol objectives and Russia has not adopted any second round targets. On the positive side, France has determined to ban the sale of all petrol and diesel cars by 2040, and coal will no longer be used to generate electricity after 2022. Norway will ban the sale of petrol and diesel cars by 2025, and Netherlands will do the same by 2030.Unfortunately, the entire process is based on the belief that the major polluters will voluntarily reduce their emissions but so far none of the stated targets have been met (16). The lack of an enforcement mechanism has been criticised and that only a Carbon Dioxide tax would force down emissions to meet the stated objectives of the Framework Convention (17).

2.6 Doubts

There are many within the scientific community who are sceptical, citing previous climate change evidence in the geological record, the unpredictability of the climate and the use of computer modelling to predict something so complex. Philip Stott, Emeritus Professor of Biogeography at the University of London, summed up his thoughts; "will cutting carbon dioxide produce a linear, predictable change in climate? No, in something as complex, non-linear and chaotic as climate not doing something is as unpredictable as doing something" (19).

A former President of Greenpeace Canada, Patrick Moore, has added his voice to the scepticism lobby by suggesting the environmentalists "abandoned science and logic in favour of emotion and sensationalism (20).

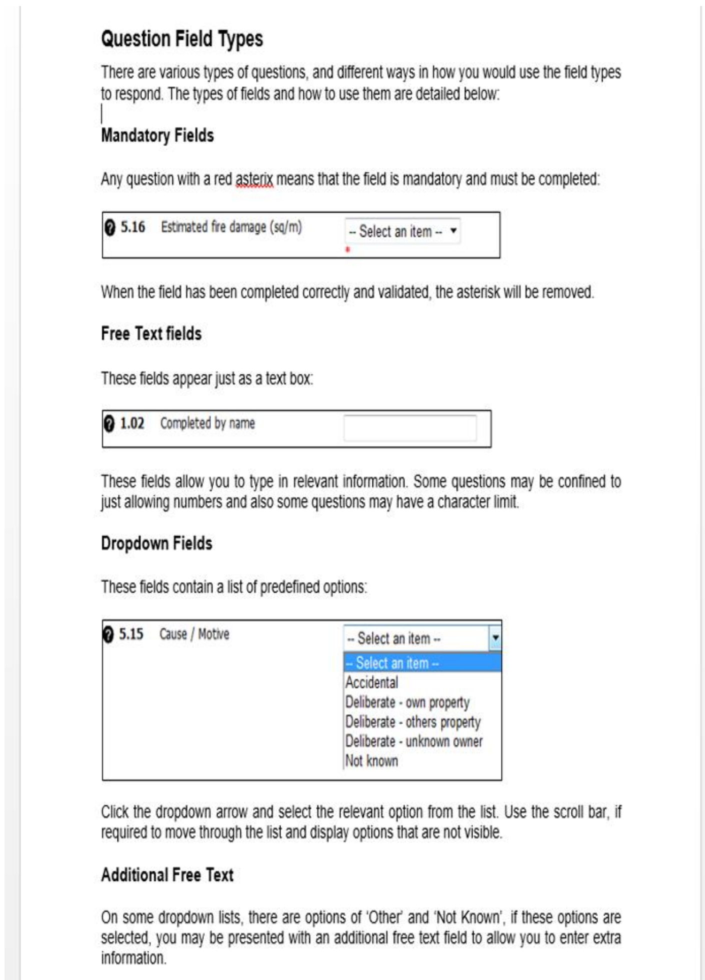
In 2009 “Climategate”, a term coined by a Telegraph journalist, was the result of emails and documents from the Climate Research Unit, one of the world's leading climate change institutes based in the University of East Anglia, being hacked and published weeks before a summit in Copenhagen (21). The published material was used to suggest that climate change was a scientific conspiracy and that data had been deliberately manipulated. In spite of denials from the CRU, climate change opponents have pointed out inconsistencies and exaggerations in both the data and findings. That said, there are also critics that say the IPCC underestimates the problem. Either way, there is ongoing research or mounting evidence from which a clearer picture of the health of the planet and the effect that the human species has on it can be drawn.

2.7 Current position

Only through research and evidence will the political mood change. In early October 2018, the Intergovernmental Panel on Climate Change, the IPCC, issued a report following three years of research, that the agreed target of limiting temperature rise to 2 Degrees Centigrade above pre-industrial levels this century at the Paris Agreement in 2016 is now likely to be missed and efforts are “off track” to the extent that we are heading for a rise of 3 Degrees Centigrade in the same time frame, and that the “guard rail” of 1.5 Degrees Centigrade rise will be missed as soon as 2030.

2.8 The Fire and Rescue Services’ Incident Recording System (IRS)

In 2009 the Department for Local Government and the Communities introduced the electronic Incident Recording System, to "modernise the collection and subsequent statistical handling and publication of incident data from the Fire and Rescue Service"(22). This is the only means used by United Kingdom Fire and Rescue Services to record the incidents they attend and the particular details of who and what was involved, where, when and how did it happen. It presents the investigating officer with a menu of exhaustive options from which to pick all of the details that can be analysed in order for Fire and Rescue Services to develop Integrated Risk Management Plans, the Corporate Plan to resource and manage the risks relevant to each service.



Question Field Types

There are various types of questions, and different ways in how you would use the field types to respond. The types of fields and how to use them are detailed below:

Mandatory Fields

Any question with a red asterix means that the field is mandatory and must be completed:

5.16 Estimated fire damage (sq/m) -- Select an item -- *

When the field has been completed correctly and validated, the asterisk will be removed.

Free Text fields

These fields appear just as a text box:

1.02 Completed by name

These fields allow you to type in relevant information. Some questions may be confined to just allowing numbers and also some questions may have a character limit.

Dropdown Fields

These fields contain a list of predefined options:

5.15 Cause / Motive -- Select an item --

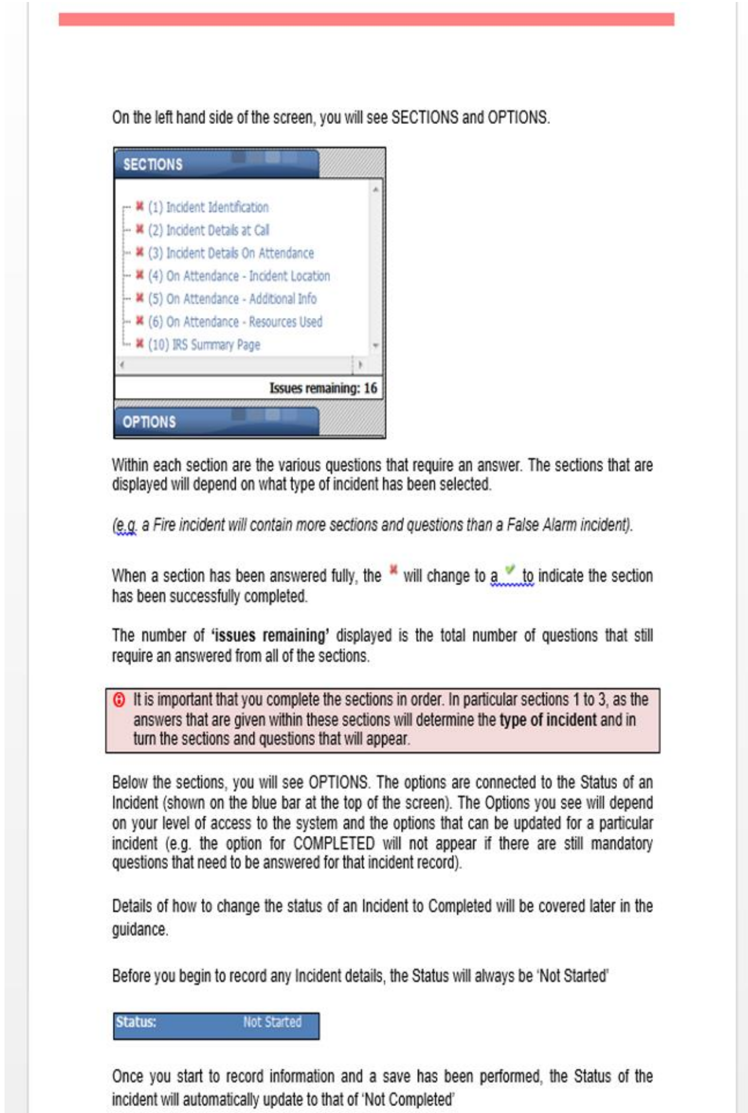
-- Select an item --
Accidental
Deliberate - own property
Deliberate - others property
Deliberate - unknown owner
Not known

Click the dropdown arrow and select the relevant option from the list. Use the scroll bar, if required to move through the list and display options that are not visible.

Additional Free Text

On some dropdown lists, there are options of 'Other' and 'Not Known', if these options are selected, you may be presented with an additional free text field to allow you to enter extra information.

Figure 4 - Some of the required questions in the IRS.



On the left hand side of the screen, you will see SECTIONS and OPTIONS.

SECTIONS

- (1) Incident Identification
- (2) Incident Details at Call
- (3) Incident Details On Attendance
- (4) On Attendance - Incident Location
- (5) On Attendance - Additional Info
- (6) On Attendance - Resources Used
- (10) IRS Summary Page

Issues remaining: 16

OPTIONS

Within each section are the various questions that require an answer. The sections that are displayed will depend on what type of incident has been selected.

(e.g. a Fire incident will contain more sections and questions than a False Alarm incident).

When a section has been answered fully, the will change to a to indicate the section has been successfully completed.

The number of **'issues remaining'** displayed is the total number of questions that still require an answered from all of the sections.

It is important that you complete the sections in order. In particular sections 1 to 3, as the answers that are given within these sections will determine the **type of incident** and in turn the sections and questions that will appear.

Below the sections, you will see OPTIONS. The options are connected to the Status of an Incident (shown on the blue bar at the top of the screen). The Options you see will depend on your level of access to the system and the options that can be updated for a particular incident (e.g. the option for COMPLETED will not appear if there are still mandatory questions that need to be answered for that incident record).

Details of how to change the status of an Incident to Completed will be covered later in the guidance.

Before you begin to record any Incident details, the Status will always be 'Not Started'

Status: Not Started

Once you start to record information and a save has been performed, the Status of the incident will automatically update to that of 'Not Completed'

Figure 5 - Sections and Options within the IRS.

The IRS requests information about an incident in a logical sequence, and it is relevant to set out what information is collected at the scene;

Section 1. Incident identification; details of the unique Incident Number, the date and time, who attended the incident, including which Fire and Rescue Service, the fire appliance call sign and the Officer in charge.

Section 2. The incident details at call; this includes the time and date of the call to the fire service, the caller's identification and phone number, and the type of incident described by the caller.

Section 3. The incident details on attendance; this is information that begins to be collected as the Officer in charge assesses the incident and sends messages back to the Fire Control. This information will be in the form of either Informative messages, or Assistance messages. It requires details on the type of incident such as Fire, Special Service (that is, non-fire emergency such as a Road Traffic Accident), a False Alarm or other incident type. It also requires information about casualties and rescues.

Section 4. This is the part detailing the exact location of the incident.

Section 5. Additional Information; how was the fire discovered and whether or not there was a fire alarm. Whether anyone was in the building and if it is normally occupied and some brief information about the likely cause.

Section 6. Resources used; including how many and what type of fire service vehicles and equipment was used to resolve the incident.

Section 7. Action; what actions were taken by any members of the public prior to the arrival of the firefighters, and then the subsequent action when they arrived.

Section 8. Damage; how the fire started, including whether or not it was accidental or deliberate, any dangerous substances involved or explosions, information about the premises, including the dimensions of the property, the room or compartment of origin, whether or not drugs or alcohol were factors, and the extent of fire, heat and smoke damage.

Section 9. Involvement of persons; how many were rescued, the extent of their injuries and what treatment was provided at the scene.

Section 10. Summary Page; this is the opportunity to use free text to describe the scene and provide detail of any subsequent actions post fire, such as community reassurance.

Section 11. Cost benefit analysis questionnaire; a subjective assessment of whether or not the actions of the Fire and Rescue Service save a life or property.

The IRS is comprehensive but is limited by the skill and experience of the investigator to be able to determine the origin and cause of the fire, and also the area of damage by fire is blocked in areas such as 0-5, 6-10, 10-20 metres squared.

2.9 Greenhouse Gases

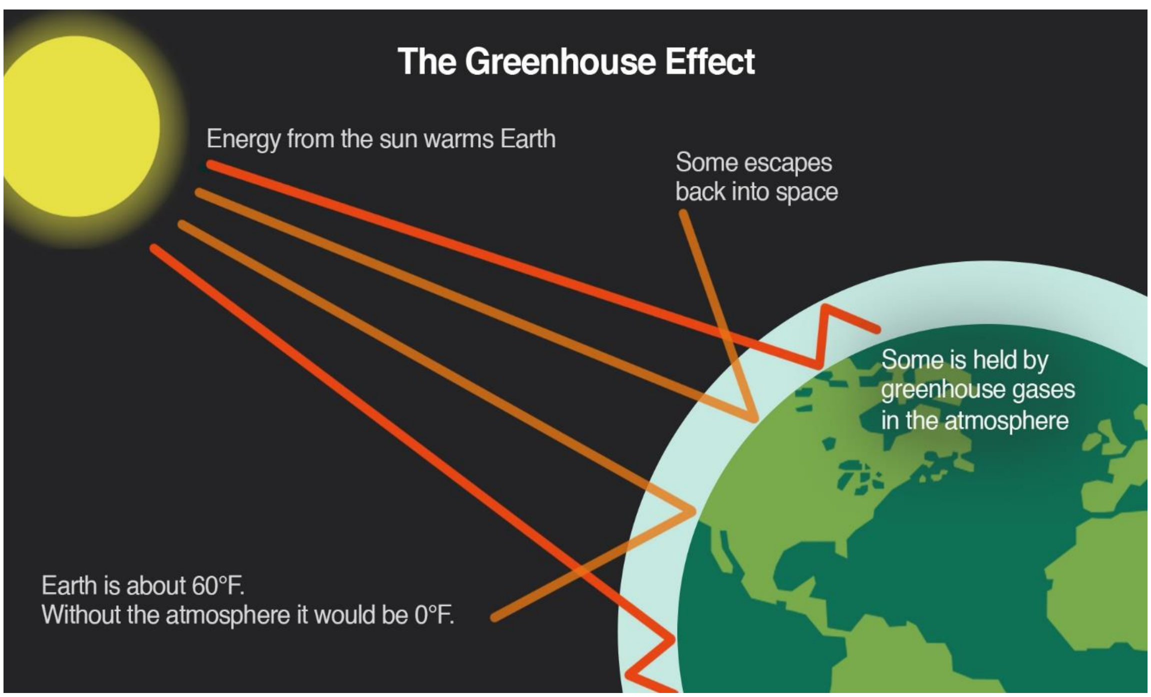


Figure 6 - The Greenhouse Gas Effect. From the World Meteorological Organisation Annual Greenhouse Gas Bulletin, October 2016, 60 ° Fahrenheit is 15.5 ° Celsius, and 0 ° Fahrenheit is – 18 ° Celsius.

Figure 6 above shows how the atmosphere traps some of the reflected energy from the sun. Greenhouse gases increase the ability of the atmosphere to trap that energy, therefore increasing the atmospheric temperature.

In order of the most abundant in the atmosphere, the "Greenhouse Gases" are; Water Vapour, Carbon Dioxide, Methane, Nitrous Oxide, Ozone, Chlorofluorocarbons and Hydrofluorocarbons.

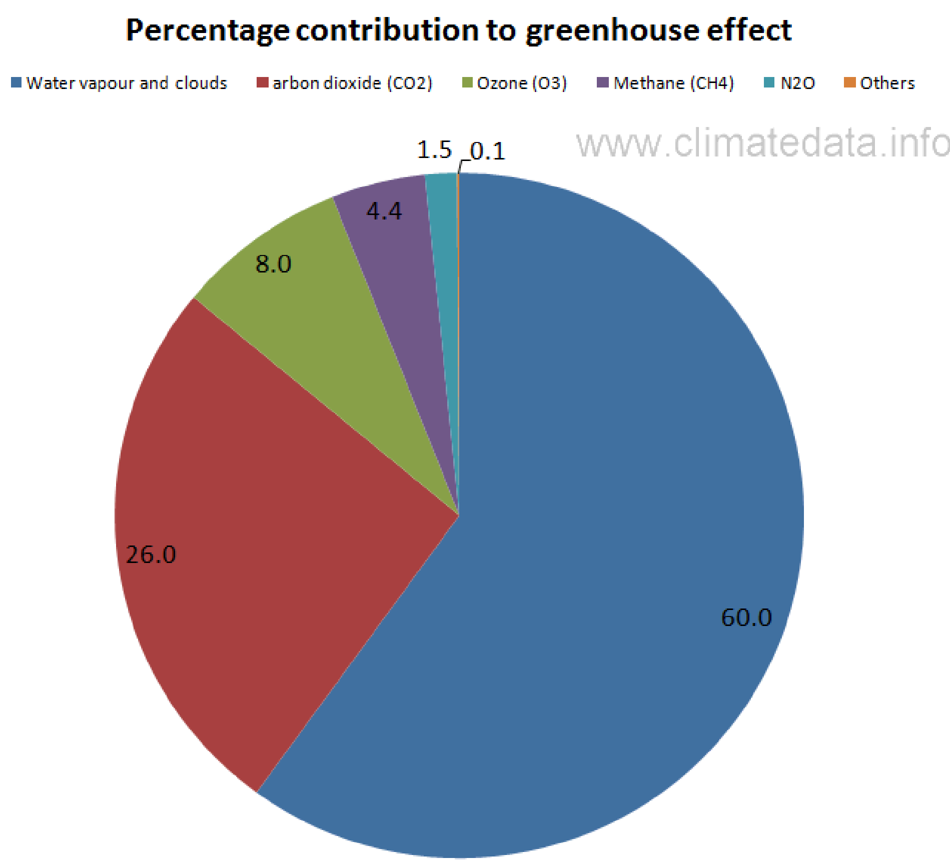


Figure 7 – Percentage contribution of gases to the greenhouse effect

Figure 7 shows the five major Greenhouse gases by percentage proportion. Chlorofluorocarbons and Hydrofluorocarbons are included in others. The figure is a guide only and is based on Kiehl and Trenberth, Earth's annual global mean energy budget, Bulletin of the American Meteorological Society, Vol 78 No 2, 1997.

2.10 Water Vapour

Water Vapour is by far the dominant Greenhouse Gas but it is largely a natural phenomenon.

The presence of water vapour in the atmosphere is directly related to the atmospheric temperature. In other words, the warmer the atmosphere the more water vapour and vice versa. A clear evening in spring or autumn will produce a drop in temperature possibly resulting in a morning frost, whereas a cloudy evening will trap heat and keep temperatures higher.

Therefore, if another agent causes an increase in atmospheric temperature, in this case Carbon Dioxide, more water evaporates which in turn increases the atmospheric temperature further. This is referred to as a "positive feedback" and might double the warming effect of Carbon Dioxide.

Water Vapour is also a short lived Greenhouse Gas in that water vapour falls as rain and snow as the amount held in the atmosphere varies over a period of hours and days as a result of the prevailing weather conditions.

2.11 Carbon Dioxide

Carbon Dioxide, however, is removed from the atmosphere over much longer time scales. Most sources of Carbon Dioxide are natural and they are countered by natural Carbon Dioxide sinks; for example the natural decay of organic material in forests, grasslands and the emissions from forest fires is balanced by the absorption of Carbon Dioxide by photosynthesis of new plant growth. Unfortunately, the balance has been affected by the apparent increase of Carbon Dioxide emissions as a result of human activity.

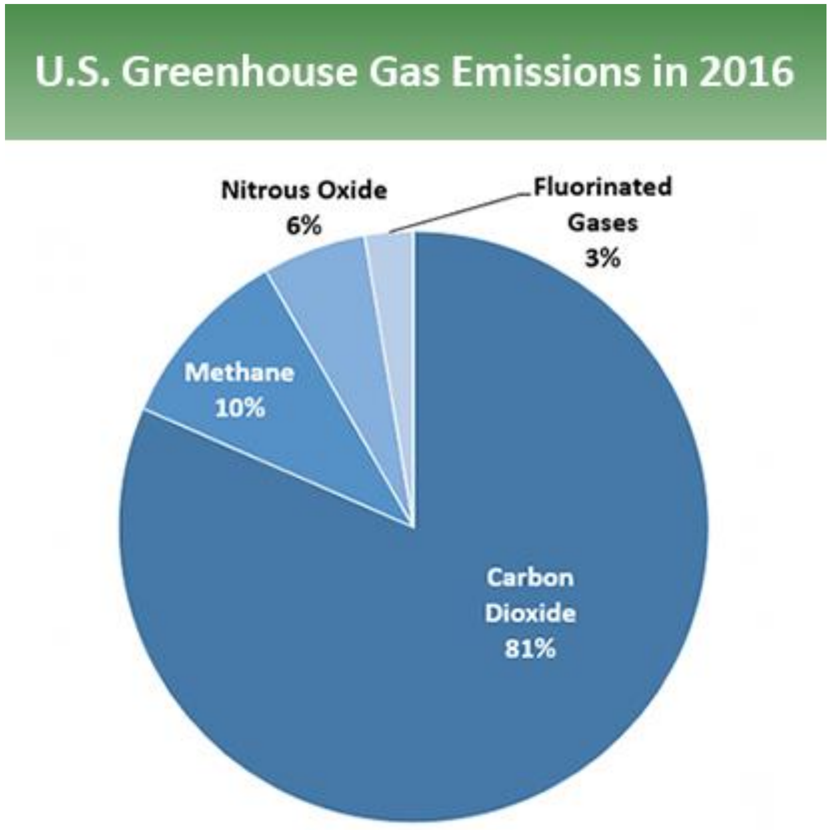


Figure 8 - Removing Water Vapour from the emissions.

It is clear from this diagram from the U.S. emissions in 2016, that Carbon Dioxide represents the largest contribution to the Greenhouse Gases total. United States Environmental Protection Agency Overview of Greenhouse Gas Emissions 2016.

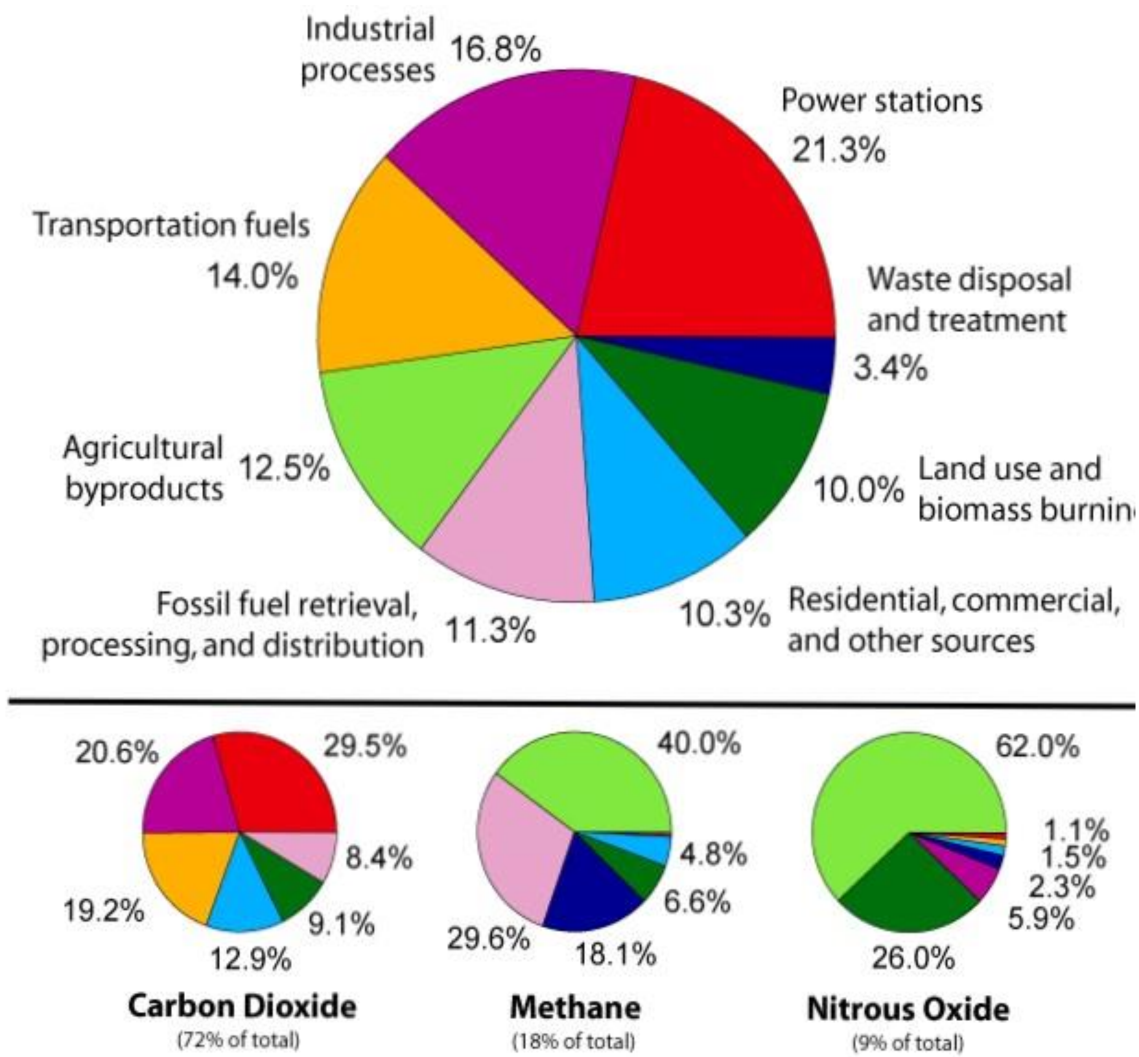


Figure 9 - Contribution of anthropogenic sources of the major Greenhouse gases

Figure 9 represents the contribution of anthropogenic sources of the major Greenhouse gases, by percentage and by sector. For example, 21.3 % of the total emissions were created by power stations which in turn was responsible for 29.5 % of the total Carbon Dioxide emissions. European Union Emissions Database for Global Atmospheric Research (EDGAR) 2000.

2.12 Methane

Methane is the next significant Greenhouse Gas. Although short lived in the atmosphere, it usually only lingering for about ten years, it is capable of trapping up to one hundred times more heat in the atmosphere than Carbon Dioxide although over a very limited period of time. Methane is the result of the use of fossil fuels in industry, transport and energy production and, importantly, the animal agriculture industry.

2.13 Nitrous Oxide

Nitrous Oxides, referred to as NOx, have almost three hundred times the heat trapping ability compared to Carbon Dioxide over a hundred year period, but because of its very low concentrations, its impact is only a third that of Carbon Dioxide. It is also implicated as the most significant ozone depleting substance, the substance that is layered around the earth's atmosphere and prevents the harmful Ultra Violet A and B waves from passing through, implicated in the increased levels of skin cancer. It has been estimated that 30% of the atmospheric NOx is as a result of human activity; an extremely efficient oxidiser for both rocket motors and internal combustion engines, aerosol propellant, medicinal use as an anaesthetic and pain relief, and more recently as a recreational drug because of the euphoria and hallucination effects. Natural events are occasionally responsible for significant atmospheric consequences. The Tunguska Meteorite of 1908 has been estimated to have produced 0.4 Teragrams (10^{12} grams) of Nitric Oxide in the lower atmosphere, causing acid rain over a vast are downwind for up to three months, because of the fast conversion of Nitric Oxide to Nitric Acid, before it fades away (40).

2.14 Chlorofluorocarbons and Hydrofluorocarbons

Chlorofluorocarbons and Hydrofluorocarbons are chemicals used ostensibly as refrigerants. CFCs were banned as a result of their ozone damaging properties and replaced by HFCs, however both are anthropogenic and have some impact with regards global warming.

2.15 Global Warming Potential and Atmospheric Lifetimes

The two most important factors in measuring Greenhouse Gases are 1. How much energy can they absorb and 2. How long do they persist in the atmosphere? The Global Warming Potential is a measure of those factors for a given gas, and the higher the GWP value the greater the ability of that gas to linger and absorb energy. Carbon Dioxide is the baseline as it persists in the atmosphere for thousands of years and, therefore, has a GWP of 1. This means that Methane, for example, with a 100 year GWP value of 28 (Figure 9) will cause 28 times more warming over a 100 year period than an equivalent mass of Carbon Dioxide.

Greenhouse Gas Global Warming Potentials and Atmospheric Lifetimes

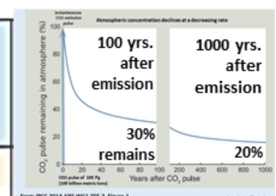
'The removal of all the human-emitted CO2 from the atmosphere by natural processes will take a few hundred thousand years' (IPCC 2014 WH1 Box 6.1)

15-20% of a CO2 emission will still be in the atmosphere in the atmosphere after 1000 years

Adapted from IPCC 2014 AR5
Appendix 8. A , Table 8.A.1

*No single lifetime can be given.

Chemical name	Chemical formula	Life time years	GWP 20 years	GWP 100 years
Carbon dioxide	CO2	see*	1	1
Methane	CH4	12.4	84	28
Nitrous oxide	N2O	121	260	265
Chlorofluorocarbons	2 examples			
CFC-11	CCL3F	45.0	6900	4,660
CFC-12	CCL2F2	100.0	10,800	10,200
Hydrochlorofluorocarbons	2 examples			
HCFC-21	CHCL2F	1.7	543	148
HCFC-22	CHClF2	11.9	5280	1760



Adapted from IPCC 2014 WG1 TFE.7, Figure 1

Peter Carter Climate Emergency Institute

Figure 10 – Greenhouse Gas Global Warming Potentials and Atmospheric Lifetimes (IPCC Climate Change 2014 Synthesis Report).

The table above provides a comparison of the Global Warming Potential, the relative measure of the ability of a greenhouse gas to trap heat in the atmosphere. It is part of the Kyoto Protocol and compares each gas to Carbon Dioxide with a GWP of 1.

2.16 The Carbon Cycle

The Carbon Cycle is the process by which the Carbon, essential for life on earth, is balanced within the Biosphere. Green plants remove Carbon from the atmosphere, where it exists as Carbon Dioxide, by Photosynthesis and processes it into protein, fat and carbohydrate molecules. Animals eat the plants, absorbing the Carbon as protein, fat and carbohydrates. Both plants and animals return Carbon into the atmosphere in the form of Carbon Dioxide, a result of respiration, the process by which carbon containing sugars and oxygen create energy for living. Both the plants and animals die and decay which provides the food source for microorganisms. Some of that decaying material is trapped and is effectively removed from this balanced cycle.

Humans, it is argued, have affected that balanced cycle in a number of adverse ways. An increase in agriculture, both animal and plant, in order to feed a growing global population, whilst at the same time deforesting huge areas of land to make way for industrial farming. Deforestation, especially in the tropical rain forests described as the “lungs of the planet”, removes the green plants which absorb atmospheric Carbon Dioxide, in favour of monocultures like rice and wheat which make up the vast majority of the worlds food supply, and for animal agriculture. The industrial methods which are used to farm these monocultures to not encourage biodiversity and the intensity to which they are farmed along with chemical additives to enhance yield does not allow for the land to be fallow and recover.

There is some speculation that, in spite of the high farming yields, half of what is grown is used to support animal agriculture, a food source predominantly for first world countries resulting in many human populations suffering starvation. The irony is that both animal agriculture is a significant contributor to atmospheric Carbon emissions in the form of Methane and, as global warming is expected to continue, the climatic changes will have a detrimental effect of those high intensity farmed monocultures.

Another way in which humans have altered the carbon cycle is the release of trapped Carbon in the form of fossil fuels. Decaying animal and especially plant material was trapped and fossilised and through the process of burial, heat and pressure, converted to the fossil fuels predominantly used for our energy supplies; oil, gas and coal. All of this “trapped” Carbon was removed from the carbon cycle millions of years ago but it has been released back into current cycles creating a surplus which the earth cannot manage due to the removal of much of its recycling capacity.

Carbon emissions are, therefore and rightly so, the main focus of the scientific community in terms of greenhouse gases and how best to manage their effects. There are a number of “headline” sectors that are responsible for the bulk of Carbon emissions; In the UK they are Energy supply, Business, Transport, Public, Residential, Agriculture, Industrial processes, Land use, land use change and forestry (LULUCF) and Waste management.

Previous research into Carbon Emissions from fires has been limited. In fact, the overwhelming research has focused on Wildfires, Forest Fires and Bush Fires. Ironically, emissions from these sources are part of the current Carbon Cycle and not directly responsible for increased emissions. Added to the fact that forest and vegetation is part of Carbon sequestration as a result of photosynthesis, it is frustrating to read that emissions from these sources are down by 90% in the United States of America, mostly as a result of removing the forests for agriculture and urbanisation.

2.17 Carbon Footprint Research

The only research directly relevant to this work was that done by Dr Jim Marsden in 2008 in a paper presented to the Chief Fire Officer's Association, entitled Fire and the Environment, Understanding Carbon Footprints. Much of the presentation covered changes to Carbon Footprints by redesigning buildings, vehicle fleets and the use of integral water suppression in buildings, such as sprinkler systems, not just to save life and property, but also to reduce the emissions from fire, including Carbon Dioxide and other toxic materials.

He also proposed the use of burn rates in grams of Carbon Dioxide per square metre per second, but this never progressed to a readily useable method to predict Carbon emissions from any fire because the ability to calculate the time of the burn and also allow for the growth and development of the fire, and the eventual decay, did not exist. He acknowledged at the end of that presentation that there had been “little research to estimate the amount of Carbon Dioxide emitted from fires”, hence the research for this piece of work.

2.18 Calculating emissions

The energy sector uses a conversion factor, revised in 2016, for each of Oil, Gas and Coal to estimate the mass of Carbon Dioxide per Terra Joule (1 x 10 ^{12} Joules) of energy produced. British Petroleum BP uses 73 300 kg CO_2 per TJ for Oil, 56 100kg CO_2 for Gas and 94 600kg CO_2 for Coal. This enables the Intergovernmental Panel on Climate Change to publish statistics that the energy sector is the largest Greenhouse Gas emitting sector at 25% (23).

The transport sector uses data about the amount of fuel purchased in the transport sector, the load miles covered, and the fuel efficiency of transport systems. Research in this way enables the IPCC to estimate that transport accounts for 14% of Greenhouse Gases (24).

Other methods are available online through the Carbon Trust, for example, which enables discreet industries and businesses to calculate their own carbon footprints (25).

3 METHODOLOGY

The initial ideas for the model were inevitably focused on the existing work undertaken by Dr Jim Marsden and his burn rate results. Dr Marsden produced a CO_2 factor of 53 grams/square meter/per second together with the area for several fire types; 6 m^2 for a car fire, 20 m^2 for a dwelling, 100 m^2 for a business and 4 m^2 for a rubbish fire. It was clear very quickly that there were several disadvantages to this approach; principally there was no feasible way to determine a time factor. There was no information about the time at which the fire started, although some times were recorded as part of the data gathering in the IRS, the "Time of Stop" was recorded. This time, however, was a message to the Fire Control to indicate that no further resources would be required, rather than the time the fire was extinguished. Nonetheless it was not possible to measure the length of time the fire had been burning.

Another issue was that the rate of burning is not a constant. Figures 11 and 12 represent fire development curves for ventilation controlled fires, that is where the air supply is determined by the volume of the compartment and any ventilation is as a result of failures to doors and windows as the fire develops, or efforts by firefighters to break into the compartment; the first is simplified to represent increasing heat output until the available oxygen in the compartment is depleted and the burn rate consequently stalls and then decreases. Then the Fire Service open the compartment and enter to firefight which ventilates the fire, resulting in a rapid increase in the burn rate, until the firefighters take control and begin to extinguish the fire.

Firefighters are trained to manage the risks associated with entering fire compartments, specifically the phenomenon of a Backdraught. In an under ventilated fire, if there is sufficient heat and fuel within the compartment but a lack of oxygen, any opening can create a situation where an over pressure of hot flammable gases escape and an under pressure of cooler air enters the compartment. The boundary between the hot gasses and cooler air is called the Shear Layer, and this is where the oxygen starved flammable gases and air combine to form a flammable mix. If the temperature is sufficiently high, the flammable mix ignites and causes a deflagration, an explosive event that is forced out, usually through the opening the firefighters have just made. Whilst a Backdraught is not annotated on Figures 11 and 12, if it is going to happen it will be soon after ventilation.

As is clear, there is no linear development for the fire and it is dependent on several factors; the size of the fuel package and the rate at which it can burn, the available oxygen to support that burn rate, whether or not the compartment is ventilated, the time at which the firefighting begins and how quickly an entry point, and therefore an air track for oxygen to reach the fire, is made before the fire is suppressed and finally extinguished.

The first diagram (Figure 11) is simplified but the second is a better representation of the complex nature of fire development and those factors, described above, that impact it. The second diagram (Figure 12) shows how a similar event can be interpreted in a different way depending upon the actions of the firefighters tasked with extinguishing the same or similar fire.

In this case, the fire has reached flashover conditions following the initial growth then decay phase. Again, ventilation by firefighters or a failure in a window has increased the ventilation and therefore oxygen supply to the fire resulting in flashover. The fire then reaches full development and flattens out before peaking again as a result of the roof ventilation, before finally decaying as a result of suppression by firefighters.

It would be challenging to recreate a fire growth curve for each incident that could then be averaged over time. Added to that the type of fire and the materials involved with varying burn rates. It is for these reasons that a burn rate approach to this problem was discounted.

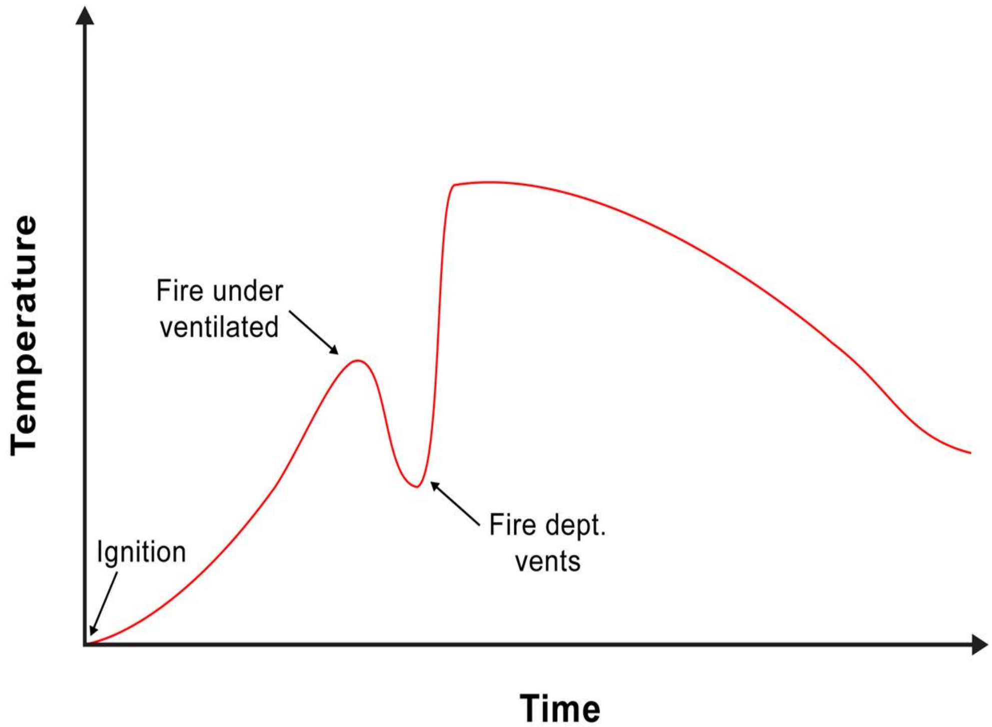


Figure 11 – Simplified fire development curve

Figure 11 shows a simplified fire development curve from the time of ignition to peak development and then decay due to limited availability of oxygen, before the firefighters enter the compartment allowing fresh oxygen in and the fire to rapidly grow before eventual extinguishment (National Institute of Standards and Technology, U.S. Dept of Commerce).

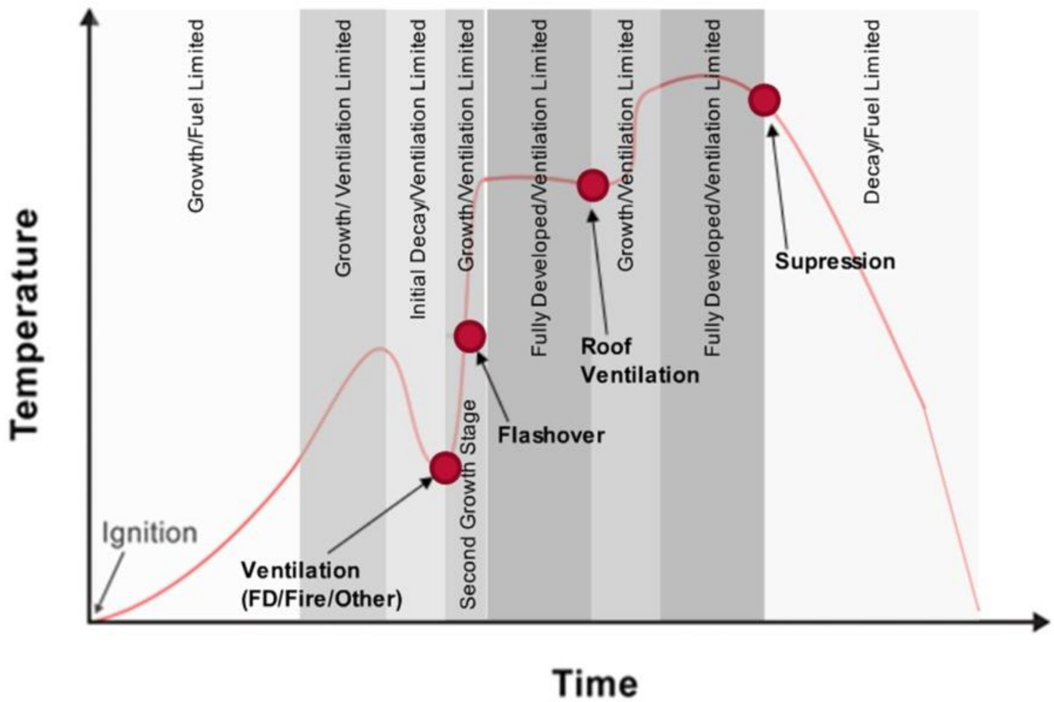


Figure 12 – More detailed fire development curve

Figure 12 provides a more sophisticated representation of fire development against time, explaining the stages and interventions throughout that timeline (Underwriters Laboratories Fire Safety Research Institute).

Another drawback would be evaluating the burn rates for the different materials involved in the fire. Unless the fire involved a homogeneous material, the relative proportions of wood, plastics, rubber, paper, foam and other materials comprising the fixtures and fittings in the compartment would need to be calculated. That would likely require burn testing and capture of CO_2 for each of those materials in a laboratory, something that wasn't available.

A possible solution to this was the Monte Carlo Method; repeated random sampling to produce a mean result, developed and used by scientists in the Los Alamos National Laboratory for the development of nuclear weapons during the Second World War (26). The Law of Large Numbers would mean the average would become close to an expected value as a result of repeating the same experiment a large number of times. This was excluded as an approach because of the availability and opportunity to conduct a large scale sample.

Further deliberations focused on what factors might affect the production and emission of Carbon Dioxide but also how it could be quantified? For example, could the “smoke” from small scale fires be captured and analysed for the constituents and somehow extrapolate those results to larger fires. What about the opacity of the smoke plume? Could the density of the smoke cloud be measured and the results used that to calculate the amount of CO2 contained within it? Each proposal was met with a negative answer; the skill set of the author was limited to basic chemistry and so the discipline of gas chromatography would not be an option, nor were there the resources and besides which there was no accounting of what might be burning in real fire situations. The density of smoke clouds could not be measured in real world conditions.

Another approach was to design a formula based on the influencing factors. The amount of CO_2 would have to be a function of the specific composition of the fuel and therefore its burn rate, the mass of the fuel, a time factor, an adjustment for the growth and decay in the fire development, the available oxygen supply dependent upon the size of the compartment and any ventilation. Time and the rate of development of the fire are factors that would need considerable testing, which was not a resource available to this study, and so this approach was not considered any further.

Eventually, after exhaustive consideration of countless possible, but ultimately fruitless ideas, a potential solution began to appear. First that not everything involved in fire releases Carbon Dioxide. This was a tentative adventure into organic chemistry, but it was apparent that CO2 is wholly dependent upon the Carbon content of what is burning and so it would be essential to know the source material. Second was that the only data collection for fires is by firefighters reporting incidents as part of the Incident Recording System, IRS.

Ultimately, the need to use the data gathered by the firefighters for the Incident Recording System, the need to keep the method simple due to limited resources narrowed the options to only one; a theoretical model based on the availability of Carbon, the type of fire and the area damaged.

The advantages were obvious; the model would be simple to develop and easy to explain to those who would be responsible for gathering and processing the data, the firefighters. There was a host of data already collected and reported to UK Government Fire Statistics by the UK Fire and Rescue Services year on year. The limits to the model would be the accuracy of the data gathered at the scene, but that would be consistent with every other approach to solving the question, as only the firefighters are responding to and reporting on every fire. There are other assumptions that are inherent, such as the area damaged that is input into the IRS would be damage as a result of complete combustion and all Carbon released during the combustion process. Another obvious limitation is that not every fire is reported and not every fire is dealt with by Fire and Rescue Services. Some fires burn out before they are seen either due to location, lack of fuel or oxygen or members of the public extinguish them without recourse to calling the Fire Service.

As a result, it was clear that burn rates was not the approach this work should take but rather a model based on the information that is already reported; namely the type of fire and how much was burned. This simple idea began to evolve; Carbon Dioxide is formed when Carbon and Oxygen join together and is, along with Carbon Monoxide, a by-product of the process of Combustion. Given that Oxygen was a pre-requisite of combustion, from the Triangle of Combustion, and that there was an abundance of it in the environment, all that was needed was the Carbon part of the process. Soon the simplicity of the idea began to dissolve when it became apparent that there was more to it than simply calculating the total amount of "stuff" that was burned. First of all, not everything that burns gives off Carbon Dioxide; there followed a crash course in organic chemistry, the study of the structure and properties of materials containing Carbon atoms, in order to identify the Carbon elements in fuels. Next was the issue that although there was lots of Oxygen available, there was also a significant amount of Nitrogen in ambient air, approximately 79 %, and whether or not it would play any role in this research. Then, of course, not everything burns completely and Carbon Monoxide, as already mentioned, is a normal by-product of every fire. So, although the foundation of a straightforward approach to tackling the objectives was beginning to evolve, there were still some significant questions to be answered.

Nitrogen

Nitrogen remains largely uninvolved in combustion until it reaches temperatures significantly over 1500 C and is completely unaffected at temperatures below 800 C. Most compartment fires commonly reach an average of 900 to 1000 C maximum, with flashover occurring over 600 C. With average temperatures of 900 to 1000 C, it is implicit that temperatures will peak much higher. The effects of compartment temperature on ambient Nitrogen is not in the scope of this study, however, it is assumed that the effect on the Nitrogen is limited and, as a result, Nitrogen can be disregarded as having an impact on Carbon Dioxide emissions in this study (27).

Carbon Monoxide

As a result of low temperatures and incomplete combustion, Carbon Monoxide is inevitably produced during combustion. In fact it is probably the most significant contributor to fire fatalities. From the point of view of this research, Carbon Monoxide is unstable and is short lived, with a life span of approximately one month, converting to Carbon Dioxide. As a result, for this study, Carbon Monoxide is assumed to stabilise as Carbon Dioxide and ignored (28).

After much time considering small scale material burn tests in a lab, to gas chromatography and somehow measuring the density of “smoke”, the study turned to the most prevalent investigative tool used for fires and the information required of it; The Incident Recording System, used by fire investigators to record incident data.

The IRS is the tool used by all fire officers who investigate and record the causes and damage as a result of fire, and it requires the investigator to record the type of fire, the location of the fire and the area of the fire. It does not require any assessment of how long the fire has been burning but rather the amount of material that has been burned.

As a result, the burn rate during the growth, fully developed and decay stages become irrelevant. All that needs to be established is how much damage has been caused by the fire to a known Carbon emitting fuel. So, in essence the model was to be constructed from a set of data that was already being collated as part of the investigation process for the fire report, and it would require no extra work on the part of the fire investigator.

The only thing left to consider was what had been burning in order to quantify the Carbon Dioxide emissions. This seemed straightforward as well until it was found within this study that not everything that burns contains Carbon. Welcome to the world of Organic Chemistry.

Rarely is a fire event subject to forensic investigation. Normally that is at the request of the Police investigating a crime, but occasionally the Fire and Rescue service will undertake an investigation as to the cause of the fire. Whilst it is incumbent on the investigating officer to establish a cause, it has no relevance to this work.

Although every fire is a unique event, there are a number of generic fire types that represent the vast majority of fires attended by Fire and Rescue services; house fires, normally specific rooms such as kitchens, lounges and bedrooms, car fires, rubbish outside and wheelie bins are some frequent types.

There was now the basis for a model that was sympathetic to the data collection and all that was needed was to establish the amount of Carbon content burned to determine the Carbon Dioxide emissions. This became the point at which the first theoretical assumptions had to be made. Using the generic fires as examples to establish a known Carbon content for each. Eventually a decision was reached that since rooms are essentially similar to other rooms that fulfil the same function and that the only difference would be size, a room factor could be created; for example, a bedroom contains a bed, a wardrobe and a dresser or chest of drawers, the only difference would be a larger bedroom would have either larger furniture or more of it and a larger bed than a smaller bedroom. The difference between a child's room and the parents' room. This would be the same for all room types, and even extended to commercial office spaces; the carbon content could be estimated for each type of room to include furniture, textiles including clothing and bedding, food for example. The beauty of this approach was that the area affected was part of the data set gathered.

Therefore, laboratory testing and sophisticated chemical analysis could be dispensed with and instead theoretical limits would be considered. Using the information required from the IRS and considering assumed Carbon content of materials burned, the model could be designed and the prototype was to be the Wheelie Bin.

4 CHEMISTRY and MODEL DEVELOPMENT

Having decided that a theoretical approach was the only way to progress this work, it was necessary to understand some principles of Chemistry and especially Organic Chemistry, the study of the properties, structure and reactions of materials containing Carbon.

It is fundamental to understand that not everything that burns will contain Carbon but only those that do will provide the Carbon to produce Carbon Dioxide. Combustion is a chemical process involving a fuel and oxygen that creates both heat and light. The process of combustion is often described using the Fire Tetrahedron.

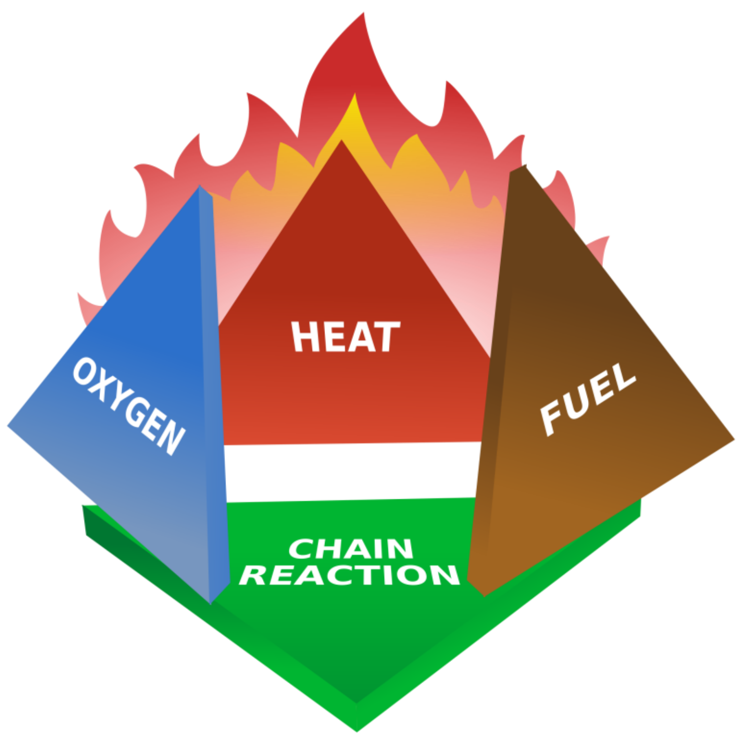


Figure 13 - The Fire Tetrahedron and the relationship between heat, oxygen and fuel and the chain reaction that defines Combustion.

Combustion is defined as the reaction between oxygen, fuel with sufficient heat to thermally decompose the fuel to release the flammable vapours, and the uninhibited chain reaction that continually generates heat to release more flammable vapours from the fuel.

For this model the limiting factors are the amount of Organic, or Carbon-based fuel, and the extent of the fire damage until suppression by firefighters.

During combustion, molecules of fuel and oxygen are energised and collide. In doing so they give up and exchange electrons, changing the original molecules into something else. Some energy is left over which is transformed into heat and, if hot enough, light.

For combustion involving an organic molecule, wood for example, the energetic reaction between the wood and the oxygen results in the production of carbon dioxide and water, assuming the combustion process is complete, along with some heat and light energy. This is referred to as a stoichiometric combustion reaction, where the total mass of the reactants is equal to the total mass of the products, thereby obeying the law of conservation of mass.

This Stoichiometric reaction can be easily demonstrated by using Cellulose, the chemical compound that is paper and wood. Cellulose is a molecular compound of Carbon, Hydrogen and Oxygen. It has 6 molecules of Carbon, 10 molecules of Hydrogen and 5 molecules of Oxygen. It is written;

$$\mathbf{C_6H_{10}O_5}$$

The reaction with Oxygen is then described in the formula;

$$\mathbf{C_6H_{10}O_5 + 6\ O_2 = 6\ CO_2 + 5\ H_2O}$$

This is a balanced equation that assumes complete combustion, therefore there are 6 molecules of Oxygen required to combust 1 molecule of Cellulose, and the reaction changes those molecules, through the application of sufficient heat, to 6 molecules of Carbon Dioxide and 5 molecules of Water, actually Water Vapour.

As already described, this formula represents complete combustion, that is all of the reactants are fully involved and altered in the process. In reality, complete combustion rarely happens for the reasons previously described; the growth curve of a fire starts with a slow burn rate, accelerating to a peak level before decay as a result of a lack of oxygen. Then a ventilation event occurs, possibly a window failure or the actions of fire crews entering the compartment, which re-oxygenates the fire. The fire reaches a new peak intensity before the effects of suppression tactics by the firefighters eventually extinguishes the fire.

This results in particles of unburned material and Carbon Monoxide mixed with the Carbon Dioxide and Water Vapour to produce "smoke". When the Oxygen supply is limited and temperatures are also limited, Carbon is not completely oxidised and presents as solid particles, or soot, in the smoke. With limitless quantities of Oxygen, the combustion process is unchecked and of such high temperatures normally, organic materials like cellulose are completely oxidised to Carbon Dioxide and water. Partial oxidation of Carbon also produces Carbon Monoxide, a colourless and toxic gas. It is the result of a limited Oxygen supply and is almost always produced in compartment fires and is the principle cause of fire fatalities. However, for the purposes of this study, Carbon Monoxide will ignored; it is short-lived in the atmosphere and, within a few months is converted to Carbon Dioxide. Similarly, for the portion that is estimated to have been damaged by fire, it will be assumed to have been completely combusted with no solid Carbon particles, or soot, deposited.

It is important at this point to address the issue of Nitrogen, the largest component of the air we breathe at approximately 79%. Nitrogen is an inert gas in the atmosphere at ambient temperatures but at high temperatures will react with oxygen to produces Nitrogen Oxides, referred to as NOx, a significant and damaging Greenhouse Gas. Temperatures need to reach

1600° Centigrade in order Nitrogen to participate in a molecular reaction with Oxygen to produce Nitrogen Oxide. Thermal conditions are the principal method of NOx production as a result of combustion. Two other conditions are described as Fuel and Prompt sources; the first is when Nitrogen-bearing fuels are combusted and Prompt refers to any condition not explained by either Thermal or Fuel sources (29).

Although other forms of Anthropogenic Nitrogen emissions result in the damaging Nitrogen Oxides, such as fertilisers, fossil fuel burning in industry and the internal combustion engine, the fact that the types of fire this work is interested in do not reach such elevated temperatures. In fact compartment fires flashover at approximately 600 Centigrade, the point at which all the available fuel within the compartment is ignited. This temperature is based on work by Dr Vytenis Brabrauskas, referenced in the previous chapter (30). Therefore it is safe to exclude any effects of Nitrogen on this work.

To determine the Carbon content of the fuel it is important to know how much carbon contributes to the fuel molecule. Having introduced Cellulose as the organic molecule in the balanced equation for combustion, it seems reasonable to use Cellulose to demonstrate how to do that.

The molecular formula for Cellulose is;

$$\mathbf{C_6\ H_{10}\ O_5}$$

Each atom has a relative atomic mass; Carbon is 12, Hydrogen is 1 and Oxygen is 16.

Therefore the molecular mass of Cellulose can be calculated as;

$$\mathbf{C\ (6x12) + H\ (10x1) + O\ (5x16) = 72 + 10 + 80 = 162}$$

In Cellulose, Carbon has a molecular mass of (6x12) = 72.

Therefore, Carbon represents 72/162 of the molecular mass of Cellulose, i.e. 44.44%.

For every 1 kilogram of Cellulose therefore, Carbon makes up 444.4 grams.

Carbon joins with Oxygen to form Carbon Dioxide as CO_2 i.e. one atom of Carbon joins with two atoms of Oxygen to form the compound Carbon Dioxide, the molecular mass of which is;

C (1x12) + O (2x16)

Carbon joins Oxygen to form Carbon Dioxide in the ratio 12 : 32 or 1 : 2.667.

Therefore 1 kg of Cellulose, when completely combusted, will produce;

444.4 + (2.667 x 444.4) = 1 629.61 grams or **1.6 Kg of Carbon Dioxide**

This method was then checked using the formula **Moles = Mass /Molecular Mass** and assuming stoichiometric balance due to complete combustion, and this gives the same result;

Combustion of Cellulose formula is C_6 H10 O_5 + $6O_2$ -> $6CO_2$ + $5H_2O$, assuming complete combustion.

Or 1 mole of Cellulose burns with 6 moles of Oxygen to produce 6 moles of Carbon Dioxide and 5 moles of water in the form of water vapour.

Equation states that for every mole of Cellulose completely combusted there is a yield of 6 moles of Carbon Dioxide, a ratio of 1 : 6, using 6 moles of Oxygen in the process.

Moles = mass / molecular mass.

The molecular mass of Cellulose is C (6x12) + H (10x1) + O (5x16) = 72 + 10 + 80 = 162

Therefore the number of moles of Cellulose is moles = 1000 g / 162 = 6.172

At a ratio of 1 : 6 the number of moles of Carbon Dioxide is 6 x 6.172 = 37.032

Re-arranging the formula, the mass of Carbon Dioxide = moles x molecular mass

The molecular mass of Carbon Dioxide is C (1x12) + O (2x16) = 44

Therefore, the mass of Carbon Dioxide produced for every 1000 g of Cellulose is 37.032 x 44 = 1629.4 g or **1.6 kg of Carbon Dioxide**.

5 APPLYING THE MODEL

A test of the model was to use it for a fire type routinely dealt with by Fire and Rescue Services. Continuing the theme of Cellulose as the principal organic material tested so far, the prototype for the model was a paper recycling Wheelie Bin.

The Wheelie Bin in question is a 240 litre household recycling bin used exclusively to recycle paper, cardboard and similar paper based waste, weighing 20 kilograms and made from PET plastic.

This was chosen as the prototype because it is exclusively filled with a homogeneous organic fuel, Cellulose. Some assumptions were necessary for the calculations; the wheelie bin and its contents were completely combusted, the contents are exclusively cellulose, the bin is only half-filled and an average density of paper/card was used.

Wheelie bins are never completely combusted, there is always some debris left at the end or the firefighters, or indeed householder, often intervene and extinguish the fire. The decision taken that the bin is only half-filled acknowledges that packaging is not always flattened, there are gaps within the bin due to shape and orientation of packaging placed inside. Finally, due to the variety of paper and card based materials that are recycled it was considered appropriate to use a mean density to represent that spectrum.

240 litres equates to a volume 0.24 m^3, which when filled with paper/card materials with a mean density of 800 kg/m^3, yields a potential organic mass of 192 kg.

Assume the bin is approximately half-filled, the available mass of organic fuel can be assumed to be 100 kg.

With a known proportion of Carbon with the Cellulose molecule of 42 %, the available carbon is estimated at 42 kg.

The plastic bin, 20 kg of PET plastic will yield 12.6 kg of Carbon (63 % of the plastic is Carbon).

Using the method described in Chapter Four, the mass of Carbon Dioxide from the bin fire will be;

(42 + 12.6) + 2.667 x (42 + 12.6) = 200.2 kg Carbon Dioxide.

Further types of fires were then included in the application of the model in order to build a wider and more representative sample of fires attended by the Fire and Rescue Services. They are as follows;

- Skips and Bonfires/Rubbish fires
- Cars.
- Compartment fires, further sub divided into kitchen, lounge, bedroom and offices

5.1 Skips

A 6 cubic metre skip was considered for this example, as a medium sized skip, half-filled due to voids and then halved again because of non-organic material. This leaves a potential Carbon source material of 1.5 m^3.

Again using a medium density paper/card figure of 800 kg/m^3, this assumes a mass of 1200 kg of organic material. At 42 %, this equates to 504 kg of Carbon, which in turn will yield

504 + 2.667 x 504 = <u>1 848 kg Carbon Dioxide.</u>

Figure 14 - Photograph of a typical skip fire

5.2 Cars

Using an "end of life" salvage estimate of the materials used in a car it is possible to identify the Carbon containing elements (31);

Over 70% of the weight of a vehicle is ferrous in the form of steel, 9% plastics, then 3% each glass and tyres, 2% rubber, and finally 1% each of electrical items, carpets amongst other things. From this list it is possible to identify the organic materials; rubber, tyres, carpets and plastics, representing about 15% of the mass of a vehicle.

Choosing a generic car to represent this section required some acknowledgement that cars come in various sizes; ranging from small cars weighing in at 900-1100 kg like a Fiat Punto, a Ford Focus between 1000-1400 kg, a BMW X5 at 1500-1800 kg and Estates and 4 wheel drive cars at over 3000 kg, but assuming most cars are in the hatchback/saloon category, the mass of the representative car was chosen to be 1500 kg.

76 % of a car's mass is steel and, although containing Carbon, it can be disregarded, because it does not decompose at temperatures experienced at car fires. That leaves 24 % non-steel components, and only 15 % containing Carbon, such as rubber, plastic and nylon. No account is taken of any fuel in the car.

So, using a medium sized car of 1 500 kg mass, the available organic material is 225 kg, yielding 162 kg of Carbon.

This in turn yields 162 + 2.667 x 162 = <u>594.05 kg Carbon Dioxide.</u>

Figure 15 - Photograph of a typical car fire

5.3 Compartment Fires

These are sub divided further into domestic type compartments, namely lounge, kitchen and bedroom; not only are these perhaps the most common domestic fire settings but between them they are probably representative of any room in a dwelling, and then the commercial setting, an office.

Each was considered in turn to assess the carbon yielding materials in each. Therefore, in turn;

5.3i Bedroom;

Approximately 5 x 5 metres squared contains

Bed Frame	Wood	100 kg	42 kg Carbon
2 x Side Tables	Wood	20 kg	8.4 kg
Wardrobe	Wood	50 kg	21 kg
Dresser	Wood	50 kg	21 kg
Mattress	PU Foam	50 kg	32 kg
Clothing	Cotton	100 kg	42 kg
Total Carbon Load			228 kg

Therefore total Carbon Dioxide yield for a 25 m2 Bedroom is 228 + 2.667 x 228 = 836 kg

Therefore the Bedroom factor is **33.44 kg CO2/m^2**

Figure 16 - Photograph showing aftermath of bedroom fire

5.3ii Lounge;

Approximately 5 x 5 metres squared contains

3-piece suite	Wood	100 kg	42 kg Carbon
	PU Foam	100 kg	64 kg
Shelving/Tables	Wood	150 kg	63 kg
Books	Paper	100 kg	42 kg
TV	PVC	5 kg	2 kg
Total Carbon Load			213 kg

Therefore the Carbon Dioxide yield for a 25 m^2 Lounge is 213 + 2.667 x 213 = 782 kg

Therefore the Lounge factor is **31.28 kg CO_2/m^2**

Figure 17 - Photograph showing aftermath of lounge fire

5.3iii Kitchen;

Approximately 5 x 5 metres squared contains

Units	Wood	500 kg	210 kg Carbon
Table/Chairs	Wood	100 kg	42 kg
Food	Starch	150 kg	63 kg
Total Carbon Load			315 kg

Therefore the Carbon Dioxide yield for a 25 m^2 Kitchen is 315 + 2.667 x 315 = 1155 kg

Therefore the Kitchen factor is **46 kg CO_2/m^2**

IsoButane, often referred to as R600a, is the common refrigerant used in modern fridges and freezers. Domestic appliances will have approximately 80g of the refrigerant stored in the compressor and circulation system (41).

IsoButane is C_4H_{10}, with carbon making up 83% of the molecular mass, at 66g. Therefore, the carbon dioxide yield from the refrigerant will be 66 + 2.67 x 66 = 242.2g, or 0.24kg. In comparison to the potential total carbon dioxide yield from a fully involved kitchen fire, measuring 25m², has been calculated at 1155kg, the contribution of the refrigerant is negligible.

However, it is worth noting that whilst the carbon dioxide yield is low, the potential contribution of IsoButane as a flammable gas to the development of the fire is significant.

Figure 18 - Photograph showing aftermath of a kitchen fire

5.3iv Office;

Approximately 4 x 4 metres squared contains

Desk	Wood	60 kg	25 kg Carbon
Chairs	Wood	40 kg	17 kg
Computers	PVC	40 kg	16 kg
Shelving	Wood	100 kg	42 kg
Paper	Paper	200 kg	84 kg
Total Carbon Load			184 kg

Therefore the Carbon Dioxide yield for a 16 m2 Office is 184 + 2.667 x 184 = 675 kg

Therefore the Office factor is **42 kg $CO2/m^2$**

Figure 19 - Photograph showing aftermath of an office fire

5.4 Testing the Model

Early on it was important to assess whether or not the model was able to generate results that could be scrutinized and also contextualized, that is compared alongside other reportable Carbon Dioxide emissions, in order to have some sense of perspective with regards the scale of the emissions from fires.

Using Incident Recording System data for fires in Greater Manchester from 2010;

There were 1433 reported Wheelie Bin fires.

Using the Carbon factor for Wheelie Bins this represents 1433 x 200.2 = 286.9 tonnes of Carbon Dioxide.

During the period 4/09 to 3/10 there were 1646 Car fires in GMFRS.

Using the Carbon factor for Cars this represents 1646 x 594.05 = 977.8 tonnes of Carbon Dioxide.

Using transport emissions as a comparator, the distance from Manchester to London is 163 miles and the following modes of transport have Carbon Dioxide emissions;

- Car 33.6 – 67.5 kg depending on engine size
- Train 14 kg
- Coach 4.9 kg
- Plane 45 kg

Therefore the 2010 fire emissions statistics suggest that:

- 1433 wheelie bin fires are comparable to 3188 return journeys by plane from Manchester to London
- 1646 car fires are comparable to 10 864 return plane journeys

6 LARGE SCALE AND UNIQUE INCIDENTS

The previous chapter demonstrated the model using volume fires such as wheelie bins, skips, cars and identifiable compartment fires such as kitchens and bedrooms, for example. However, the model needs to be relevant for those large scale, less common fires that do not easily fit into the aforementioned categories but yet still contribute to the carbon emissions within our built environment.

With that in mind the study has included two incidents that were significant; one was a national disaster that had Pan European consequences, and the second a prolonged incident in the city of Manchester, that impacted the lives of residents for two weeks. They are the fire at Buncefield Fuel Depot in 2005 in Hertfordshire and a fire in 2014 in Salford involving Refuse Derived Fuels. Both incidents were protracted, stretched the resources of the Fire Services and represented the type of incident that could be considered the polar opposite to those volume fires.

6.1 BUNCEFIELD

Buncefield, pictured in Figure 20, is situated near to the M1 motorway near Hemel Hempstead, was the fifth largest oil products storage depot in the UK. The site was split into three sections; Hertfordshire Oil Storage Ltd (HOSL) jointly owned and operated by Total UK Ltd and Chevron Ltd; British Pipeline Agency Ltd (BPA), a joint venture between BP Oil and Shell Oil UK; and a seperate BP Oil UK Ltd section.

These were "Top Tier" COMAH sites (Control of Major Accident Hazards Regulations 1999) and had planning consent to store 194 000 tonnes of hydrocarbon fuels (32).

Figure 20 - Buncefield Oil Storage and Transfer Depot before the explosion.

On Saturday 10th December 2005, unleaded petrol was being delivered to one of the storage tanks. The investigation concluded that automatic alarms that should have operated and stopped the delivery to tank failed, and so the level continued to rise. By the early hours on Sunday morning 11th December, unleaded petrol started to overspill the tank roof.

CCTV showed that a white vapour, a likely mix of hydrocarbon vapours and ice crystals, had spread to a diameter of 360 metres across the site and beyond. Witnessed by members of the public and tanker drivers on site waiting to fill their vehicles, the fire alarm button was pressed at 0601. This automatically started the firewater pump. The investigation concluded that this was the likely ignition source for the almost immediate Vapour Cloud Explosion.

Although there were no fatalities, over 40 people were injured and the fire, the largest in peacetime UK, engulfed 20 fuel tanks on the site. Figures 21-24 show the fire and resulting damage. The environmental, social and economic toll was considerable. The fire lasted five days but the long term impact is still being assessed by the Environment Agency as a result of pollutants, including fuel, firefighting foam and water, entering a potable water aquifer.

Figure 21 - The Buncefield Depot at the height of the fire

Figure 22 - One tank continues to burn whilst firefighting attempts are making progress

Figure 23 - The smoke plume seen from above

Figure 24 - The aftermath

Buncefield was an oil storage facility with a planning consent capacity of 194 000 tonnes of hydrocarbon products. Alkanes are the basis of all petroleum products and therefore the general formula of Alkanes is the root for the Carbon Dioxide calculation at this incident;

Alkane formula $C_n H_{n+2}$

Alkanes from Pentane C_5 to Octane C_8 are the most common molecules in petrol. To estimate the amount of Carbon Dioxide produced as a result of the Buncefield fire it is reasonable to use Octane as the specific alkane for this calculation. The specific formula for this calculation becomes;

Octane formula $C_8 H_{18}$

The proportion of Carbon in the Octane molecule is;

Molecular Weight is C (8 x 12) + H (18 x 1) = 114, with Carbon representing 96/114, or 84%

Therefore, using the model it is possible to estimate the Carbon Dioxide produced as;

(194 000 x 84%) + 2.667 x (194 000 x 84%) = 597 574 tonnes CO_2

6.2 DUNCAN STREET

Close to midnight on 3rd March 2014 firegighters from Greater Manchester Fire and Rescue Service attended a fire in a building containing approximately one thousand bales of Refuse Derived Fuel.

Figure 25 - The skyline of Manchester

The site, unknown to the Fire and Rescue Service, was believed to have been an unlicensed waste storage facility. Approximately one thousand one tonne plastic wrapped bales were stored in a single storey portal framed building, about 80 metres long and 20 metres wide close to the city centre of Manchester.

The blaze is likely to have started as a result of the particular properties of stored Refuse Derived Fuel (RDF). RDF can be defined as "selected waste and by-products with recoverable calorific value can be used as fuels replacing a portion of conventional fossil fuels if they meet strict specifications" (33). Effectively it was considered a way to recover energy from burning non-recyclable waste rather than sending it to landfill. With the introduction of a landfill tax in 1996, and the rising charge, from £8 per tonne in 1996 to £88.95 per tonne from 1st April 2018, RDF became an attractive option for waste management. Inevitably, with those rising costs, the incentive to store large quantities of RDF in often unseen locations were there.

The hazard, though, is the materials that are often included in the stored RDF. It is supposed to be combustible materials including non-recyclable plastics, paper, cardboard, and other corrugated materials with metals, stones, glass and other foreign materials processed out, to produce a pelletized homogeneous material that could be a substitute for fossil fuels. In fact, what was seen at Duncan Street was baled waste that included waste food, garden waste, biohazardous materials such as soiled nappies, and hardcore materials such as concrete blocks to add weight to the bales. All of this in addition to paper, card, plastics.

Figure 26 - Baled waste in the form found at the Duncan Street fire.

The consequence of the organic matter in the bales is that micro-organisms begin a process of anaerobic fermentation, in conditions where oxygen is not present. The result of this process is the production of Methane (34). That stored RDF can spontaneously ignite has been well documented and followed an explsion in a treatment plant in Japan that caused the death of 2 firefighters (35).

At Duncan Street it is likely the baled waste, stored 3 bales high inside the single storey building, had been fermenting for a significant time and eventually ignited as a resuklt of spontaneous combustion. Initially the fire was limited to one or two bales, but as the waste material was removed by means of an excavator, the bales were ripped open allowing Methane to be released and gather in the roof space. Eventually a flammable mix was achieved and, with a flaming fire as the ignition source, the entire building was engulfed in flames. It took two weeks to fully extinguish the fire.

Figure 27 - Early on in the fire at Duncan Street. The fire has broken through the roof of the storage facility

Figure 28 - The view inside

Figure 29 - The intensity of the fire and instability of the stacked bales meant that firefighters had to attack the fire defensively, from the outside

Figure 30 - The bales were stacked almost to the roof of the storage facility

Figure 31 - Damping down

The relative components of RDF have been studied and sampled. Below is a list of the various materials that make up a typical sample of RDF (36).

Paper & Cardboard	32%
Plastics, all types	22%
Food & Garden Waste	17%
Textiles	8%
Sanitary cellulose	4%
Metals	4%
Wood	3%
Other (brick, glass, footwear, soil, ceramics, Hazardous)	10%

Excluding Metals, Textiles and Other as containing little or no Carbon, it is possible to estimate the percentage of carbon in a sample of RDF.

The Carbon factors for paper/cardboard/wood/sanitary cellulose is 42%, Plastics 40%, Food & Garden Waste 42 %, A one tonne bale of RDF can be estimated as containing 323 kg of Carbon.

Therefore the potential Carbon Dioxide emission is;

$$323 + 2.667 \times 323 = 1\ 184 \text{ kg Carbon Dioxide per tonne bale.}$$

Approximately 1 000 bales of RDF were consumed in the fire at Duncan Street, yielding approximately:

1184 tonnes of Carbon Dioxide

7 RESULTS

Using the values developed for the model for the various volume fires, the Incident Recording System can be used to provide annual Carbon emissions for each. The IRS information for 2014-15 is the data set for the first calculations. With the cooperation of Greater Manchester Fire and Rescue Service Data Management Team, the emissions factors were added to the IRS. The full table can be found in Appendix 2014-15 Results, but the totals for reported fires in each category are as follows;

From 1st April 2014 to 31st March 2015, of the total 11 669 fire attended;

Wheelie Bins;	fires produced 185 800 kg
Small Fire in the Open;	fires produced 1 364 000 kg
Skips;	fires produced 676 368 kg
Kitchen Fires;	fires produced 1 214 630 kg
Bedroom Fires;	fires produced 268 167.5 kg
Office Fires;	fires produced 44 310 kg
Car Fires;	1 102 fires produced 654 643.1 kg
Total;	5 283 fires produced **4 571 678 kg**

Source; GMFRS IRS and UK Government Statistics for GMFRS 2014/5, www.gov.uk/government-data-tables-fire-aug2018.xlxs.

The model is able to predict the Carbon emissions from approximately 48% of all the fires attended by GMFRS that year. The remaining 52% are fires originated in other compartments, either domestic or commercial, other buildings such as sheds and garages and other outdoor fires, such as waste management sites and grass fires to name but a few. Effectively, anything that could not be classified as one of the fires listed above. It will also include those fires such as the ones described in Chapter Six, the large scale and unusual fires like Buncefield and Duncan Street.

The final total represents an estimation of the Carbon Dioxide emissions from 48% of the fires attended by GMFRS. This allows an estimation of an "average" fire, with 5 283 fires producing more than 4.5 million tonnes, it follows the average fire produces 865 kg of Carbon Dioxide.

There are clear limitations to this approach, in that there are more dwelling fires than other building fires, there are almost twice as many dwelling fires than car fires, but secondary fires that include wheelie bins and small fire in the open are, by a significant factor, the majority of fires attended. Also, the England figures include both Metropolitan Fire Services such as London, Manchester, West Yorkshire and South Yorkshire, Merseyside, Tyne and Wear and the West Midlands, along with predominantly rural, or "Shire" services which represent the rest, which will have a lower proportion of fires in built environments. To counter that, the Metropolitan services have significantly more built environments and greater populations, with proportionally more fires.

So, whilst that caveat to the figures is acknowledged, it is still relevant to use this average emissions factor to reach an "order of magnitude" figure for total emissions., at least until such time as the yearly statistics can be further and forensically examined.

Table 1 – Estimated Carbon Dioxide emissions

YEAR	GMFRS FIRES	CO_2 @ 865 kg	ENGLAND FIRES	CO_2 @ 865 kg
2010/11	18 276	15 808 740	228 407	197 572 055
2011/12	15 688	13 585 808	223 937	193 705 505
2012/13	12 027	10 403 355	154 456	133 604 440
2013/14	13 112	11 341 880	171 343	148 211 695
2014/15	11 669	10 105 354	155 037	134 107 005
2015/16	12 361	10 692 265	162 247	140 343 655
2016/17	12 412	10 736 380	161 997	140 127 405
2017/18	12 780	11 054 700	167 150	144 584 750

The table above gives a quick illustration of the estimated Carbon Dioxide emissions in Kg's for fires in both Greater Manchester and England, year on year from 2010/11 to the last UK Government statistical year, 2017/8. These are also represented in the figure below. The variation in Greater Manchester is between just over 10 000 tonnes per year to almost 16 000 tonnes per year, with no obvious trend up or down over the 8 year period illustrated.

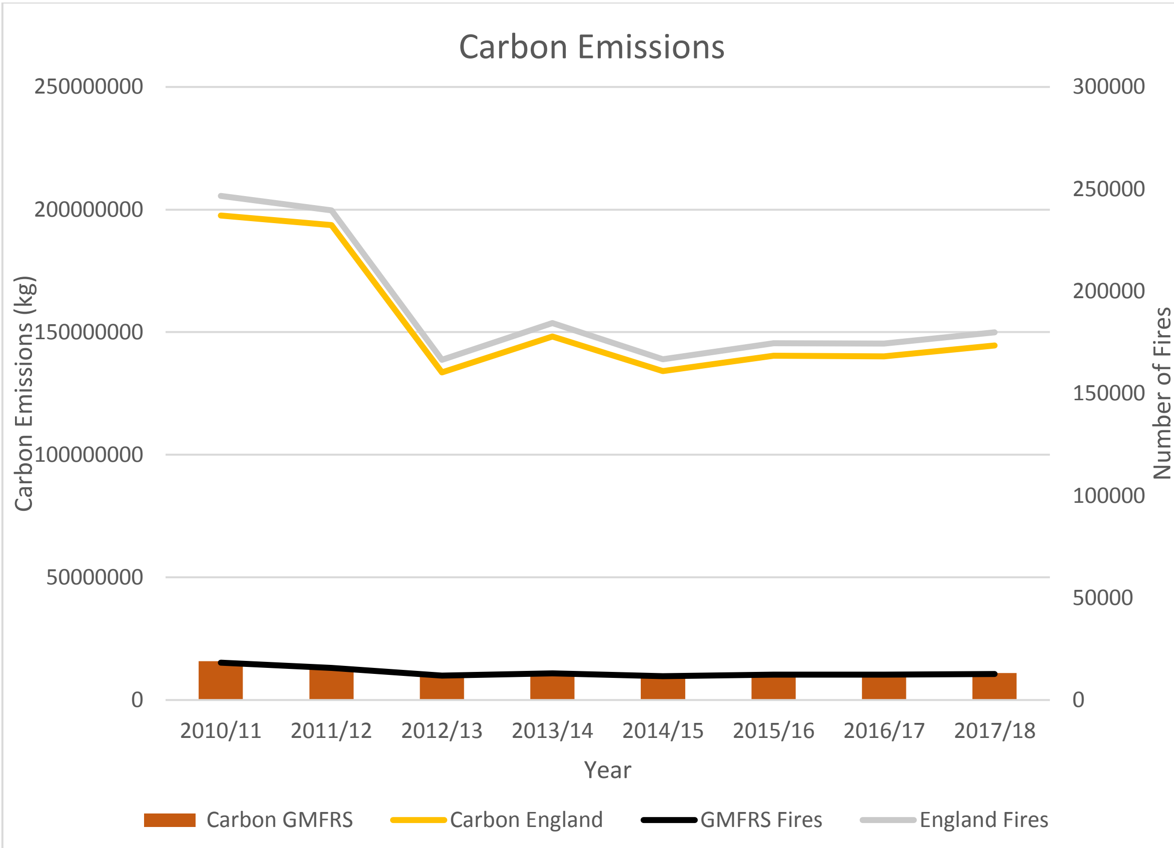


Figure 32 - Chart showing Carbon Emissions from 2010/11 to 2017/18 for Greater Manchester and England

In England as a whole, the range is from just over 130 000 tonnes to almost 200 000 tonnes per year, again with a relatively consistent figure of around 140 000 tonnes per year for the last few years.

Those figures need to be put in context, not only with regard to the total Carbon Dioxide emissions, but also the sector specific values. The Department for Business, Energy and Industrial Strategy published data for this, covering the years 1990 to 2016, and these figures will be used as the comparators (37).

As of 2016, the total United Kingdom Greenhouse Gas emissions was estimated at 468 million metric tonnes, down from 800 million metric tonnes in 1990. The Carbon Dioxide emissions have been estimated as 379 million metric tonnes, down from 600 in 1990. In order of the highest contributors, the seven significant emitting sectors are;

Transport	26%	(2% drop since 1990)
Energy Supply	25%	(57% drop since 1990)
Business	17%	(29% drop since 1990)
Residential	14%	(13% drop since 1990)
Agriculture	10%	(16% drop since 1990)
Waste Management	4%	(70% drop since 1990)
Other	4%	(75% drop since 1990)

Therefore, the contribution from fire in the built environment in 2016 can be estimated as 0.04% of total Carbon Dioxide emissions. (140 000 tonnes as a percentage of 379 million tonnes).

The figures for fires in Greater Manchester can also be compared with the Greater Manchester total Carbon Dioxide emissions. In July of 2018, Manchester Climate Change Annual Progress Report was published by Manchester City Council Neighbourhoods and Environment Scrutiny Committee (38).

The total estimated emissions for 2017 are 2.1 million metric tonnes, slightly down from 2016 at 2.2 million metric tonnes. The principle sectors responsible are listed as Business at 960 000 tonnes, Transport at 623 000 tonnes and Domestic at 571 000 tonnes. The contribution by fire in 2016 is the equivalent to approximately 0.5% of total Carbon Dioxide emissions. (10 000 tonnes as a percentage of 2.2 million tonnes).

Compared to the estimate for the UK, this represents a tenfold increase in the contribution from fires to the total in Manchester. It is possible to explain this difference by acknowledging the vast majority of UK Fire and Rescue Services are essentially rural, with only London and six other recognised metropolitan fire and rescue services. Therefore, the UK fire statistics taken nationally are likely to be less than if the focus is restricted to the predominantly “built environments” served by those seven services.

8 Conclusions

The stated Aim of this work was to develop a model to predict the Carbon emissions from fires in the Built Environment and, in doing so, understand and evaluate that impact. The objectives that were identified to support that aim were to keep it simple, use existing data gathering techniques and do all of it with limited resources.

The stated Aim has been met, and a simple model has been designed that uses the existing data gathering system, the Incident Recording System, and that can predict the Carbon emissions from those fire attended by Fire and Rescue Services.

Furthermore, the Model sits comfortably with other methods for calculating Carbon emissions in other sectors; for example, the method used to calculate Carbon emissions in the Transport Sector and used by UK Government relies on the amount of fuel purchased, the load miles travelled and the energy efficiency of the transport systems.

The limitations of the Model are a function of the IRS in that in reports estimated area damaged in blocks of 5s, 10s and 100s square metre, and therefore potentially creates a high estimate of damage reported. There are also built in assumptions in terms of the Carbon content of the types of fires themselves, with averages used for wheelie bins, skips and cars, and the contents of the various compartments. However, the potential inaccuracies of this approach should not invalidate the methodology used for the Model development. Rather, fine tuning of the values used for the Carbon contents might be the focus of further study.

The results themselves suggest that the Carbon emissions from fires in the Built Environment represent 0.0004% of the total UK emissions from all sectors, and therefore insignificant in that context. However, that figure is the result of this research and was not known beforehand.

With regards the Fire and Rescue Service, it has the potential to inform the tactics of firefighting, especially in large scale and unique circumstances. The Fire and Rescue Service has a responsibility to save life, save property and the environment, and so fires are always extinguished by the firefighters or, at least that is the usual approach. Normally there is a concern for fire spread and further damage to property, the need to fight the fire to search for and rescue victims and only in specific circumstances are fires allowed to burn out. They might include situations when the fire is beyond the reach of the hoseline and where the fuel load is limited and no potential for fire spread or harm to persons is possible. However, with an understanding of the Carbon emissions impact and notwithstanding the other potential pollutants contained within the fire emissions, the Incident Commander might decide to allow that large and unique incident to burn out under control knowing that the damage to the environment is less than if an aggressive attack with foam and the ensuing contaminated water entering the watercourses, an issue raised at the Buncefield fire.

This project has produced an estimate of the carbon emissions with the acknowledged limitations identified above, and in resource efficient manner. It has created a template method for the calculation of carbon emissions using an estimate of the Carbon content of an organic fuel, and has the potential to be a relevant calculator for any process or activity that creates energy from any such organic fuel.

Further research might take this template as a cost effective method to determine sector specific Carbon emissions by calculating the before and after values of organic materials used in those sectors; forest and wildfires by the area damaged by fire, whereas currently estimates are made using burning efficiency factors. Instead, an average fuel density could be identified for particular forest type and the extent of the damage could then provide an estimate of the emissions.

Similarly, energy sectors burning known quantities organic fuels, such as coal could estimate the Carbon emissions from those known initial quantities, and also determine an environmental efficiency factor, amount of energy per amount of Carbon emitted, which when compared with other energy sectors might promote the use of and greener fuels.

The transport sectors might also benefit from a simple calculation that identifies the fuel loads before and after a journey to determine the emissions.

With regards Carbon Tariffs, a simple and consistent calculation across all sectors might be a fairer way to establish high emitting activities and charge accordingly and may even be a simple way for consumers to make informed choices when purchasing energy dependent goods, such as cars.

Further research will improve the carbon emission results by more accurately measuring the Carbon content of compartment fires, although it is doubtful, given the low emission results from this research that a more accurate system of measuring and recording fire damage in the Incident Recording System will emerge.

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10 Appendix 1 – Example IRS Data

Figure 33. The IRS Data for Greater Manchester covering several years has been utilised in order to estimate the Carbon Emissions from fires. Each year there were thousands of incidents and the data from these has been recorded in spreadsheets. These spreadsheets are provided electronically with this thesis. An example of some of the data provided is given in the figure below. Please note that address and incident recording number have been removed.

1	Date	Station Admin Area	Borough	Estimated Damage Area m2	Co2 Category	Co2 Base Score	Co2 Total Scor
2	01/04/2014	W61	Salford		Small Fire in the Open	200	200
3	01/04/2014	W53	Bolton	5	Kitchen	46	230
4	01/04/2014	E40	Tameside		Small Fire in the Open	200	200
5	01/04/2014	E37	Bury	5	Kitchen	46	230
6	01/04/2014	S19	Manchester	200	Kitchen	46	9200
7	01/04/2014	E40	Tameside	50	Kitchen	46	2300
8	01/04/2014	E37	Bury		Small Fire in the Open	200	200
9	01/04/2014	E39	Tameside		Small Fire in the Open	200	200
10	01/04/2014	S14	Manchester	20	Kitchen	46	920
11	01/04/2014	S11	Trafford		Small Fire in the Open	200	200
12	01/04/2014	E37	Bury		Small Fire in the Open	200	200
13	01/04/2014	S21	Stockport		Small Fire in the Open	200	200
14	01/04/2014	S12	Trafford	10	Small Fire in the Open	200	2000
15	01/04/2014	E38	Bury		Small Fire in the Open	200	200
16	01/04/2014	W57	Wigan		Small Fire in the Open	200	200
17	01/04/2014	E36	Bury		Small Fire in the Open	200	200
18	01/04/2014	E36	Bury		Skip	1848	1848
19	01/04/2014	W57	Wigan		Small Fire in the Open	200	200
20	01/04/2014	E30	Rochdale		Skip	1848	1848
21	01/04/2014	E39	Tameside		Small Fire in the Open	200	200
22	01/04/2014	S19	Manchester		Small Fire in the Open	200	200
23	02/04/2014	W50	Bolton		Skip	1848	1848
24	02/04/2014	W50	Bolton		Skip	1848	1848
25	02/04/2014	E37	Bury		Skip	1848	1848
26	02/04/2014	S17	Manchester	50	Small Fire in the Open	200	10000
27	02/04/2014	S10	Trafford		Skip	1848	1848
28	02/04/2014	S17	Manchester	5	Kitchen	46	230
29	02/04/2014	E35	Oldham	5	Bedroom	33.5	167.5
30	02/04/2014	E42	Tameside	5	Kitchen	46	230
31	02/04/2014	W61	Salford	0	Kitchen	46	0
32	02/04/2014	W59	Salford	5	Kitchen	46	230
33	02/04/2014	E39	Tameside	5	Kitchen	46	230
34	02/04/2014	S19	Manchester	5	Kitchen	46	230
35	02/04/2014	W58	Salford		Small Fire in the Open	200	200
36	02/04/2014	W62	Salford	100	Bedroom	33.5	3350
37	02/04/2014	S21	Stockport		Small Fire in the Open	200	200
38	02/04/2014	E36	Bury		Small Fire in the Open	200	200
39	02/04/2014	W53	Bolton		Skip	1848	1848
40	02/04/2014	W56	Wigan		Small Fire in the Open	200	200
41	02/04/2014	W55	Wigan		Small Fire in the Open	200	200
42	02/04/2014	E32	Rochdale		Small Fire in the Open	200	200
43	02/04/2014	S19	Manchester		Small Fire in the Open	200	200
44	03/04/2014	W53	Bolton	5	Small Fire in the Open	200	1000
45	03/04/2014	W50	Bolton	10	Small Fire in the Open	200	2000
46	03/04/2014	S17	Manchester		Skip	1848	1848
47	03/04/2014	E39	Tameside		Small Fire in the Open	200	200
48	03/04/2014	S15	Manchester	5	Kitchen	46	230
49	03/04/2014	E33	Oldham		Small Fire in the Open	200	200
50	03/04/2014	S14	Manchester	5	Bedroom	33.5	167.5
51	03/04/2014	W50	Bolton		Small Fire in the Open	200	200
52	03/04/2014	S18	Manchester		Small Fire in the Open	200	200
53	03/04/2014	W50	Bolton		Small Fire in the Open	200	200

Figure 33 - Example of IRS data from the 2014/15

11 Appendix 2 - Organic Materials

In order to determine the Carbon Dioxide yield at any fire it is important to know what has been combusted and if it was organic i.e. Carbonaceous.

Once that is determined, the next step is to isolate the Carbon fractions from the material compounds, and to do that a list of the chemical formulae for each of the organic compounds was required in order to determine the proportion of Carbon in each.

For each of the fire types a list of the likely or known material components was made, for example the car example was researched and, other than steel, 15% of its mass was organic, such as rubber, plastic and nylon. Each of those organic compounds needed to be assigned a proportion of the overall mass of the car and then the compound itself disassembled to determine the mass of Carbon for each.

Similarly, the compartment fires would typically contain items such as mattresses, TVs and computer, sofas and chairs each of which would be comprised of chemicals such as PU Foam, Polystyrene, Rubber and PET plastics.

All of the formulae used to determine the Carbon contents for those items are listed below.

They are;

Cellulose	$C_6 H_{10} O_5$	42 % Carbon	Paper, wood, foodstuffs
Polystyrene	$C_8 H_8$	92 % Carbon	
PU Foam	$C_{25} H_{42} N_2 O_6$	64 % Carbon	

Rubber	$C_5 H_8$	88 % Carbon
PET Plastic	$C_{10} H_8 O_4$	63 % Carbon
PVC Plastic	$C H_2 = C H Cl$	39 % Carbon
Hydrocarbon	$C_{16} H_{34}$	85 % Carbon