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Additional information

The Recognition of Fires Originating from Photovoltaic (PV) Solar Systems, Appendix B electronic data files are available by contacting the author at: simon@prometheus-fs.co.uk

The Recognition of Fires Originating from Photovoltaic (PV) Solar Systems.

A thesis submitted for the degree of

Master of Science

By

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33,170 words, over 144 pages.

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I wish to mention the co-operation of Kraus and Naimer in freely providing information on their KG20 T104/D=P003KL51V DC isolator. I hereby state from the outset that this research in no way

singles out this particular component as unreliable, on the contrary it shows there is no evidence that this particular model of DC isolator is less reliable than any other, if fitted correctly.

Finally, I have some personal friends I need to thank. Mr Andy Batchelor, Dr Charlie Peet, Mr Harry Preston, Mrs Louise Peregrina, Mr Martin Collins, Mrs Wendy Dowden and Miss Charlotte Moss. Miss Moss and I co-operated in some aspects of experimental research and this will be detailed in the appropriate text within the thesis.

This period of research has been a most rewarding and stimulating experience. I believe this research has the potential to save many lives, reduce distress and loss of property due to fire, something I originally joined the fire service to do in 1978. I will endeavour to put the knowledge I have gained to that end in my continuing career as a forensic fire investigator.

Simon Smith

March 2016

Abstract

There has been an observable increase in the fitting of photovoltaic (PV) solar panels on the roofs of buildings in the UK over the last decade. The origin of some fires in domestic and commercial properties has been attributed to PV systems. This thesis examines the ability of fire examiners to recognise and record details of fires believed to have originated from PV systems, as well as investigating the effect of internal heating in direct current (DC) isolators to the point at which they fail.

National fire data was examined along with the methods for collecting and collating these data. This clarified that national fire data cannot identify the specifics of electrical fires. Validity of these data was then tested by identifying the confidence and competence in the recognition of the origin of fire, (especially when associated with PV systems), of some fire staff responsible for collecting fire data. This suggests that some fire scenes examiners are not confident in their own ability to recognise fires originating from PV systems. Evidence for fires occurring in PV systems in Kent between 2009 and 2014 was then examined, including a cold case forensic review of the evidence. This provided an indication that a potential common point of failure, which may lead to fire originating from a PV system, was to be found within the DC section of the PV circuits and probably within the DC isolator switch itself. Experimentation revealed that internal heating of a terminal connection can lead to changes of the phase of the insulating material, causing failure of structural integrity and therefore allowing an arc to be established. Observable post fire indicators associated with this mechanism of failure have been identified as well as hydrocarbons evolved from pyrolysis of isolator insulating material.

Finally, areas for further experimental research and training of fire staff are suggested as well as the modification of recording mechanisms and building regulations.

Contents

Abbreviations

AC	Alternating Current
DC	Direct Current
DCLG	Department for Communities and Local Government
DECC	Department for Energy and Climate Change
EM	Electromagnetic
ESFRS	East Sussex Fire and Rescue Service
FRS	Fire and Rescue Service
FSE	Fire Scenes Examiner
ICS	Incident Command System
IRS	Incident Recording System
IR	Infrared
KFRS	Kent Fire and Rescue Service
MoU	Memorandum of Understanding
PV	Photovoltaic
PV-T	Photovoltaic - Thermal Hybrid
QM	Quantum Mechanics

Chapter 1 Photovoltaic Energy

1.1 Introduction

There has been an observable increase in the fitting of solar alternative energy systems (known generically by the public as solar panels) on the roofs of many buildings in the UK (DECC 2012). Such solar systems could be solar thermal systems designed to capture IR EM energy in the form of heat, these are correctly named solar panels or photovoltaic (PV) systems designed to generate electricity, known by the solar industry as solar modules (MCS 2015; Prasad and Snow 2005 p.25; Shipp *et al*. 2014; Sundog 2015). As the efficiency of PV electrical generation decreases by 0.4 - 0.6% for every degree Celsius rise in temperature above 25º C (Leung Ray 2010; Lund *et al*. 2008; Prasad and Snow 2005 ch.6), there is a third hybrid combined system on the market, where PV material in an electrical generation module is cooled by a thermal system. These hybrid PV-T systems increase the efficiency of PV electricity generation and produce heat as a by-product which then can be used as a further alternative energy source. The amount of heat generated by a typical PV-T system is so high however it has to be stored, or dissipated, using further alternative energy systems, such as phase change storage, or ground pumps (MCS 2015; Solar Panels.Co 2012).

It is noticeable that solar systems are becoming ubiquitous. It is also apparent that fires are being reported nationally by the media as having originated from PV systems (BBC Leicester 2013; BBC 2014; BBC 2015). Concerns regarding PV safety are also being raised amongst the fire community, leading to research regarding the safety of firefighters involved in dealing with an incident where PV has been fitted (Backstrom and Dini 2012; Fink 2011; Shipp *et al*. 2014; Smith 2013).

An understanding of electrical theory is required by investigators of fire scenes (DeHaan, Kirk and Icove 2012 ch.10), this has to be applied by them to be able to recognise the origin of fires as arising from PV systems, and therefore assist in addressing these concerns.

1.2 Electrical theory

Electricity is the movement of electrons through matter. Matter is constructed of atoms, containing positively charged protons in the atoms' nuclei which are surrounded by electrons with a negative charge. Dissimilar charges attract each other and like charges repel each other. Therefore, if an electron in a conductor is repelled by a negative charged force, its neighbouring electrons will be equally repelled and create a flow of electrons through the material (Babrauskas 2003b pp.534-553; DeHaan, Kirk and Icove 2012 p.404; Nave 2012). This flow of electrons, referred to as current and identified by the symbol (I), is measured in amperes (A). The force causing the flow of electrons is created by a potential difference in charge between two points in a connected circuit and is referred to as voltage, measured in volts (V).

The flow of electrons through a conductor depends on the nature of the material, the applied voltage and the material's temperature. Materials which allow electricity to pass readily are referred to as conductors; materials which do not allow electricity to readily pass through them as insulators, and materials which electricity will pass through under certain conditions, as semi-conductors (DeHaan, Kirk and Icove 2012 pp.412-413; Ivison 1977 Ch.1 & 2; Montgomery and McDowall 2008; Nave 2012).

QM band theory postulates that atoms making up the molecules of matter are bonded one to another by the electrical attraction of dissimilar charges. One form of this type of bonding is referred to as valence bonding. The electron energies in the material form discrete bands of energy known as conduction bands and valence bands (Ebbing 1999 p.911; Nave 2012) [see fig 1 (i)].

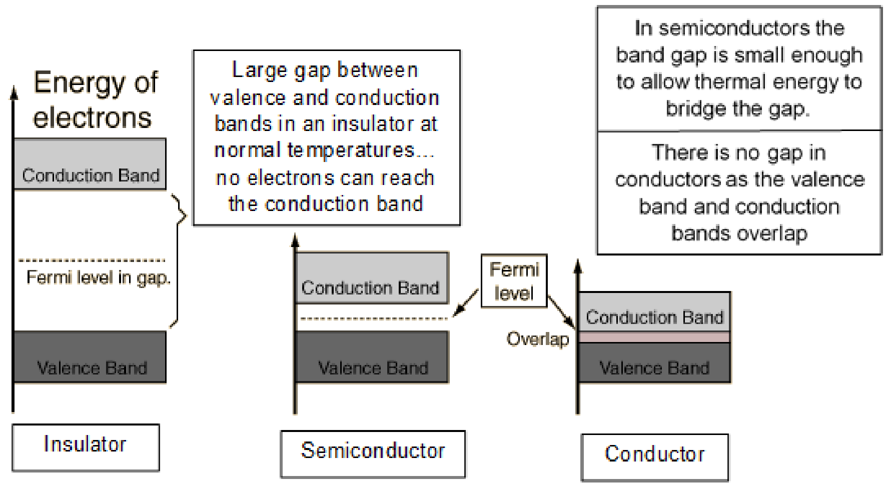


Fig 1 (i) Diagram showing the 'Band Theory' of solids adapted from Nave (2012)

Electrical current flows through the conduction band in the form of free electrons. The resistance to electron flow through a material is measured in ohms (Ω).

The relationship between current (I), Voltage (V) and Resistance (R) is described by Ohm's law which states *'the current in a conductor is directly proportional to the applied voltage <u>provided all physical conditions remain constant</u>'* [author's underline]. This relationship can be demonstrated in the formulae: **V = I x R** or **I= V/R** or **R= V/I** (DeHaan, Kirk and Icove 2012 pp.408-410; Montgomery and McDowall 2008). However, if physical conditions do change, for example the material heats up, then the characteristics (*e.g.* resistance) of that material will also change [see fig 1 (ii)] (Nave 2012).

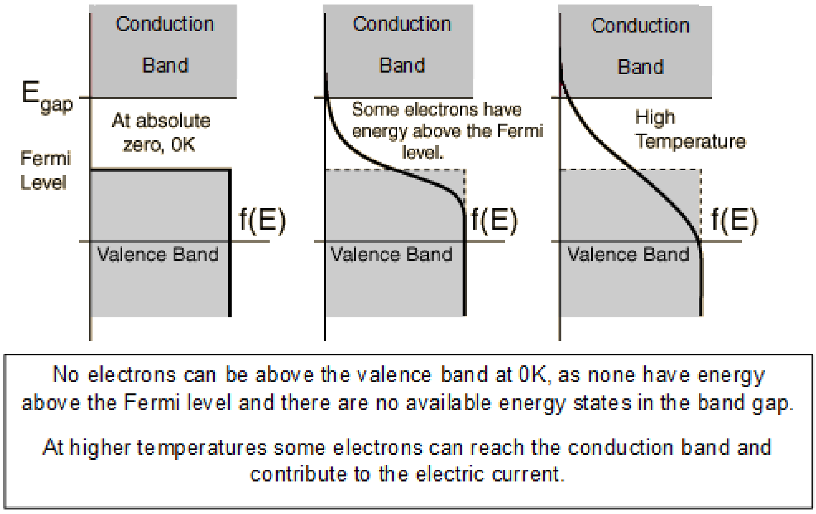


Fig 1 (ii) Diagram showing electron energy level change due to heating adapted from Nave (2012)

Theoretical electrical power is measured in watts (W) and can be calculated by multiplying the current and the voltage: **W = I x V**. However, in electricity generation the output of a generator is sometimes expressed as volts amps (VA), or more usually (kVA). This is due to the fact that some electrical power is lost during the generation and transmission of the electricity from the generator to the place of required use due to ohmic loss (resistance heating) and induction (Calgary 2015; Montgomery and McDowall 2008).

1.3 Photovoltaic theory

The sun, the nearest star to our planet, is a sphere of gas in which nuclear reactions occur due to gravitational forces. The sun radiates energy generated by these nuclear reactions across the complete electromagnetic (EM) spectrum [see fig 1 (iii)].

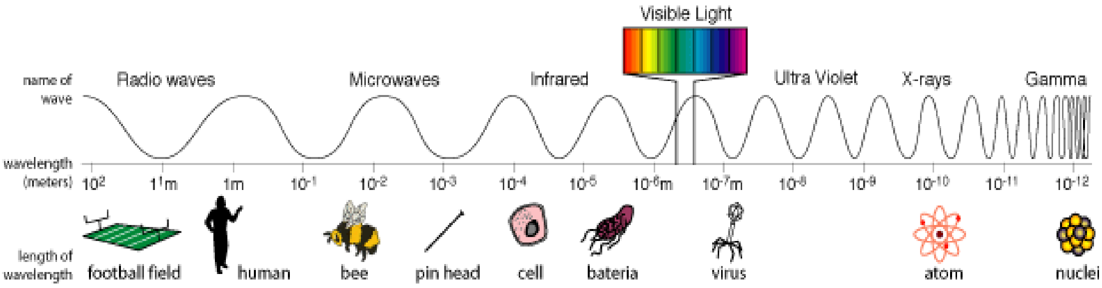


Fig 1 (iii) The Electromagnetic Spectrum adapted from (NASA 2015)

This EM energy (sunlight) radiates through the solar system, decreasing by the inverse square of the distance, as it dissipates in four dimensions and is the main energy source responsible for heating planet Earth to habitable conditions. Sunlight's infrared EM wavelengths can be felt on the skin as radiated heat; those in the ultraviolet wavelengths cause sunburn to exposed skin. The narrow band of EM wavelengths from 400 - 700 nanometres (nm), is the visible light spectrum (NASA 2015).

Becquerel discovered and named the photovoltaic effect in 1839 during experiments with electrodes, when he observed that electricity is produced from light shining on metals (Lund *et al*. 2008). Maxwell discovered magnetic and electric fields were one and the same and he named the phenomena electromagnetic (EM) energy. In the classical view, as the name suggests, EM radiation propagates in waves that switch between electric and magnetic properties, perpendicular to the direction of propagation. Planck postulated that EM radiation across the full spectrum was made up of packets, (or quanta) of energy, called photons by Einstein. The photon is a massless particle which moves at the speed of light (c) now accepted as 2.99792458×10^{8} m/s, or approximately 300,000 km/s in a vacuum (Ebbing 1999 p.278; Nave 2012). Planck showed the photon holds quantum energy in proportion to the frequency of the radiation and the constant of proportionality (h), being 6.626×10^{-34} joule seconds, now called Planck's constant.

Giving the expression: **E = hv** : Where E is the energy expressed as joule (J), h is Planck's constant, and v (or sometimes written as f) is the frequency of the EM radiation (Ebbing 1999 p.280; Nave 2012).

The energy of photons striking a semiconductor material which displays the photoelectric effect (as used to make a PV cell) excites electrons surrounding the atoms which bonded together, make up that material. This causes those excited electrons to change position within the bands of energy surrounding the atoms, breaking them free of their valence band, thus creating holes and moving the free electrons into the conduction band, thereby causing the potential for a direct current (DC) to exist (Ebbing 1999 p.280). These subsequent free electrons can be forced to move by the application of differential electrical charges called doping (Backus 1976 p.15; Nave 2012). Most commonly available solar cells use either amorphous or crystalline silicon, doped with phosphorous and/or boron, to apply negative and positive charges to the material and thereby create the electrical current. Space exploration and the search for alternative energy has stimulated further rapid development in PV technology in order to supplement spacecraft battery life and reduce the rate of climate change. Yet despite much research the main chemical element used in the manufacture of PV modules remains silicon (Backus 1976 p.394; DECC 2012; DECC 2013; DECC 2014; Gov.UK 2014; Harrabin 2015; Prasad and Snow 2005 ch.2; Pulfrey 1978 p.115; Solar Panels.Co 2012; Spanggaard and Krebs 2004; Sundog 2015)

Once generated, direct current (DC) created by the photovoltaic effect can then be either used as DC or, for more convenience, it can be converted to alternating current (AC) at mains voltages such as 230 volts AC at 50 hertz, as supplied by the National Grid in the UK, or 120 volts AC at 60 hertz as supplied in the USA (MCS 2015; Prasad and Snow 2005 ch.6; Sundog 2015).

1.4 Photovoltaic circuits

PV modules are typically constructed of wafer solar cells, connected with each other in series to form a module. The material displaying the PV effect is normally laminated between a dark coloured plastic backing and a glass fronting, then held in a lightweight metal or plastic frame (Backus 1976 p.34; Lund *et al*. 2008; Sundog 2015). Each module will nominally generate approximately 35-40 V DC open circuit (Voc) at between 5 and 8 A short circuit (Isc), depending on the manufacturer (Mayfield 2012; Shipp *et al*. 2014; Smith 2013).

PV modules cannot be turned off, for any light above the threshold value reaching the surface of the module will generate electricity (MCS 2012 p.14; Prasad and Snow 20053 ch.6; Sundog 2015). This physical nature of PV modules is causing concern amongst some firefighters with regards to fighting fires in buildings with live high DC voltages present, and these concerns were even raised during interviews for this research [see appendices B2.3.2 and B2.3.4]. Research has been carried out in Europe and the USA to ascertain power levels produced by artificial light and flame. It has been found illumination from artificial light (and even flame) can cause significant power to be generated which may affect the safety of firefighters engaged in fighting a fire where PV is present, regardless of the cause of the fire (Backstrom 2014; Global Fire Research 2015; Shipp *et al*. 2014; UL 2015). This research is on-going (BRE 2016).

Neither can PV system DC circuits be fuse protected, due to the operating current of a PV system being near to the short circuit current for the DC circuits; meaning any fuse (or other circuit protection such as a micro circuit breaker (MCB)) would operate during normal use (BSI 2011; MCS 2012).

For these reasons the most recent guide to the installation of PV systems (MCS 2012 p.77) recommends that a 100mm x 100mm sign [see fig 1 (iv)] be fixed adjacent to the mains electrical suppliers cut out, in a premises fitted with PV modules on the roof. This recommendation is not legally enforceable, nor does it account for premises where the PV modules are not fitted on the roof of that building (being located on adjacent out-houses, or in the garden for instance). It is not retrospective (BSi 2015 p.4), nor does it account for subsequent removal by occupiers, wear and tear, or firefighters' observational skills. The MCS recommendations have however been "…*written to be the technical standard to which MCS registered installation companies are expected to meet in order to gain and / or maintain their MCS certification…*" (MCS 2012 p.13).

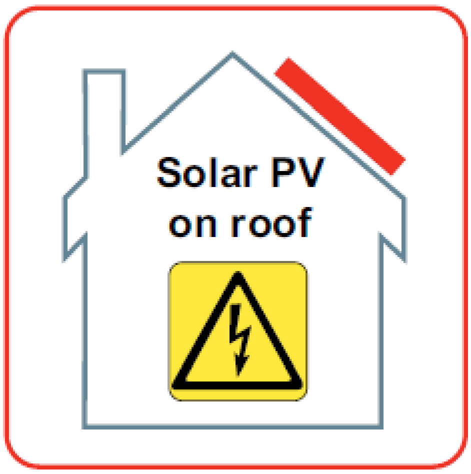


Fig 1 (iv) Fire fighters PV fitment advisory sign adapted from MSC (2012 p.77)

Research is being carried out into arc protection on PV DC circuits using Radio Frequency EM detection (Cotterell 2015). However, arc detection and prevention is difficult for these circuits; for once an arc is detected, it has to be dealt with in a circuit which may remain energised unless a physical break is made to it <u>before</u> the established arc. Therefore, by simply automatically switching off the current at the DC isolator should an arc be detected, there is the potential to make such an arc worse (*ibid*).

For easy domestic use and connection to national power systems, such as the UK National Grid, DC electrical power, as generated by a PV module, has to be converted into useable AC mains power. This is accomplished by using an inverter and a voltage reducer, usually combined into one unit. Inverters use switching circuitry technology to reverse the current, thus inverting the position (flow) of the current as shown on a graph [see fig 1 (v)] (BSi 2011; DTI 2006; MCS 2012; Sinetech 2015).

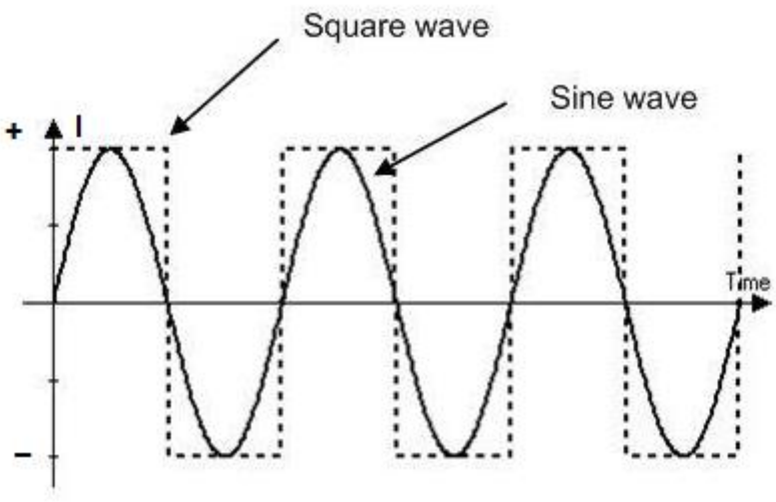


Fig 1 (v) Diagram showing the difference between square and sine waves

adapted from Brooks (2011)

In its most basic form such a device creates a square wave AC, with the current simply alternately switching between equal positive and negative values in a given time period; for example 50 times a second (50 hertz) for UK mains values (Prasad and Snow 2005 ch.6; Sinetech 2015; Sundog 2015).

This can be modulated using a series of steps to smooth out the waveform so that it more closely resembles the sine wave form of AC [fig 1 (iv)], as generated by an alternator's windings rotating in an electromagnetic field (or vice versa), as used to generate the majority of mains AC power (EDF 2015). The DC voltage from PV modules is reduced to mains voltage levels (230 V UK, 120 V USA) by either using transformers or switching circuitry at the same time as the current inversion is taking place (*ibid*).

There are two basic types of inverter which may be found in a PV system; the more common string inverter, or the micro inverter (Sundog 2015). A micro inverter is normally attached directly to a single, or pair of PV module(s) and mains voltage circuitry then enters the building from immediately adjacent to the module.

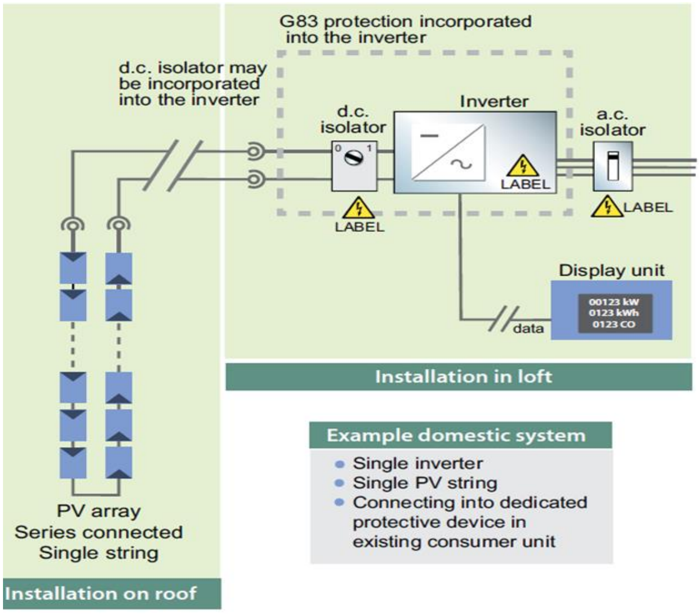


Fig 1 (vi) Basic schematic diagram of a PV domestic (string) solar system (MCS 2012)

A string inverter is normally located inside the property and receives DC voltages from an array made up of a string of PV modules connected together in series, [fig 1 (vi)] or from a group of series connected strings, themselves then connected in parallel to form an array (MCS 2012; Sundog 2015). By connecting electrical components such as PV modules in series, the voltage each produces is multiplied by the number of modules in the array and the current remains constant. If the modules were connected in parallel to each other, the voltage would remain constant but the current would multiply (Nave 2012). Wiring regulations and guidance show how by using both series and parallel wiring this effect can be used to optimise the efficiency of wiring for PV arrays (BSi 2011; MCS 2012) [fig 1 (vii)].

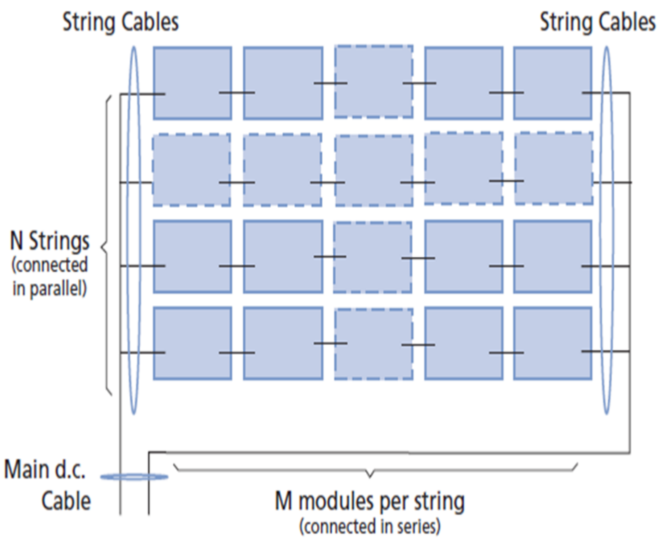


Fig 1 (vii) Diagram showing PV series strings connected in parallel to form an array (BSi 2011)

Therefore, if 10 modules are connected in series, with each one capable of producing 35 V DC, then there is a potential for 350 V DC to be routed through a property to the inverter (Mayfield 2012; Prasad and Snow 2005 p.26; Shipp *et al*. 2014; Smith 2013). The Department for Trade and Industry (DTI) 'Guide to the Installation of Photovoltaics in Buildings', notes that PV string arrays in the UK '*typically operate with array voltages in the range of 120* [*sic*] *to 500 volts DC'*

(DTI 2006). The MCS guide (2012) discusses open circuit voltages in excess of 1,000 Voc. These guides set out regulations for specific cabling, connectors and switching capable of handling the expected DC power to be found in a PV string system. A typical domestic system is capable of producing 2-4 kilowatts peak (kWp) and a commercial array can produce many megawatts peak (MWp) (Shipp *et al*. 2014).

An inverter has to be connected to mains AC to receive its own power supply, as well as to supply power to the National Grid. Inverters have to be separated from the DC and AC supplies (where power is coming into the inverter) and AC feed cabling (where AC power is leaving the inverter) by specifically designed DC and AC switches, referred to as isolators. Should the National Grid mains voltage supply be cut to the inverter, the device is required by regulation to shut down, thus preventing power entering the National Grid and therefore potentially harming power workers (BSi 2011; DTI 2006). However, it must be remembered that the DC circuits will always remain live up to the DC isolator, with electrical power output dependent on the frequency and intensity of light falling on the PV modules (Backstrom and Dini 2012; Cotterell 2015; MCS 2012; Shipp *et al*. 2014; Smith 2013; UL 2015).

1.5 Increase in installation

In recent years there has been a steady and readily observable trend for the increase in the installation of PV on many buildings in the UK (DECC 2012). This is unsurprising as Department for Energy and Climate Change (DECC) data [see fig 1 (viii)] shows domestic PV fitment to be the largest sub sector of the UK PV market (DECC 2014).

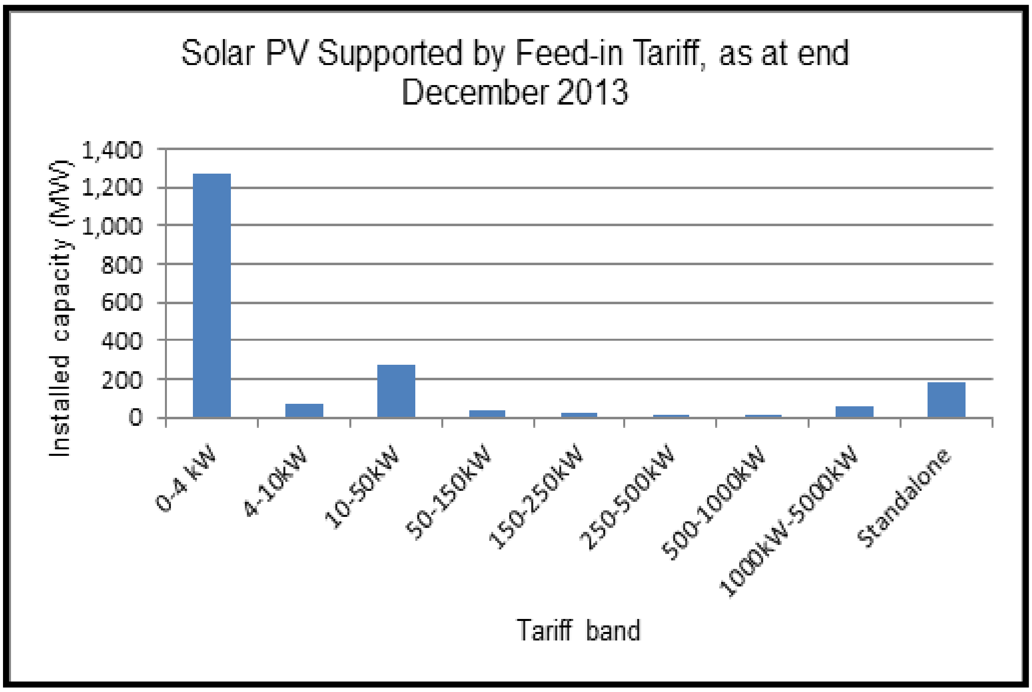


Fig 1 (viii) Solar PV supported by Feed-in Tariff (DECC 2014) showing domestic PV (0 – 4 kW) as the largest sub sector of PV fitment

A simple satellite image mapping search shows many roofs adorned with PV modules, for as stated by DECC *'We have seen domestic roof-top projects become an established part of the transition to a low carbon economy, with around 2000 being installed each week'* (DECC 2014).

Fig 1 (ix) below shows a satellite map image of the Salisbury Road area of Canterbury, very close to the University of Kent. PV modules can be observed on seven of the domestic dwellings in the image.

Fig 1 (ix) Satellite image of the Salisbury road area of Canterbury (Google Maps 2014)

Building integrated PV, including the use of transparent PV as glazing in roofs and windows, could be disguising the abundance of PV, so numbers of PV systems fitted in the UK are probably higher than directly observed (Prasad and Snow 2005 ch.1; Sundog 2015). This increase in the fitting of PV to premises in the UK can, in part, be seen to be as a response to government initiatives to reduce global climate change by encouraging the use of alternative energy supplies (DECC 2014).

1.6 International drivers for alternative energy

There is a growing body of scientific evidence indicating planet Earth is undergoing a period of climate change. Research has indicated that increased levels of greenhouse gasses in the atmosphere, such as carbon dioxide (CO_2), are the most likely cause for this change (The New

Scientist 2014). Therefore, international agreement has been sought to ensure a global reduction in the emanation of greenhouse gases from energy generation. In order to address this issue the Rio Earth Summit of 1992 led the United Nations (UN) to formulate an international agreement in 1994 called ‘The United Nations Framework Convention on Climate Change’, 195 countries were parties to the convention by 2014 (UN 2014). Named after the Japanese city where it was adopted, the Kyoto Protocol is an international agreement linked to the United Nations Framework Convention on Climate Change. The protocol sets enforceable greenhouse gas reduction targets for signatories, with recurring reporting periods to identify compliance. The first commitment period started in 2008 and ended in 2012 (*ibid*).

Being an industrialised nation and a signatory to the convention, the United Kingdom has a duty to enforce greenhouse gas emission reduction by physical, or market based measures (where greenhouse gas emissions are sold off to developing countries). The UK Government has adopted a mixed approach to the problem (Gov.UK 2014). This has led to the enactment of the Climate Change Act in 2008 (Climate Change Act 2008). The Act places an obligation on DECC to oversee and ensure compliance with climate reduction targets and in order to do so sets a target for 2050 to reduce greenhouse gas emissions in the UK to at least 80% lower than those in 1990 (*ibid*). PV electricity generation is considered to be a key method in achieving this statutory target and DECC has introduced the UK Solar PV Strategy in order to achieve this.

Governmental feed-in tariffs have therefore been used to encourage the wider use of domestic PV, by allowing house owners to feed electricity into the National Grid and be paid accordingly for their contribution to the national supply. However, DECC halved the feed-in tariff for anyone who installed and registered PV installations from 3 March 2012. This change was widely publicised at the time and is most likely responsible for the increase in installations seen in the spring of 2012, as people attempted to register before the reduction in the tariff [fig 1 (x)] (DECC 2014).

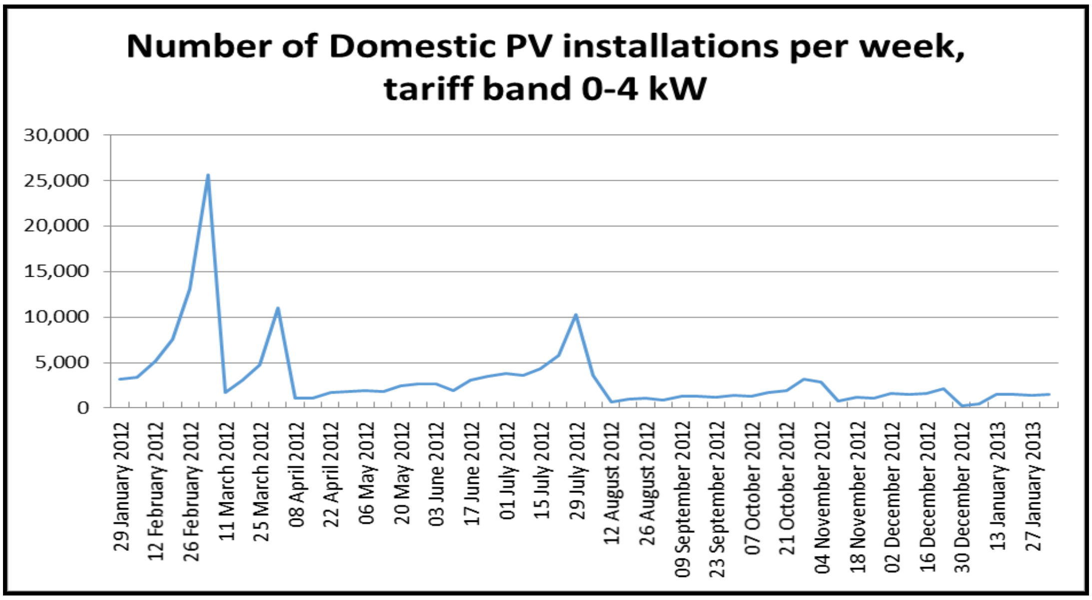


Fig 1 (x) Number of domestic PV installations Jan 12 to Jan 13 tariff band 0-4KW (DECC 2014)

This effect has again been noticed in the spring of 2015, with government tariffs changing in April of that year. This has led to a noticeable increase in installation and it is reported '*as much new capacity has been installed in the first three months of this year* [2015] *as in the whole of 2014' (*Harrabin *2015)*. These tariff change induced peaks in UK PV installation may have caused demand for PV components to outstrip supply.

Chapter 2. Investigating Fires Originating from PV Systems

2.1 Fire science theory

Combustion is a chemical reaction where energy is released. This is normally simplistically described as a chemical reaction producing heat and light, and is therefore an exothermic reaction (Chang 2013 p.233; Ebbing 1999 p.155). Certain specific conditions must be fulfilled for combustion to take place. These are usually represented graphically as the fire triangle [fig 2 (i)].

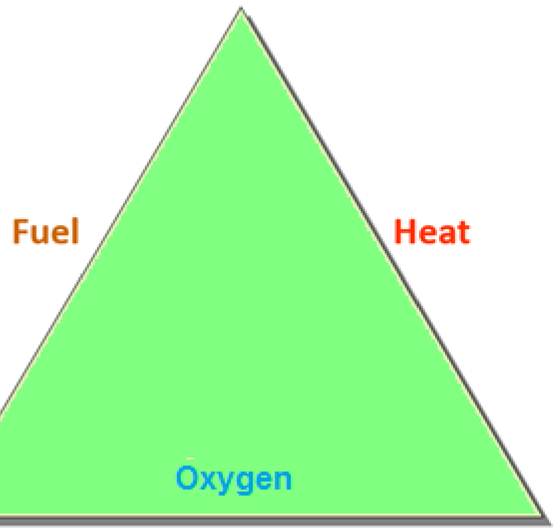


Fig 2 (i) The fire triangle adapted from (Babrauskas 2003b p.6)

Firstly, a fuel is required and is represented by one side of the fire triangle. The fuel has to have its temperature raised sufficiently to allow it to enter its vapour phase for combustion to occur [see appendix A], heat is therefore a second side of the fire triangle. In basic terms combustion is an oxidation reaction, therefore there has to be a source of oxygen. This can be supplied from the atmosphere, (containing oxygen at approximately 20% at sea level), another gaseous oxygen source, or from an oxygen containing chemical such as a nitrate. These three conditions therefore create the fire triangle (Babrauskas 2003b p.6; DeHaan, Kirk and Icove 2012 p.33).

However, the requirements of combustion are more correctly graphically illustrated by the fire tetrahedron model [fig 2 (ii)]. This is because for combustion to be continuous once an ignition temperature has been reached there has to be a sustained chemical reaction between the fuel and the oxygen. This is best represented by the three dimensional shape of a pyramid (or tetrahedron), with each face representing one of the four elements required for combustion to occur. When firefighting, the removal of one of the four elements represented by the faces of the tetrahedron, will cause the combustion to cease and the fire is thereby extinguished (DeHaan, Kirk and Icove 2012 p.33).

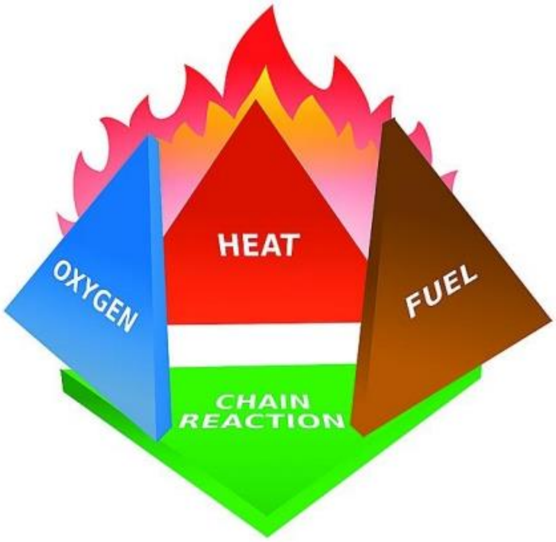


Fig 2 (ii) The fire tetrahedron adapted from (DeHaan, Kirk and Icove 2012 p.34)

For example, removing the heat (cooling), usually using water; displacing oxygen by smothering, usually using foam, specialist dry agents or inert gases; removing the fuel, by shutting off a fuel supply, or creating a fire break in crops; or directly inhibiting the chemical reaction, usually achieved chemically using a halogenated compound (Fire Service Manual 2001 ch.11; Firesure 2011).

The process of changing a substance's phase state to vapour, and/or causing the substance to decompose into lighter compounds and elements by the introduction of heat, is called thermal decomposition, or pyrolysis (Babrauskas 2003b p.18; DeHaan, Kirk and Icove 2012 p.28).

2.2 Pyrolysis, Flammable Limits and Ignition Energy

There are different definitions of pyrolysis depending upon the source of the definition. Many chemists define it as thermal decomposition of a material in the absence of oxygen (Babrauskas 2003b pp.18 & 238). However, for the process of combustion potentially leading to a flaming fire, a substance needs either to change to its gas phase (sublimate and/or, liquefy and evaporate to a gas or vapour) [see appendix A] or decompose to smaller molecules. This is referred to as pyrolysis within the fire industry (Babrauskas 2003b pp.237-238; DeHaan, Kirk and Icove 2012 p.125; Daeid 2004 p.3).

The molecules which make up combustible solids such as timber or synthetic plastics are too large for oxidation to progress to combustion. Therefore, these large molecules have to decompose for flaming combustion to occur. When heated, long chain polymers break up (crack, or isomerise) at various temperatures, reverting into various component chemicals (monomers) from the polymer; or they may form molecules, or isomers, of new compounds (Lentini 2013 p.54). As these molecules are very small and are heated, they emerge from the substance as a gas, leaving a residue behind. This residue may be a solid carbonaceous matrix called char, or a liquid, depending of the chemistry of the original solid (Babrauskas 2003b p.238; Lentini 2013 p.57; Chang 2013 p.139; Ebbing 1999 p.441).

Gases or vapours emerging from a substance due to pyrolysis may be observed by the naked eye as very light blue in colour. Often misinterpreted as smouldering (Lentini 2013 p.63) and sometimes described by witnesses as white smoke, these gases are referred to in the fire industry as pyrolysis product(s). In order for flaming combustion to occur these pyrolysis products have to be mixed to appropriate proportions with oxygen (air). This is referred to as being within the flammable limits. If there is too much fuel the mixture is said to be too rich, or above its flammable limit; too little fuel, the mixture is too lean, or below its lower flammable limit. Pyrolysis products within their flammable limits then have to be either pilot ignited by a spark, or flame, above their minimum ignition energy (MIE), or heated until they reach their auto-ignition temperature (AIT) [see paragraph 2.3] (Babrauskas 2003b p.66 & pp.238-239). As MIE reduces with an increase in temperature a lower ignition energy is required to ignite hotter pyrolysis products (Babrauskas 2003b p.77)

2.3 Ignition temperatures

The first ignition temperature reached is flashpoint (FP). This term is applied to the temperature of a gas or vapour, where if an ignition source such as a spark or flame is introduced, the gases will momentarily ignite and self-extinguish, creating flashes of flame. Firefighters are taught to recognise this effect as one of the precursors to flashover (when fire spread develops exponentially, to fully involve a compartment) when it occurs at the neutral plane of the hot smoky gas layer. Firefighters sometimes refer to these phenomena as the 'Dancing Angels' (Avillo 2008). If pyrolysis products continue to be heated they will quickly reach their ignition point, otherwise known as the flame point. This is the lowest temperature at which if an ignition source such as a spark or a flame is introduced the flammable vapours and gases will ignite and remain alight after the ignition source is removed. If there is no ignition source close enough to the pyrolysis product to ignite it, and heat continues to pass into the pyrolysis product, a temperature is reached whereby the vapours or gases will automatically ignite without exposure to a spark or flame. This is known as the auto ignition temperature (AIT) (Babrauskas 2003b pp.13-16; DeHaan, Kirk and Icove 2012 p.94; Mansi 2012).

It is important consider all the above factors when ascertaining the likelihood of flaming combustion of a substance. For example, under standard conditions nylon is a solid. However, it has been known for some time that when heated nylon can thermally decompose to a number of vaporous hydrocarbons. Both Achhammer *et al* (1951) and Straus and Wall (1958) showed examples of these hydrocarbons from pyrolysis of nylon to include propane and butane when nylon is heated to 400ºC in a vacuum. Ignition data for propane and butane are shown in table 2 (i).

Substance	MIE in air mJ	Flash Point Deg C	Auto Ignition Temp Deg C	Lower Flammable Limit vol %	Upper Flammable Limit vol %
Propane	0.26	-104	500	2.1	9.5
Butane	0.26	-60	408	1.85	8.4

Table 2 (i) Ignition data for propane and butane.

Adapted from Babrauskas (2003b pp.1028 -1050)

Although a temperature in the region of 408ºC - 500ºC is required to auto-ignite these two possible pyrolysis products from nylon, we can see that ignition of these products could occur if they were within their flammable limits and exposed to a relatively low energy spark. This will be discussed further in Chapter 6.

2.4 Temperature and heat

The law of conservation of energy, as incorporated into the first law of thermodynamics, tells us that energy cannot be created or destroyed but can only be converted from one form to another, and that heat moves from a hot body to a cold body until both are at the same temperature and a state of equilibrium is reached (Schroeder 2000 pp.17-18).

As discussed, heat can transfer through empty space by the processes of EM radiation. However, heat can also move through liquids and gases by changes in density of matter caused by the movement of molecules. This is called convection.

Heat is also transferred by direct contact; this is called conduction. The rate at which heat energy flows at the molecular level in a material through direct contact depends on a constant of proportionality called thermal conductivity. In liquids and gasses heat is conducted due to molecular collisions, with energy being passed from a fast molecule to a slower one. In solids it is transferred either by molecular (lattice) vibration, and/or by the movement of electrons in the conduction band of matter. The process of thermal conduction in metals and semiconductors, is similar to electrical conduction. In the case of thermal conduction however, electrons pass kinetic energy one to another rather than being stimulated to move by the application of a potential difference in electrical charge. In general terms matter which is a good electrical conductor will also be a good thermal conductor and vice versa (Nave 2012).

The amount of energy which may be contained within matter depends on its heat capacity. The heat capacity (C) of an object is the amount of heat required to raise its temperature per degree temperature increase (Housecroft and Constable 2010 ch.2 & p.597). This can be expressed as: $C \equiv \frac{Q}{\Delta T}$. Where Q represents heat energy and ΔT represents the change in temperature. As heat capacity varies depending on the mass of the object, a more useful measure is specific heat capacity (c), being the quantity of heat required to raise one gram of a substance by one degree Celsius (or one kelvin), expressed as: $c \equiv \frac{C}{m}$. (Ebbing 1999 p.246; Schroeder 2000 p.28).

The speed and efficiency at which an object increases its temperature is dependent on both its heat capacity and thermal conductivity. Matter with a low heat capacity rises in temperature more quickly for a specific heat input per second than matter with a high heat capacity. A large mass with a low heat capacity and a high thermal conductivity may rise in temperature uniformly. If the large mass has a low thermal conductivity, a locally heated area (for example a direct point of contact with a heated metal rod allowing conduction to take place into the matter) would get hotter before the bulk of the substance, as the heat is unable to pass quickly into the mass. For example, copper has a specific heat capacity of 385 J Kg^{-1} K^{-1} and would rise in temperature faster than nylon which has a specific heat capacity of 1700 J Kg^{-1} K^{-1} (DiracDelta n.d.). Copper has a relatively high thermal conductivity of 385 W m^{-1} K^{-1} (Nave 2012) and therefore conducts heat readily. Nylon 6,6 however has a low thermal conductivity 0.33 W m^{-1} K^{-1} and does not (Babrauskas 2003b p.1074).

However, the amount of heat in a substance also depends on the circumstances, specifically whether work is also being done to the substance (*Schroeder 2000 p.28*). Heat can pass into an object and the temperature of that object may not rise. This is because the energy passing into the matter is being used to do work, the object may expand, decompose, or a change may occur in the phase state of the material, from a solid to a liquid, or gas, for example. The heat required to do this work is referred to as latent heat (Schroeder 2000 p.32).

Total change in energy within a system is the sum of the heat added to (or removed from) the system and the work done to the system. This can be expressed as: $\mathbf{\Delta U = Q + W}$. Where ΔU represents the change of energy of the system, Q represents heat transferred in or out of the system and W represents work done to the system. (Chang 2013 p.236; Housecroft and Constable 2010 p.593; Schroeder 2000 p.19).

Internal energy of matter is therefore dependent on the type of matter, change of heat to and from it, any work being done to or by it (such as phase state change, decomposition or chemical reactions) and the pressure applied to it.

2.5 Enthalpy and Entropy

Enthalpy (H) is a representation of the total internal energy of matter. It is a state function being determined by the temperature, pressure and volume of the substance and not its history (Housecroft and Constable 2010 p.62). This is represented by Hess's law which states the enthalpy change for a reaction is independent of the route by which the reaction is achieved, but depends only on the initial and final stages. Enthalpy for matter can therefore be calculated by adding its internal energy to the product of its volume and the pressure applied to it (Chang 2013 p.256; Ebbing 1999 p.240; Schroeder 2000 p.33).

This can be expressed as: **H = U + PV**, where H represents enthalpy, U represents internal (heat) energy, P represents pressure applied to the matter and V represents the volume of the matter. Enthalpy will therefore change dependent on the work required to be done on, or by, a material during chemical reactions, or phase state changes. For an exothermic reaction the enthalpy change is negative, as energy is lost from the original material. For endothermic reactions enthalpy change is positive, as heat energy is drawn from the surroundings (Ebbing 1999 p.761).

Entropy (S), is a measure of the degree of randomness, or disorder, of the particles and energy in a system. An increase in temperature (T) will likely cause an increase in Entropy S. (Chang 2013 pp.780-784; Housecroft and Constable 2010 p.617; Schroeder 2000 p.75).

Schroeder (2000 p.151), tells us there are four qualities, or 'thermodynamic potentials' to be considered when calculating the total energy of matter, with energy changes associated with both volume change (Helmholtz free energy) and from changes in pressure (Gibbs free energy) needing to be considered as well as heat and work [fig 2 (iii)]

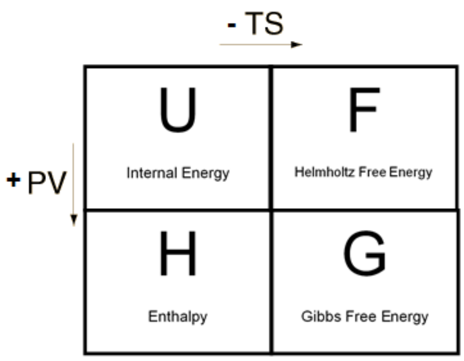


Fig 2 (iii) The four thermodynamic potentials. Adapted from Schroeder (2000 p.151)

2.6 Activation Energy

In general terms sufficient energy has to enter a system in order for a chemical reaction to initiate, as energy (heat) is required to raise the kinetic energy of a reactant's molecules in order to break their chemical bonds before new bonds can be formed [fig 2 (iv)]. This is called activation energy and may be considered as an energy hump or barrier which has to be overcome before a reaction can take place (Babrauskas 2003b p.32).

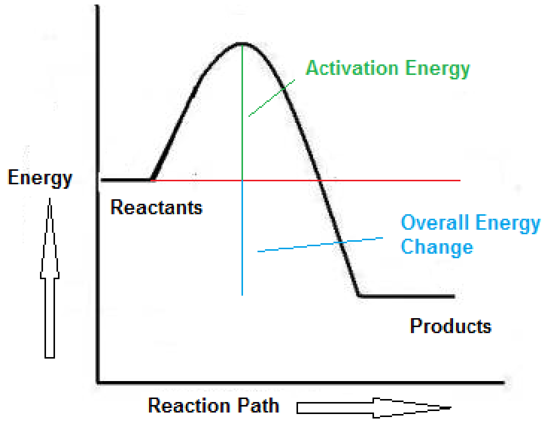


Fig 2 (iv) Activation energy hump or barrier. Energy has to be added to the system Green line in order to initiate the reaction. Adapted from Babrauskas (2003b p.32)

In a fire we therefore have a complex chemical situation when a compound is potentially changing its volume and phase state, being exposed to pressure changes caused by convection currents, decomposing due to heat and then igniting. Energy is required to cause a volume change, overcome the latent heats of fusion and vaporisation and thus create a phase state change, followed by energy to initiate combustion (Babrauskas 2003b p.32). The chemical reaction of combustion then evolves products and energy is also required for the formation of these products (ibid p.25).

2.7 Heat or Enthalpy of combustion

The heat of combustion is the energy released as heat when matter undergoes complete combustion with oxygen. To calculate the energy change involved in a chemical process we have to subtract the enthalpy of reactants from the enthalpy of products. This can be shown as a thermochemical equation indicating the physical state of the reactants and products as well as the energy change (Housecroft and Constable 2010 pp.69 - 76).

For example, the burning of methane in air to form gaseous carbon dioxide and liquid water, showing 891 kJ of energy is liberated per mole by the exothermic reaction [fig 2 (v)] (Babrauskas 2003b p.26).

$$CH_4\,(g) + 2\,O_2\,(g) \rightarrow CO_2\,(g) + 2\,H_2O\,(l)$$

$$\Delta H_f^0 \quad -75 \quad 0 \quad -394 \quad -286 \quad kJ\,mol^{-1}$$

$$\Delta H_c^0 = [\Sigma \Delta H_f^0\,(products)] - [\Sigma \Delta H_f^0\,(reactants)]$$

$$\Delta H_c^0 = [(-394) + 2\,(-286)] - [(-75) + 2(0)]$$

$$\Delta H_c^0 = -891\,kJ\,mol^{-1}$$

Fig 2 (v) Thermochemical equation for the formation of carbon dioxide and water from the combustion of methane in air. Adapted from (Benfield 2014)

2.8 Electrical causes of fire

The energy required to heat a substance to cause pyrolysis and for the chemical reaction of combustion to potentially be initiated, can be supplied by electricity either doing work on matter, or directly heating that matter. We have seen that matter falls into three categories of electrical conductivity, partially dependent on temperature: conductors, semiconductors and insulators. Metals are good conductors, plastics are usually good insulators but may allow some current to pass under certain conditions (Nave 2012; Babrauskas 2003b p.775; DeHaan, Kirk and Icove 2012 ch.10). The conductors in the PV switchgear used in this research are metals (brass or copper). The terminal block insulating material is plastic (nylon 6,6) (Kraus & Naimer Limited 2015).

For an ‘electrical fire’ *per se* to be established we need to comply with the fire tetrahedron theory and therefore require fuel and oxygen in sufficient proportions for the chemical reaction and create a self-sustaining fire. Oxygen (O_2) is normally supplied by the atmosphere and will be assumed to do so for the purposes of this research. Fuel for an ‘electrical fire’ is normally initially supplied by decomposing electrical insulation plastics (polymers). These plastics have to be heated sufficiently by an electrical fault for pyrolysis to occur. A flaming fire will only occur if the resulting pyrolysis products from heated insulating material are mixed in appropriate proportions with O_2, reach the appropriate ignition temperature and ignite. Ignition can be supplied by exposure to a pilot ignition source above the minimum ignition energy for the evolved pyrolysis products, or if the mixture reaches auto ignition temperature (Babrauskas 2008; Babrauskas 2003b pp.65-77).

The social science section of this research has shown that not all reported 'electrical fires' are actual fires [see section 5.4]. It is possible the production of pyrolysis product from an overheated electrical circuit or component could be observed by a witness, or detected by mechanical means during the heating period prior to combustion becoming self-sustaining. Visible or detectable pyrolysis products would probably be described as smoke by a lay witness, or an automatic detection signal could be activated (DeHaan, Kirk and Icove 2012 p.313; KFRS 2014) [see appendices B1.3, B2.3.6 and B2.3.7]. Therefore, an electrical fault causing switchgear to overheat could be described as being 'on fire' by members of the public witnessing visible pyrolysis product, or an automatic fire alarm could be activated by pyrolysis vapours and the fire service called to attend for either case. This could occur in some domestic properties, for automatic smoke/fire detectors are sometimes required for domestic dwellings, as outlined in Approved Document B of schedule 1 of the Building Regulations. They are not however required in an unoccupied roof space, where PV systems inverters and associated circuits are sometimes located (DCLG 2015). We will see in later chapters that incidents of this nature could be recorded as either a fire or as a false alarm *(KFRS 2014)* [see appendix B1.3].

Electricity can supply sufficient heat energy to initiate combustion from radiated heat (electric arcs and/or electrical tracking) and/or from heat generated by work done on conductors and insulators (ohmic heating) by electricity passing through high resistance contacts, or from overload of design parameters (Babrauskas 2003b pp.540 & 549; DeHaan, Kirk and Icove 2012 ch.10; KFRS 2014).

2.8.1 Electric arcs

Electric arcs occur when a current jumps between conductors and passes through gas (or ionised gas). We have seen that direct electric current has a constant value and that alternating current cycles through the zero value point many times a second. For example, mains AC current changes between positive and negative values 50 times a second in the UK (50 Hz) and 60 times a second (60 Hz) in the USA. Therefore, no current is flowing 100 times a second for UK mains power, or 120 times a second in the USA. This causes any AC arc to spontaneously extinguish as the current cycles through the zero values, and the arc may not re-establish when the cycle reverses (Babrauskas 2003b p.541). This affects the intensity and sustainability of an electric arc, for once an arc is established from a DC supply it is more difficult to break than for an AC one (Babrauskas 2003b p.545; Cotterell 2012). The temperature of such an arc varies according to the power involved and distance between the conductors, however it can be many thousands of degrees. This can raise the temperature of metal conductors to above their melting point (copper melts at 1083^{o} C) and then carry molten metal globules within the electric (plasma) arc. Metallic material carried in the plasma stream can cause a post fire indicator of identifiable metallic splatter and beading, after the globules of molten metal collect and condense on the conductors. Beads can form at the end of a conductor in the case of line (or series) arcing and on the sides of conductors in the case of cross conductor (or parallel) arcing (Babrauskas 2003b pp.546 & 795; Daeid 2004 pp.82 & 87; DeHaan, Kirk and Icove 2012 ch.10 p.454; ESFRS 2015; Hobbs 2010). Metallic splatter can sometimes be observed adhering to such beads, enabling the localised melting and beading caused by arcing, to be distinguished from melting which may have been caused by heat from flame impingement (Babrauskas 2003a).

2.8.2 Tracking

Tracking is a situation where electric current passes over the surface of insulating materials. Tracking can be caused by damp or the creation of a conductive carbon path on the surface of an insulator, or semiconductor. Dampness can be introduced by poor installation practices, ageing, weathering, or the direct application of water (due to firefighting perhaps?). Carbonisation, the reduction of organic matter to char (which is an electrical semiconductor) (Babrauskas 2003b p.775; DeHaan, Kirk and Icove 2012 p.431) can be caused by heating, including repeated low temperature heating. An electrical current will take the path of least resistance and may pass along a tracking path on the surface of an insulator, causing localised heating of the exterior of the insulator, or the substrate on which the insulator is mounted. If this substrate is combustible, ignition of that material may occur (Babrauskas 2008; Babrauskas 2003b pp.312 & 546; DeHaan, Kirk and Icove 2012 pp.432 - 434; Hobbs 2010).

2.8.3 Resistive heating or ohmic loss

When an electrical current passes through the conduction band of matter, free electrons are stimulated to move. In order for this to occur these electrons have to overcome their inherent random movement. This change from random kinetic movement to an organised direction requires energy, which therefore creates resistance to electrical flow and means the electrical current is doing work. This work raises the temperature of the matter and stimulates photons to be emitted from the surface, the converse of the process discussed earlier. As the temperature of the conductor increases these photons of EM energy can be emitted as IR (heat) or visible light EM energy. This effect can be observed from a simple electric bar fire or incandescent light bulb (Ivison 1977 p.2; Montgomery and McDowall 2008; Nave 2012).

Resistance to current passing through a conductor is proportional to the length of the conductor and inversely proportional to the cross sectional area of the conductor (Nave 2012). As discussed, any electric current passing through a conductor creates heat as electrons making up the conductor collide. If too much current is forced through a conductor of too small a cross sectional area excessive heating will result and an overload is said to have occurred. Heating can also result from high resistance caused by a loose electrical connection, for such connections may not maintain the appropriate surface contact area in the terminal proportional to the cross sectional area of the conductor. Furthermore, loose connections can allow for the formation of oxides on the surfaces of the metal within a connection. Oxides are highly resistant to electrical flow, creating a resistance between the surface contacts of the conjoined conductors. A loose connection can therefore lead to localised heating of an electrical connection (Babrauskas 2003b p.550; DeHaan, Kirk and Icove 2012 ch.10; Hobbs 2010; Mansi 2012). Vickers *et al* (2010) have shown that this can occur at very low voltages.

2.8.4 Semiconductor heating

We have seen that conductivity through solids is dependent on the ability of free electrons to move in the conduction band of materials and that resistance to electrical conductivity is caused by the need for work to be done in imparting energy to those electrons. Some materials intrinsically display semiconducting properties, and we have seen that electrical conductivity and the photovoltaic effect of semiconductors can be raised by doping (adding materials such as boron, gallium or aluminium) to increase conductivity. Band theory tells us that at temperatures above absolute zero (0K or approximately -273ºC) internal kinetic energy in intrinsic semiconductors, such as silicon (Si), causes electrons to break free from valence bands and become free electrons in the conduction band. A 'hole' is left from where the electron broke free and electrical conduction also takes place between these holes, with hole conductivity occurring in the reverse direction to electron conductivity; this effect changes with temperature [fig 2 (vi)] (Lund *et al*. 2008; Nave 2012).

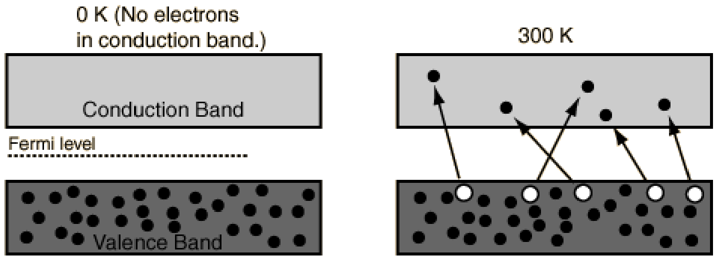


Fig 2 (vi) Electrons move to conduction band leaving holes adapted from Nave (2012)

Physical and chemical properties of insulating materials can change with degradation due to heating, weathering and ageing. As volatile compounds evolve from hydrocarbon based insulators, such as PVC, remaining materials have been seen to change their conducting properties (Chen *et al*. 2006). The effects of thermal degradation and UV weathering on the properties of nylon (polyamine) insulating materials have also been examined and methods of enhancing and extending these properties explored (Amin and Amin 2011; Glot, Golotina and Shardakov 2015; Jia *et al*. 2014; Thanki and Singh 1998). As the insulation properties of materials alter they may become semiconducting. This may result in resistive (ohmic) heating within the insulation material and Vickers *et al* (2010) have shown that resistive heating in semiconductors and circuitry, such as printed circuit boards, can occur at very low voltages.

It is possible therefore that any one, or a combination of any, of the above electrical causes of fire may allow fire to originate in the components of a PV system.

Chapter 3. The Investigation of Fires in the UK

3.1 Forensic fire investigation

De Haan (2012 ch.1) and Babruskas (2003b ch.1) (both American authors) tell us fires should be investigated based on the application of scientific principles. However, who should investigate, along with which skill sets and knowledge are required in order to do this, are the subject of much debate (UKAFI 2013). After many years of discussion, a protocol for UK fire investigations is currently being drafted (Daeid *et al*. 2014).

No single service is tasked with carrying out forensic fire investigation (FI) in the UK. Rather FI is carried out by numerous practitioners at differing times depending on the circumstances. These various professionals bring differing skills, knowledge and experience to a fire scene. However, in order to establish the truth, all fire investigators must apply the same rigour or evidence may be lost. Those attending a scene must work symbiotically and with mutual respect to discover the truth. This is well established amongst fire professionals and is classed as interagency (or partnership) working (Mansi 2012; Daeid *et al*. 2014; UKAFI 2013). As an established method for fire investigation this can be powerful, however, the hierarchy that forms within this interagency approach could suppress confidence levels in some of those professionals involved.

Klein (1999 ch.5 & 16) postulates that confidence in one's own ability increases with experience. This is especially true for emergency service staff who rely on naturalistic decision making as their normal day-to-day paradigm. For in the first instance the people examining fire scenes in order to establish the origin and cause of a fire are firefighting officers and not primarily fire investigation experts. These first responders are the people tasked with reporting fire data to the Government (KFRS 2015). They are also tasked with initialising further investigation as required, by identifying whether a fire is accidental or deliberate (DCLG 2014). Therefore, data used nationally to develop and steer strategy is based on records created by non-experts. However, Klein (1999 p.104) also suggests front line staff can be taught to '*… learn like experts'*, building their experience and confidence by repeated exposure to incidents, training and working in a team with experts. Using these experiences to accurately determine information such as the origin and cause of a fire requires both knowledge of fire science (DeHaan, Kirk and Icove 2012 p.2) and an understanding of the big picture, such as the relevance of accurate data input, to allow the development of team decision making (Klein 1999 ch.14).

3.2 Strategic decision making

National UK Government, local Government and fire and rescue authorities increasingly apply modern management techniques, especially in times of public service austerity (Chalabi 2013). These techniques, including data analysis and target setting, use data gathered from fire incidents to develop appropriate operational and fire safety strategies (KFRS, 2015). Knowledge gained is also used by industry, non-governmental organisations and charities, to inform, challenge and modify public behaviour, identify trends in product failure, develop safer alternatives and give guidance to members of the public, manufacturers and installers (CLG 2014). Examples of this would be Electrical Safety First (formerly the Electrical Safety Council), who give advice on electrical safety to the public (Electrical Safety First 2015), or potentially the Microgeneration Certification Scheme (MCS), which is responsible for standards and licensing of PV installations (MCS 2015).

If strategic decisions regarding public safety are to be appropriately made based on data, these data must be accurate, valid and relevant (Bernard 2011 pp.23 & 41-47; Newing 2011 ch.15 & 16). Therefore, fire data should be accurately ascertained and recorded. If data in the system are invalid, or based on false assumptions, then an inappropriate business model can be developed by managers (Johnson *et al*, 2006 p.13 & p.462). Strategic decisions made based on such misleading data can be potentially damaging, creating a false sense of security and/or allowing inappropriate tactics to be employed to lay ghosts which do not exist (Haug, Zachariassen and Dennis 2011). For example, from a fire perspective, data may indicate the largest numbers of fires in domestic kitchens are caused by the ignition of oil and fat. This may lead to the assumption by analysts and community safety managers that these fires are being caused by the widespread use of deep fat cooking methods (chip pans). Whereas the actual cause of these fires could be poor housekeeping leading to the ignition of fat deposits in dirty ovens and/or grill pans. Inappropriate home (community) fire safety advice may therefore be given challenging the use of deep fat cooking, which members of the public may feel is not applicable to them, leading to relevant fire safety advice being ignored, thereby negating the principle of targeting advice based on data. For instance, in the early 2000's KFRS targeted home fire safety advice on cooking, including the purchase and deployment of specialist chip pan demonstrators and supporting staff for interacting directly with the public to reduce the frequency of chip pan fires. By 2008 national fire data showed the numbers of chip pan fires *per se* had fallen by half in 10 years (DCLG 2010 p.29) and members of the public were openly criticising the use of these vehicles to give a perceived out of date home cooking fire safety message. Therefore, KFRS changed its message to include other forms of cooking with oil, including woks, ovens and grill pans. KFRS did not immediately re-badge its *'Chip Pan Demonstrators'* necessitating the accompanying staff to explain why the message was still relevant (KFRS 2009).

Public sector managers may also feel personally threatened or disempowered by targets based on invalid data, potentially leading to the collection and collation of false data, or even the manipulation of data by managers to better reflect a perceived short term performance for personal or political expediency (Haberberg and Rieple 2008 p.649) this can be an example of managerialism (Jury 2012).

A great deal of public money, time and effort can be wasted employing fire staff to give inappropriate fire safety messages based on inaccurate data, or a flawed extrapolation of those data. Fire safety (or firefighting) advice based on inaccurate, invalid, or unreliable data collected from fires supposedly originating from PV systems, or missed from fires incorrectly judged to have started from other causes, could mislead the public (and/or the fire and PV industries) as to the dangers from PV systems on fire, or the potential for cause of fire from PV systems. Accurate, valid and relevant data shared between national and local government departments, industry and services will allow appropriate safety messages to be given and received. Following a fire attributed to PV in 2015, an FRS gave a press release stating "*… solar panels were [sic] no more dangerous than any other electrical product…*" (BBC 2015). This research examines if there is sufficient empirical evidence to make such a nationally reported assertion at this time, by examining the factors affecting the accuracy and validity of fire data with regards to PV in Kent. Further research is required to ascertain the accuracy and validity of fire data nationally and whether managerialism is affecting the collection and collation of national data.

3.3 Fire investigation practitioners

In the UK, fire and rescue services, the police, private forensic services providers (FSPs), the Health and Safety Executive (HSE), or specialist investigators, such as the Air Accident Investigation Branch (AAIB) or the marine equivalent (MAIB), all have a responsibility to investigate fires. It may be that two or more of these agencies will work together in a multi-agency approach but the particular agency tasked with carrying out a specific fire investigation will have primacy depending upon the relevant legislation governing the need for the specific investigation (KFRS 2014; Daeid *et al*. 2014).

If crime is suspected the police have primacy to investigate a fire, whether set as a crime in itself, or to mask another crime. However, in England and Wales there is no specific crime of arson. Setting a fire which causes damage to another person's property is covered by the Criminal

Damage Act (1971) and the term arson is used as shorthand where criminal damage is caused by fire (Criminal Damage Act 1971). If a person is killed by someone using fire as a weapon, the potential crime is murder. If a person is careless or reckless as to whether or not a fire set by them causes harm to a third party and that party dies, the crime is most likely involuntary manslaughter. This burden of proof as to the personal intent and knowledge of the alleged perpetrator is the reason for the all-encompassing charge of arson with intent to endanger life being used in the early stages of an investigation (CPS 2008). An example of both these charge types being the fire which occurred at Wood Hill, Spinney Hills, Leicester, on Friday, 13th September 2014 (Healy 2014). Fire may be used by a criminal to mask other crimes such as burglary, and again the police have primacy to investigate for such situations. Significantly for this research, an accidental fire may even result in a police led criminal investigation, either because the cause of the fire was initially unknown, or because alternative charges such as corporate manslaughter, or potentially those covered under negligence law (CAB 2015) may be brought. This could be applicable to a poorly installed or manufactured PV system.

If a person has a fire in their house or vehicle and that property is insured, their insurance company may appoint a private forensic fire investigation company to carry out an investigation on their behalf. Such private fire investigation companies are tasked primarily with ascertaining the appliance, or other item, responsible for the origin and cause of the fire, in order to allow the insurance company to recover costs, or establish the possibility of fraudulent claims (Burgoynes 2015; Hawkins 2015). If fire is considered to be a factor in an industrial accident, air crash, or marine incident, the specific agencies responsible for investigating those incidents will take fire into consideration as part of their investigations (AAIB 2015; HSE 2015; MAIB 2015). However, as first responders' fire and rescue services are the gatekeepers of further investigation through the national Incident Recording System (IRS) (DCLG 2015; Mansi 2012).

3.4 Powers to investigate fire

The provision of a fire and rescue service in the United Kingdom is dictated by Act of Parliament. The 1947 Fire Services Act governed fire services set up and run by local authorities following the disbanding of the National Fire Service (NFS) after the Second World War (Fire Services Act 1947). The Act gave numerous powers to local authorities to establish and run a fire service, called fire brigades in most cases in those days (Ewen 2010; Klopper 1984). However, the 1947 Act did not place a duty on these fire services to investigate the origin and cause of fire, neither did the Act give any powers to carry out fire investigation. Fire services were however required to report the most likely origin and cause of fires they attended to the Home Office, which at that time was the governmental department with responsibility for fire services. This was carried out using a form, FDR1, which by the end of its use was a comprehensive four-page tick box and free entry paper document [see appendix B1.1]. Form FDR1 was completed by the attending fire service officer as soon after the event as practicable. The form asked numerous questions including those as to the origin and cause of the fire and the most likely ‘appliance, act, or defect’ *(KFRS 2014)*, which may have contributed.

In 2000, governmental responsibility for the fire and rescue service changed from the Home Office to the Department for Transport Local Government and the Regions (DTLR). Responsibility then moved in June 2002 to the Office of the Deputy Prime Minister (ODPM), and finally to the Department for Communities and Local Government (DCLG) in 2006 (DCLG 2015). The new department changed from using the paper based FDR1 to a paperless electronic reporting system called the Incident Recording System (IRS) for collecting fire data (KFRS 2014). Responsibility for inputting data into the system remained with the fire service junior officer (now known as a supervisory manager) who first attended the scene. Completion of the IRS requires the attending supervisory manager to ascertain, amongst other things, whether they believe the fire to have been started accidentally or deliberately. The following table [table 3 (i)] from the KFRS IRS guidance document shows the acceptable possibilities.

Motive	**Guidance**
Accidental	*Caused by accident or carelessness (not thought to be deliberate).* *Includes fires which accidentally get out of control e.g. fire in a grate or bonfires.* *Includes fires started by children under 9 years old unless there is evidence to suggest otherwise.*
Deliberate – own property	*Where a fire is started deliberately.* *Own property refers to the normal occupiers - including a child in their own house.*
Deliberate – others property	*Where a fire is started deliberately by somebody who is not an occupier of the property.* *This includes fires in non-residential buildings where the owner is not involved e.g. fires in office buildings, fires in barns, cars.*
Deliberate – unknown owner	*Where a fire is started deliberately but it cannot be determined whether it was own or others property.*
Not known	*Use where there is general uncertainty about the cause or motivation of the fire.* *'Not known' should only be used if absolutely necessary.*

Table 3 (i). Definitions for 'accidental' or 'deliberate' fires and guidance for selection of option as per KFRS IRS guidelines (KFRS 2014)

Data inputted into IRS is based purely on the attending operational fire manager's view; there is no requirement for validation or any supporting evidence as indicated in the excerpt from the KFRS IRS guidance below.

'Question 8.1 – What was the cause of the fire?

Select the option that best describes the main cause of the fire. It is not necessary to be ***certain*** *that the fire was due to the cause given, only that the cause was one that could be reasonably supposed, given the evidence available.'* KFRS IRS guide (2014).

Various data are also inputted into IRS at the same time, including identifying the room or compartment of origin of the fire, the most likely item, act, defect, or omission from which the fire originated and any power source. Data from the IRS is collected and collated by fire and rescue services, shared with the DCLG and published annually.

The 1947 Fire Services Act was repealed and replaced by the Fire and Rescue Services Act 2004 (Fire and Rescue Services Act 2004). The 2004 Act amalgamated many powers from the original 1947 Act and the Fire Precautions Act 1971 (Fire Precautions Act 1971). The Fire Precautions Act gave powers for fire and rescue services to authorise members of staff to inspect premises as 'Authorised Inspectors' in order (amongst other things) to ensure there were adequate means for escape from a building for the persons resorting to those premises. Inspections resulted in documentation, such as a fire certificate, being issued to show that means of escape from premises were safe for the numbers of people using those premises. Fire safety authorised inspectors were empowered to enter a property, including the power to take any person with them, carry out inspections, collect evidence, including the use of photography, and to interview responsible people and witnesses. It was an offence under the Act for a person to obstruct an authorised Fire Safety Inspector in the course of their duty.

The 2004 Fire and Rescue Services Act gave powers to fire and rescue services to investigate fires and the investigatory powers of Fire Safety Inspectors were incorporated into section 45 of the Act in order to empower fire and rescue services to investigate the origin and cause of fire (Fire and Rescue Services Act 2004). Although fire and rescue services were given the power to carry out fire investigations, the Act did not make fire investigation a specific duty for them. There still remained a requirement to identify data for statistical purposes, to be reported using the IRS system as discussed previously. However, the attending fire supervisory manager's view remained all that was required to collect this data.

Several fire and rescue services, including Kent (KFRS 2015), set up fire investigation teams, many with a research element to their function, in order to support their attending operational officers. However, this was seen by many fire and rescue services and local authorities to be an additional duty and not a requirement. In these times of austerity and fire sector cutbacks (Chalabi 2013) maintaining some of these FI teams may now be seen by many to be an unaffordable luxury.

Following the drafting of the 2004 Act, an attempt was made to rationalise the statistics regarding accidental and deliberate fires. It was identified by Government statisticians that the number of fires recorded by fire services as being ‘deliberate’ was completely at odds with the number of fires recorded as ‘arson’ in police statistics (Arson Control Forum 2005). In an attempt to deal with this situation Fire Service Circular 1/2006 (and corresponding Home Office Circular No 44/2006 for the police) was drafted to give guidance on the investigation of fires where the supposed cause was not considered to be accidental (DCLG 2006). The circular identified three levels of fire scenes examination [see appendix B1.2].

3.5 Levels of fire scenes examination

Fire and Rescue Service Circular (FRSC) 1/06 (DCLG 2006) outlined a level 1 fire scene as one where the attending supervisory manager was capable of identifying sufficient information regarding the origin of fire for statistical recording purposes. Specifically, there was a requirement on the attending supervisory manager to identify if the fire was supposed as accidental or deliberate. If the attending supervisory manager was unable to identify this, then for those fire and rescue services which had a fire investigation team, further guidance could be sought from a specifically trained fire service officer. This was identified within the circular as being a level 2 fire scene. Should it be deemed necessary to call in specialist assistance from outside the fire and rescue service, this was adjudged to be a level 3 fire scene (level 3 fire scene examinations therefore covered the attendance of forensic scientists and other experts, such as electrical engineers). Fire and rescue services without specifically trained fire investigation (level 2) fire scenes examiners, either borrowed suitable inspectors from a neighbouring fire and rescue service, or defaulted to level 3.

3.6 Memoranda of Understanding

FRSC 1/06 also gave guidance on the setting up of a Memorandum of Understanding (MoU) between the local fire service and the local police service so that there was pre-agreement as to what level of resources would be deployed by each of the services to attend specific types of fire incident. One such MoU has been set up between Kent Fire and Rescue Service and Kent Police. Policies are set out within this memorandum for the investigation of fatal fires, serious criminal fires, and repeat low-level fire offending [see appendix B1.4]. There remains however the necessity for fire scenes to be examined adequately by the first attending fire service supervisory manager in order that the higher levels of examination are called for by them if required. Should an attending level 1 fire scenes examiner not recognise the situation for what it is, then assistance may not be sought and inaccurate data may well be recorded within the IRS. As the gatekeepers of further scene examination and data collection, level 1 fire scenes examiners (FSE) therefore need to be adequately trained for their role.

3.7 Training in fire investigation

There is a broad range of attitude towards the training of fire staff in fire investigation (FI) and there is not, as yet, any nationally recognised qualification for FI in the UK (Daeid *et al*. 2014).

Some fire and rescue services choose not to have specialist FI teams, relying solely on experiential learning for their supervisory and senior managers to carry out their duties as required for the completion of IRS [See appendix B2.3.6].

Fire and rescue services within the UK can train to the National Occupational Standards (NOS) and there is a NOS specific to FI (NOS 2015). However, this is not mandatory. There are training programs and continued professional development (CPD) events, organised and run by professional bodies. One example being the Institute of Fire Engineers (IFE 2015), who can examine knowledge of FI as part of grading within the institution. Another example being the International Association of Arson Investigators (IAAI), with their Certified Fire Investigator (CFI) scheme, (IAAI 2015) which is based on an American system. Again there is no requirement for any UK fire and rescue service to train any of their staff to these standards and it is acceptable to rely on experiential learning alone.

In order to give FI instruction to their specialist (level 2 FSE) investigators, fire and rescue services such as Kent, who choose to set up a specialist FI team, usually follow a set programme of training. This may include training by external specialists such as the now disbanded Forensic Science Service (FSS), the Fire Service College or private forensic services. This is usually followed by a period of experiential and specialist learning, shadowing and mentoring. The trainee specialist FI officer is normally only authorised to carry out examination of level 2 fire scenes at the end of this period and when both the trainee and assessor are satisfied with the levels of competence being displayed (Kent Fire and Rescue Service. 2014; Mansi 2012).

3.8 Tacit knowledge

Experiential learning can lead to unspoken tacit knowledge which is sometimes difficult to identify, possibly even by the person with the knowledge, or the organisation employing that person (Klein 1999 p.170). This may unknowingly lead fire scenes examiners towards conclusions regarding the origin and cause of fires based on firefighting observations alone.

Firefighting is a highly dynamic activity, it requires those commanding teams of fire fighters to make extremely quick decisions and learn to react almost instantaneously to changing situations (Brunacini 2002 ch.2). Klein (1999 ch.2 & 3) discusses that such experiential learning is essential in dynamic emergency and military services in order to allow for the development of naturalistic decision-making processes such as recognition primed decision making. Naturalistic decision-making can be enhanced by the incorporation and integration of all members of the team. However, for this to be successful all members of the team need to be aware of the situation and the required outcome. Fire and rescue services are extremely good at this with high levels of effective teamwork based on consensual command (Baigent 2001). On the other hand experiential learning can lead to the development of tacit knowledge with the perpetuation of established ideas (sometimes erroneous) and the rejection of change, or even the development of a ‘groupthink mentality’ (*ibid*). This can be exacerbated if members of the fire and rescue service (the team) are uncertain of the relevance of what they are doing (Klein 1999 pp.243 - 246).

If fire and rescue service supervisory managers are not aware of the relevance of data they collect with respect to the formulation of national operational strategic decision making, national community safety advice and guidance on the identification of trends; can they be seen to be part of a holistic team, and are data they produce accurate, valid and relevant?

Chapter 4 Forensic Science as a Multi-discipline

4.1 Competence

Forensic science is a discipline which incorporates both scientific and legal principles (CSFS 2015). Various agencies therefore have to work together to attempt to successfully complete a forensic fire investigation (DCLG 2006; DeHaan, Kirk and Icove 2012 p.658; Kent Fire and Rescue Service. 2014; Daeid *et al*. 2014). There has been much debate over the last half century as to what constitutes forensic science *per se* and who should, or should not, be considered an expert in the field. A great deal of emphasis rests on an investigation being carried out by a competent practitioner (Daeid 2010 pp.223-225 & 247-248), recognised by Courts as a person who has addressed the many and varied factors which make for competence (Doyle 2015) [see fig 4 (i)].

4.2 Confidence

Klein (1999 p.279) however, suggests that personal confidence in one's own ability is important. It is one thing to demonstrate competence, in an examination for example, but quite another to feel confident in your own ability whilst working in a team; to be able to take independent decisions, come to conclusions, make judgment calls regarding evidence and therefore, to be able to report reliably and accurately.

Fig 4 (i) Diagram showing various possible components making for practitioner competence adapted from Doyle (2015)

4.3 Multiple disciplines

Forensic science as a discipline can be seen to integrate the multiple disciplines of the natural sciences of chemistry, biology and physics. However, forensic science cannot be seen as a natural science alone, as it has a primary duty to the Courts which adjudicate in criminal or civil proceedings (CSFS 2015). It can be argued therefore the inclusion of the human element into the equation, with witnesses and forensic science practitioners adding lay and expert evidence (CPS 2014), means that forensic science should also involve the social sciences of anthropology, psychology, criminology and sociology.

For example, let us suppose a fatal house fire has occurred and explore how the differing scientific disciplines may work together to come to a conclusion. Forensic biology (pathology) will be used to ascertain the cause of death. Biology may also be used to ascertain the identity of victims (or suspects should there be suspicion of foul play) using DNA (*ibid*). Knowledge of chemistry and physics will be used by a fire investigator to ascertain the origin and cause of the fire. Should an accelerant (such as an ignitable liquid) be suspected, then samples will be taken and analytical chemistry used in order to identify the most likely fuel used (DeHaan, Kirk and Icove 2012 ch.14). However, if we examine the human element associated with this hypothetical incident, as well as a victim and possibly a perpetrator, there may be numerous conflicting witnesses. For example, there may be lay witnesses, such as passers-by, who having limited experience of observing fires could describe a huge fireball and a rapidly developing fire, being adamant in their assertion the fire must be deliberate. To counter this there will be professional witnesses, such as fire fighters, who may describe a full compartment fire development event such as a backdraft, or flashover (*ibid*). A working hypothesis must take all evidence into account (Mansi 2012) both physical and human.

4.4 Transdisciplinarity

Popper (1959 ch. *x*) asserted that you cannot prove theories or natural laws are true by documenting repeated examples in order to verify hypotheses. Just because in our experience the sun has risen every day *'…we cannot know for certain whether the sun will rise tomorrow'* (*ibid* p.252). You can however prove hypotheses to be false, because it only takes one negative case to disprove an established law or theory. An example of this is the replacement of Newtonian physics in favour of Einstein's relativity theories and quantum mechanics. All that has to be achieved forensically in order to establish reasonable doubt is to show an exception. If it can happen once, it can happen. If it has happened and it cannot be explained by current theories and the available evidence, then the theory, or the human observation and interpretation of the theory, is flawed. Or perhaps the theory is not applicable, because the circumstances at hand do not conform to those in the standard.

In order to establish the truth behind any fire incident, forensic science cannot stand as a natural science alone. It must also be more than just interdisciplinary in its approach, where information is shared on work carried out in relevant fields by natural science and social science working separately. It should be more than a multidisciplinary approach, where work is carried out across a field in parallel, but still separately. A more pragmatic methodology establishes '*transdisciplinarity'* (Newing 2011 p.13) as the norm, integrating elements from each science, thereby creating a novel approach.

Caddy in the introduction to Daeid (2010) observes:

> '*Forensic science needs to look at novel applications of methods and processes developed in other disciplines to enhance its repertoire of investigative tools' (Daeid 2010 p. xvii)*.

It can be argued therefore that to obtain epistemological truth applicable to the ontological world (David 2005 p.65), forensic science should be fully transdisciplinary (Newing 2011 p.13) in its paradigm. For the act of looking for the truth can hide the truth if we are constrained by the *'…realism and materialism of purely natural sciences'* (David 2005 p.64).

4.5 The need for a transdisciplinary approach

Fires purporting to originate from PV solar systems have been reported in national news (BBC Leicester 2013; BBC 2014; BBC 2015) and it has been stated by a fire service spokesman that *"…solar panels were* [*sic*] <u>*no more dangerous than any other electrical product*</u> [author's underline]. *Anything electrical can develop a fault through any number of reasons," (BBC 2015).* Therefore, by implication there is no difference between fires originating from such a system or any other electrical circuit. Is there empirical evidence on which to base such a view? For in order to recognise the origin of a problem, the problem itself has firstly to be recognised, reported, or otherwise raised to prominence. If data collectors are unaware of the significance of evidence they are confronted with, or under confident in their ability to recognise it, data may be missed, or misreported, allowing an emerging trend to be overlooked. If this is the case policy makers such as national Government departments will not request further data on that trend; for they will not be aware of it. For you don't know what you don't know. This can lead to the perpetuation of false assumptions at all levels, with evidence only being requested to fulfil those assumptions, and data collectors only looking for evidence in order to support those assumptions (Cole 2004 ch.19; Haberberg and Rieple 2008 p.654; Haug, Zachariassen and van Liempd 2011; Johnson, Scholes and Whittington 2006 pp.454 -466).

Applying the principles of forensic transdisciplinarity (Newing 2011 p.13) this research sets out to establish whether the increased use of PV systems is reflected by the number of fires reported as originating from such systems and if there is an identifiable common point of failure leading to fire. It also examines whether causes of fire originating from such systems are recognised by level 1 fire scenes examiners and develops an experimental method to recreate post fire indicators likely to be caused during the early stages of such a fire, in order to guide future scene examination.

4.6 Research aims

The aims of this research are to use a transdisciplinary approach in order to identify:

1. Whether fires recorded as originating within Photo Voltaic (PV) solar systems are proportionate to fires arising from other electrical circuits.
2. Whether fires which may occur where the origin should be attributed to a PV system are recognised by fire scene examiners.

3. Whether the records are valid.

4. The likely point of failure of a PV system which could cause a fire.

5. The probable mechanism for that failure.

6. Expected observable post fire indicators likely to be associated with that failure.

4.7 Research objectives

In order to achieve these aims, this research sets out to:

1. Identify potential problems with the accuracy, reliability and validity of national data with regard to PV and fires.

2. Identify the mechanism by which fire scenes examiners recognise and report a potential PV system failure which may have led to fire.

3. Identify if there may be a significant commonality of origin and cause of fire amongst known incidents where a PV system has been established as the cause.

4. Identify a method to clarify the expected observable damaged caused to plastic insulation material by internal heating of a specific section of PV system circuitry.

4.8 Research methodology

This research uses the following methods, applied in accordance with the principles of transdisciplinarity, with each method supporting and being interdependent on each other to form conclusions.

1. An examination of the Department for Communities and Local Government (DCLG) incident data (secondary data).

2. A review of Kent Fire and Rescue Service (KFRS) incident data (secondary data).

3. The gathering of primary data from level 1 FSEs, utilising a social science mixed methods approach in order to identify their levels of personal confidence in recognising PV systems as the potential origin and cause of fires.

4. A documentary analysis and qualitative review of anecdotal evidence appertaining to PV fires in Kent over a specific time period, by semi structured interviews, thereby cold case re-examining incidents where PV is known to have been present.

5. Experimental examination of heated components of a PV system, in order to develop a method to observe post fire indicators attributable to thermal decomposition and therefore develop a hypothesis regarding the origin of fire.

Chapter 5. Evidence of Fires Originating in PV systems.

5.1 National Incident Recording System data

An obvious place to start research into the recognition of fires originating from any specific electrical system would be to compare and contrast national data. Examination of these data show the numbers of PV systems being installed as an alternative energy source is rising (DECC 2015) and the numbers of fires attended by fire and rescue services is currently at a 30 year low (DCLG 2015). However, Popper (1959 ch. *viii*) tells us that data extrapolation is an interplay between frequency assumption and chance. Therefore, data collected and collated by individual FRS, DECC and DCLG have to be valid in order to formulate assumptions on the probability of the likely future occurrence of a similar event. Qualitative, quantitative and mixed methods research (Bernard 2011 ch.15; De Vaus 2002 p.5; Newing 2011 pp.57-60) was therefore carried out in order to establish the validity of data with regards to solar power and fire.

As discussed in chapter 3, every fire attended by a fire and rescue service within the United Kingdom results in an entry being made into the national Incident Recording System (IRS) by an attending fire officer, usually a level 1 fire scene examiner (FSE). A reportable fire is defined by DCLG (2015) as *'an event of uncontrolled burning involving flames, heat or smoke and to which the fire and rescue service attended*'. These data are wide ranging and show amongst other things; the compartment of origin of the fire, the severity of the fire, any fire detection affecting the outcome of the fire, firefighting methods and any fatalities or injuries sustained by people affected by the fire.

IRS also requires data to be entered regarding the supposed cause of the fire. When completing an IRS entry, the following options would be available to a supervisory manager wishing to record a cause of fire as originating from a part of a PV system:

- *‘Faulty fuel supplies-electricity*
- *Faulty leads to equipment or appliance only*
- *Fault in equipment or appliance*
- *Overheating unknown cause*
- *Other’*

Data is then requested regarding the person, or action ‘*reasonably supposed*’ to have caused the fire. The datasets are broken down into *‘age related human’*, *‘animal’*, *‘other (not person or animal, including natural occurrences)*’ and *‘not known*’ (DCLG 2015; KFRS 2014).

Fire service supervisory managers completing IRS are asked what, in their view, the source of ignition was. The KFRS guide (2014) [see appendix B1.3] clarifies that if more than one appliance is involved the supervisory manager is to identify the most likely item. Data are requested electronically via a drop down selection box within the program and have to be entered into a main dataset and sub dataset for this question [see appendix B2.3.6]. For example, there is a main dataset for *‘cooking appliance’* which is then broken down into subsets such as, *‘cooker including oven’, ‘microwave oven’, ‘grill/toaster’* etc. Examination of the national data set, KFRS guidance notes and interviews with KFRS staff reveals there is no dataset, or subset, specifically for PV systems, or DC electrical supplies, therefore the supervisory manager completing IRS for such a fire has to make a best fit (Klein 1999 ch.3) attempt to record the origin and cause. Let us explore the options available to supervisory managers who believe they have identified the origin and cause of a fire as having probably originated from a fault within a PV system.

Within the IRS *‘source of ignition’* data entry, there is a main dataset of *‘other domestic style appliance’*. There are 22 subsets to this main set. There is also a main dataset for *‘electric lighting’* with five subsets. None of these list options which would be applicable to a PV system. There is a main dataset for *‘heating equipment’* with seven subsets, one of these subsets *‘power source’* may attract entries regarding PV. There is a main dataset *‘electricity supply’* with two subsets of *‘apparatus-batteries generators, including meter, fuse, junction box’* (as these are defined as apparatus in the wiring regulations (BSi 2015 p.23)) and *‘wiring, cabling, plugs’* which may attract an entry with regard to being PV. There is also a main set for industrial equipment, which has a subset of *'other'* which may attract an entry with regard to PV, especially if the PV system is a commercial one. The final datasets which may attract entries with regards to PV systems are the catch all dataset boxes of *'other appliance'* or *'equipment other'* and *'not known'* (DCLG 2015; KFRS 2014).

It would be logical to expect that the dataset to attract the entry for a PV system failure resulting in fire would be *'electricity supply'* with its subsets of *'apparatus-batteries generators (including meter, fuse, junction box)'* and *'wiring, cabling, plugs'* (*ibid*). However, it can be seen that the categories for the source of ignition in the IRS are very broad and for electrical items such as PV systems, possible recordable sources of ignition are not specific. This means it is not possible to ascertain from the national statistics the exact type of wiring or appliance which in the view of the attending fire supervisory manager has caused a fire, only that the probable origin and cause of a fire has been attributed to electricity. Neither is it possible to ascertain the exact type and voltage of the power source. Consequently, it is not possible to ascertain from the national fire data exactly how many photovoltaic systems have failed and caused fires in a given time period.

It has not been possible to identify the total number of PV systems in the UK, as data are only available with regards to those users of PV systems who are also claiming the feed-in tariff. Those people not wishing to connect to the National Grid are not recorded, nor are records available for the numbers of PV systems installed before 2010 (DECC 2012). Therefore, it has not been possible to ascertain if the numbers of fires where the origin is believed to be from a PV system, have been increasing proportionately to the incidence of fitting of such systems. Neither has it been possible to identify if the peak demands in installation of PV caused by changes to feed-in tariffs have resulted in peaks in recorded fires.

It was therefore decided to examine local data to ascertain if these records differed in any way from national data.

5.2 Local incident data

Many fire and rescue services, being aware of the limitations of the national datasets, record additional information during the collection of the statutorily required data. Qualitative examination of interview transcripts confirmed KFRS is one such service [see appendix B2.3.6 and B2.3.7]. For example, a local update has been made to KFRS IRS giving an additional ignition source option under the electricity supply category for; 'Solar (PV) panel components/wiring' [see photo KFRS IRS1]. This additional local subset is collated within the 'Wiring, cabling, plugs' or 'Apparatus - batteries, generators' options by KFRS QA managers before being supplied to the DCLG (KFRS employees 2015). This collation of data by a remote management team could result in managerial bias as discussed in paragraph 4.5. Further research is required to confirm if this is the case.

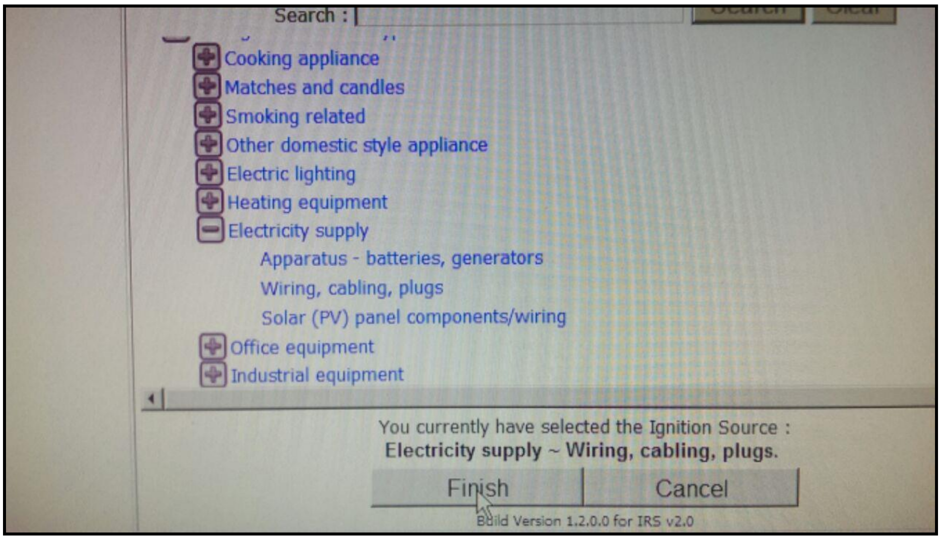


Photo KFRS IRS1. Screenshot of KFRS IRS data input program, in use to record 'electricity supply' and 'wiring, cabling, plugs' as the ignition source for an incident. Also showing 'Solar (PV) panel components/wiring' as a data subset option within the 'electricity supply' main data set (KFRS photo)

A request was made to KFRS for incident data with regards to electrical fires, and specifically records where solar power was recorded as being the cause of fire in the county. KFRS data for the period 2009 - 2014 (the period for which data were available) were examined for a secondary analysis (De Vaus 2002 p.86) for this research. These data show there are records of 6 emergency fire calls where solar energy was identified in IRS as the origin of the incident. This can be contrasted with a total numbers of reportable fires attended in the same period of 26,315. It was decided to evaluate the validity of those data with regards to solar power.

5.3 Ethical considerations

The examination of data appertaining to fires can be an intrusive process for the actors within such events, as personal data appertaining to victims and firefighting staff may be revealed during the process, potentially causing distress, or a breach of confidentiality. National fire data are considered to be open data within the definition of the Data Protection Act 1998 (Data Protection Act 1998) and therefore are freely available to the public (The Open Data Institute 2015). However, more specific local data were required for this research and therefore the following ethical considerations were addressed.

Permission was sought and received from board level principal staff within KFRS to use KFRS data and staff for this research. Permission for the release of data for research under the Freedom of Information Act 2000 (Freedom of Information Act 2000) was granted subject to limitations imposed by the Data Protection Act (Data Protection Act 1998). Therefore, fire victims' personal information in KFRS fire data was redacted by KFRS staff before transmission to the researcher. Furthermore, it was agreed to maintain anonymity of KFRS participants, thereby limiting, as far as practicable (*ibid*), secondary identification of fire victims and KFRS staff. A number of named KFRS staff were nominated by KFRS principal management to liaise with the researcher as required. This allowed direct contact to be made with KFRS staff members to request IRS data and to facilitate further contacts with appropriate KFRS staff for research.

The nominated liaison staff members were approached by the researcher to supply KFRS internal e-mail addresses for KFRS staff identified as being useful to this research. These e-mail addresses were supplied and members of staff contacted directly by the researcher to request their voluntary participation in the research. These staff included both uniformed operational and non-uniformed support staff working in the areas of IRS data quality assurance, fire investigation and operations.

KFRS fire data appertaining to fires where the presence of solar energy had been recorded in IRS were requested. On receipt of those data for the available period, five KFRS operational staff were identified as having recorded fires in IRS where the origin and cause was supposed by them to have been from solar power systems. Arrangements were made to ascertain the e-mail addresses of these staff, who were then approached by e-mail to request their voluntary participation in this research. It was revealed that one member of staff in this group had subsequently retired from KFRS. KFRS Human Resources department and appropriate Group management staff were therefore contacted by the researcher in order to ask if a request could be sent to the retired employee, by the ex-employer, to ask them if they would be willing to contact the researcher directly to discuss participation in the research. This occurred and the retired member of staff subsequently contacted the researcher by e-mail, agreeing to be interviewed.

Bernard (2011 ch.2) suggests that in research instruments can be things or they can be questions therefore, volunteers from the Fire Investigation Team (FIT), IRS Quality Assurance (QA) team and operational staff were also sought to participate in this social science based research. The research was designed to firstly identify the methods used by fire officers with IRS responsibilities to recognise and report PV fires, and secondly to assess their personal confidence in their own ability to do so. Cross method triangulation (Newing 2011 p.57) was carried out in order to establish the validity and reliability of such data, (Bernard 2011 pp.41-47; De Vaus 2002 pp.52-53). This was achieved by the use of a focus group and semi-structured interviews of managerial staff, along with semi-structured interviews and a mixed methods (Newing 2011 p.57 & ch.7) questionnaire based survey (De Vaus 2002 ch.7) of a broad spectrum of level 1 fire scenes examiners. Arrangements were therefore made to conduct the focus group and semi-structured interviews of KFRS staff whilst conforming to appropriate ethics.

The voluntary nature of participation and the commitment to maintaining anonymity with regards to the research were re-stated to all the participants on many occasions. The willingness of the interviewees to participate in the research, and to be audio recorded whilst so doing, for Newing (2011 p.112) tells us *'…recording is the only way to make a complete accurate record of the interview…'* was re-checked and noted; firstly, in e-mail correspondence, secondly over the telephone when arranging interviews, thirdly during the focus group and semi-structured interviews themselves [see appendix B2.3].

5.4 Qualitative analysis

A focus group and a semi-structured interview (Newing 2011 ch.6) were carried out with the IRS data quality assurance and fire investigation teams, in order to examine the type, quality, and scope of data collected by KFRS with regards to fires. The focus group method was chosen as the researcher is an ex-member of the KFRS FI team and therefore participants may not tolerate a more formal interview by him (*ibid*). The focus group was pre-structured [see appendix B2.1.1] and involved asking probing and convoluted questions (Bernard 2011 ch.8) leading to a full exchange of views by participants. The focus group was also used as an opportunity for the development process of the questionnaire to be used to gather data from level 1 fire scene examiners on their personal confidence in fire scene examination. This was achieved by exploring the level 2 fire scenes examiners' perception of the proposed questions during the focus group meeting. A two person group semi-structured interview was also carried out (Bernard 2011 ch.8; Newing 2011 p.101) to gather data from staff unable to attend the focus group. Focus group and semi-structured interview plans were drafted, [see appendix B2.1.1 and B2.1.3] then the focus group and a two person group interview took place in December 2014 and January 2015. The focus group was convened at Faversham Fire Station and the two person group interview was conducted at KFRS East Group Headquarters. The focus group and all the semi-structured interviews carried out for this research were recorded using a digital recorder and all conversations subsequently transcribed by the researcher [see appendix B2.3]. In order to accurately record these group conversations, including verbal interplay and also manage the focus group and group interview (*ibid*), notes were also made of the focus group conversation and the two person semi-structured interview by independent note takers, Ms Louise Peregrina and Miss Charlotte Moss [see appendices B2.2.1 and B2.2.2]. This also ensured a degree of cross-researcher triangulation to establish validity (Newing 2011 p.115).

Transcripts and the independent notes were then qualitatively analysed using a commercially available electronic qualitative analysis tool, NVivo 10, which '*…enables you to collect, organize* [*sic*] *and analyse content from interviews, focus group discussions, surveys, audio, social media, videos and webpages'* (QSR 2014). Transcripts and notes were analysed using word frequency cluster analysis, including exact match and synonyms, to identify commonality of meaning from the discussions. The data were then encoded into *'parent nodes'* and a cluster analysis repeated. The subsequent encoded data were re-read for interpretive meaning, further encoded into *'child nodes'* and then re-cluster analysed to further elicit meaning.

Fig 5 (i) NVivo word cluster from group interview data analysis

[see appendix B3.17] (QSR 2014)

Fig 5 (i) shows a word frequency analysis model of the parent nodes arising from analysis of the FIT and IRS QA team group discussions. The model shows frequency of word use by clustering. The larger and bolder the words shown in this image the more frequent the word usage. This allows closer examination of transcripts of conversations containing those words, in order to extract commonality of meaning (QSR 2014).

Qualitative analysis of the group transcripts [see appendices B2.3 and B3] shows there was an acceptance by participants that level 1 fire scene examiners (FSE) have a disparity in competence and professionalism with regards to data input in IRS; a "*… mis-balance between their knowledge and their requirement* [to] *record a cause"*, with it being "*dependent on the individual*", [or] *"…whether they have sufficient confidence, and experience to make that decision*" and that it is believed, *"Some do only what they need to do to tick the box"* [in IRS, because] "*they don't really understand what they are doing and they will use one of the* (IRS) *boxes as a prompt*" (Focus Group 2015) [see appendices B2.2.1, B2.3.7 and B3].

The focus group also revealed a view that many level 1 FSEs are not considered by the focus group participants to be competent in fire scene examination and there may be an inconsistency between the level 1 FSE knowledge and their confidence, due to lack of training, *"with new JOs* [Junior Officers or supervisory managers] *coming on, there has been a lack of training"* and information overload of staff, who find it; *"challenging to know all the operational guidance that is being put out"*. The focus group's view can be summarised by the quote *"sometimes I think that we don't fully appreciate that their knowledge in certain areas is actually very little"*.

The general consensual view from the focus group indicates that it is believed the majority of level 1 FSEs complete IRS based on experiential learning, supported by written guidance and the ability to call on level 2 FSEs for support, if it is; "…*outside their sphere of their knowledge or experience, and they don't understand what they're looking at…".* The view offered was that level one FSEs of <u>all operational roles</u> (ranks) have limited knowledge of fire investigation:

> *"…level 1 incident commander agreed with the level 2 incident commander that actually it didn't look suspicious? …so they would record it as accidental, and that is about as far as their investigation went. So neither the level 1, nor level 2 incident commanders who attended, even considered that there was an opportunity to phone the fire investigation team" (KFRS employee 2015).*

Also that *"a lot of the IRS level ones* [FSEs] *are wholly inexperienced in all aspects"* and base their supposition of a cause of fire (as recorded in IRS), on experience and information given to them by occupiers or other witnesses.

> *"…the occupier says; this is what happens, they take it at first hand. They take it that that's what they are being told, so that must be what has happened, and must be true…does the evidence they are viewing support their (the owners) suggested cause…The level one turns up at a property and the owner says "it started in my fridge", they are probably going to take that aren't they? And the IRS will say it started in the fridge then won't it? They are just going to go with it." (KFRS employees 2015).*

Level 1 FSEs view of a supposed cause is however considered to be augmented by observation of the fire scene during firefighting operations, for their training, is geared to how they can mitigate an incident*.* This view from the focus group and the IRS QA group interview will be explored in examination of transcripts of interviews with staff who have identified PV as a cause of fire. However, it was also considered that experience is becoming limited due to falling numbers of fire incidents, *"…they might just go out to one incident a year or something…"* and this may well be affecting the confidence of level 1 FSEs *"…they've then got… to fill in the IRS? Probably loath to say, I'm not really sure, but I'm reluctant to ask, because it's embarrassing…*" This confidence factor was therefore explored by a questionnaire based survey and mixed methods analysis of the views of level 1 FSEs in their own confidence levels.

The focus group discussed training and guidance within KFRS. There was a variance in view amongst the participants as to the level of training in fire scene examination and PV systems offered to KFRS staff. This was exacerbated by focus group participants' views on the value of training as opposed to guidance.

> *"I think fire investigation, it's got to be up there, but as an organisation, it's got to be balanced against the needs for everything else, hasn't it? ...If you have guidance, is that suitable and sufficient and is there any need for training? …I think [sic] is the difference between training and learning isn't it? That's the thing. There is only so much that as an organisation we can expect to train people on". (KFRS employee 2015).*

There was general agreement with a summary given by the researcher at the time of; *"you can give guidance to someone, you can produce guidance documents, you can't necessarily be sure it is understood…"* [see appendix B2.3.7].

This research also revealed the methods KFRS use to collect and collate extra data over and above that required by the DCLG. In that, KFRS requires supervisory managers to input extra data for internal quality assurance and community fire safety purposes, using both dichotomous indicators and free text entry to record data, giving more flexibility to the person inputting the data (KFRS employee 2015; Newing 2011 p.78; De Vaus 2002 ch.7).

> *"Using either a drop-down code selection, or free text entry, or single numerical entries, they outline the various different characteristics of the incident and work their way through it" (KFRS Employee 2015).*

KFRS uses free text entry boxes to collate data on specific causes of fire. This allows a text data search to be made for the identification of specific causes and this was the method used to supply the data on the number of fires which have occurred due to solar power. However, this method is constrained by the search engines, with the person carrying out the data search having to allow for spelling and typographical errors.

> "*When it gets onto the free text we have issues. Say perhaps I was searching for a particular character stream, that was say, solar-space-PV. If that was purely what I searched for and someone had entered solar-space-space-PV my search would not return the incident. So I have to be very careful when I am writing searches that involve free text …" (KFRS Employee 2015)*.

This research also revealed that realising IRS data was non-specific with regards to electrical fires, KFRS had assigned their then Fire Investigation and Research Team to carry out mixed methods research (Newing 2011 p.57) with Canterbury Christ Church University, into the identification of an electrical malfunction, as opposed to electrical appliance misuse as a cause of fire. Research carried out by them during the period April 2009 to March 2012, showed there were 999 fires attributable to electrical faults *per se*, (an ironic coincidental total given the UK emergency telephone number) with only 2 identified as having originated from solar systems (Bryant and Collins 2013).

5.5 Competence and confidence of FSEs

Examination of KFRS data has identified incidents in Kent where PV was recorded to have caused overheating and/or to have originated a fire. However, as discussed previously, the competence and confidence of the person carrying out the examination of the fire scene is important in the identification of the origin of fire. A competent and confident person will probably provide reliable, accurate data. However, an incompetent or under-confident person may not, for Dunning and Kruger (1999) tell us that cognitive bias may exist where a person's confidence outweighs their ability, the 'Dunning-Kruger Effect', or conversely where a competent person lacks confidence, the 'Imposter Effect' (Kruger and Dunning 1999; Simmons 2013).

Fire and rescue service staff follow a progressive reflective learning process designed to allow them to be mindful of their own ability, whilst gaining skills and knowledge. Staff are encouraged to gain skills and knowledge progressively throughout their career, applying them as appropriate to training scenarios and emergency situations to gain experience, thus building confidence in their own ability (Fire and Rescue Manual 2008 ch.1). Progressive levels of competence can be represented using a four square business model (Weyer 2014) [Fig 5 (ii)].

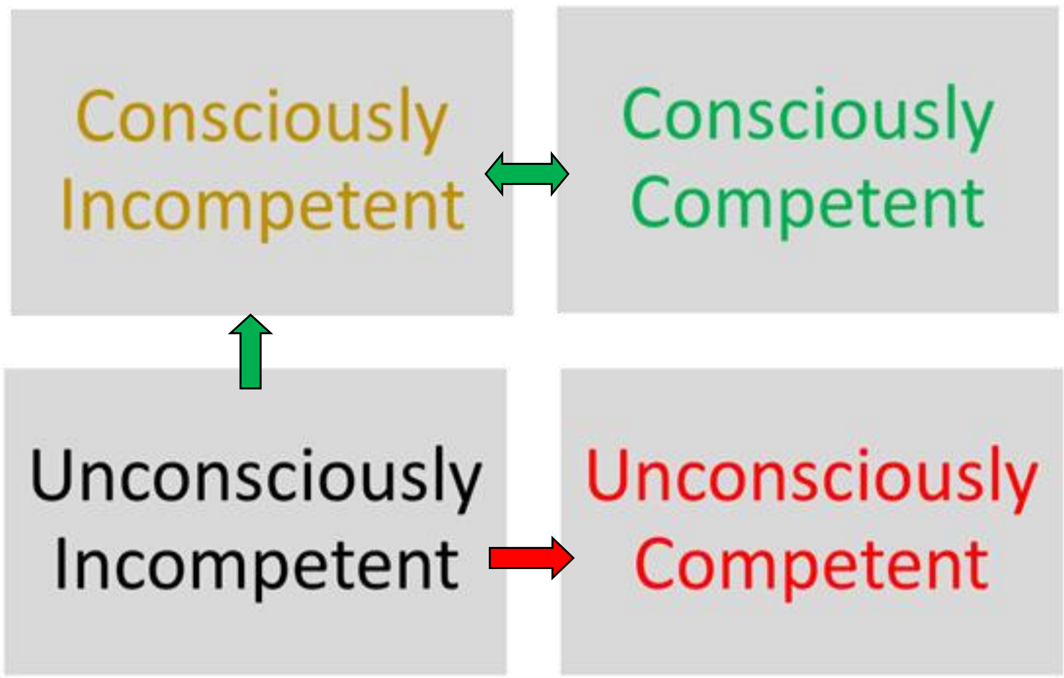


Fig 5 (ii) Four square competency model adapted from (Cole 2004 pp.141 & 163)

When a person has no knowledge they are ‘unconsciously incompetent’, they do not know what they do not know. This is represented by the lower left box in the model. For example, a person may become a firefighter recruit and receive training. As training is received, the person becomes progressively more aware of the limits of their knowledge and they then therefore become progressively ‘consciously incompetent’, as they become aware of these limits. Ultimately they will become ‘consciously competent’, being aware of what they know and how to apply it. If however there is a change in circumstance, for example a new piece of equipment or technique is brought into their required sphere of knowledge, the person moves back into the top left box, representing the fact the person is aware that they do not have the required knowledge. Training is then required until the person moves back into the consciously competent box. This is the reason for the two way arrow between the two top boxes (Cole 2004 pp.350 - 358; Fire and Rescue Manual 2008 p.12; Skills for Justice 2011). The undesirable outcome is for a person to move from the left hand lower box directly into the right hand lower box, becoming competent by experience alone, potentially overconfident in their own ability, not realising the limits of their knowledge and potentially displaying cognitive bias (Kruger and Dunning 1999).

We have seen there is a perceived variance in competence in those people tasked with recording the origin and cause of fire in IRS and this could be invalidating IRS data; for as discussed earlier, level 1 FSEs are the gatekeepers of further investigation. Level 1 FSEs have to both recognise the significance of their scene examination and reflect on their own ability and confidence in carrying out that examination, in order to be self-stimulated to seek guidance. It was therefore decided to explore level 1 FSEs perceived levels of confidence in their own ability and their propensity to seek guidance, or assistance, in carrying out fire scene examinations.

5.6 Mixed methods analysis

A questionnaire was developed which employed both closed and open questions using dichotomous and Likert scales (Newing 2011 p.78; De Vaus 2002 ch.7) and then used during

January and February 2015 [see appendix B4]. The aim of the questionnaire was to establish the levels of confidence of level 1 FSEs in their own ability to recognise the post fire indicators which identify the origin and cause of fire to be attributable to a PV system. The questionnaire was also used to quantify the levels of self-perceived knowledge of electrically originated PV fires amongst level 1 FSEs and the likelihood of them seeking assistance at a fire scene examination. The questionnaire was peer reviewed by academics at the University of Kent and re-drafted in the light of the critique received. The questionnaire was then debated at the operational quality assurance and fire investigation team focus groups in order to receive feedback on the perceived understanding of the questions by fire staff [see appendices B2.3.6 and B2.3.7]. Following this feedback the questionnaire was again re-drafted and printed for distribution.

Sample size was limited due to time restrictions placed on the researcher, therefore it was decided to sample as many level 1 FSEs as possible in a two month period. The questionnaires were taken personally by the researcher to fire establishments across the whole of Kent, where level 1 FSEs, of various operational roles (ranks) and all levels of incident command status, were asked face-to-face to complete the questionnaire. Each questionnaire was completed with the researcher present. As the researcher is a well-known ex-member of KFRS, this face-to-face interactive method elicited a high response rate. Although eliciting a high response this methodology could lead to response bias from participants (Bernard 2011 ch.9; De Vaus 2002 ch.7; Newing 2011 p.111). However, the questionnaire was designed to minimise this, by the use of a varied layout of the questionnaire style, variation in the type of questions (De Vaus 2002 ch.7) [see figs 5 (iii), 5 (iv) and 5 (v)], use of photographs and emphasis, both verbally and in writing, of the importance of honesty by the participants, augmented by the assurance of anonymity (Bernard 2011 p.160).

Level 1 Fire Scene Examiner Questionnaire Page 1

Thank you for agreeing to take part in this questionnaire.

The answers given in this questionnaire are to be used as part of my research at the University of Kent, regarding the recognition of fires in the UK potentially caused by photovoltaic (PV) systems.

The information drawn from the questionnaire will remain anonymous at all times.

Participation in this questionnaire is entirely voluntary and you may choose not to complete the questionnaire at any time.

You do not need to answer all the questions but it's really important you please be 100% honest in your answers. What you actually do and feel.

Q1	How long have you served in your Fire and Rescue Service (FRS) ?		Years	Months
Q2	What is your role (rank) within your FRS? Please tick one option only. If "other" please specify.		FF	
			CM	
			WM	
			Other	
Q3	How long have you served at this role (at this rank)?		Years	Months
Q4	What level ICS commander are you? Please tick one option only. Please show the level you usually operate at.		1	
			2	
			3	
			4	
Q5	Are you aware of the difference between Level 1 ICS and Level 1 FSE? (Please tick)		Yes	No
Q6	Do you ride in charge of a fire appliance? (Please tick)		Yes	No
Q7	Have you entered information into the IRS system? (Please tick)		Yes	No
Q8	Have you been given guidance/training in how to complete IRS? (Please tick)		Yes	No
8a	If yes, please tick what form of guidance? If other please specify	e.g. Operational use of guidance booklet	Booklet	
		Training on watch by WM or CM	On Watch	
		Structured course (at TC or on Stn by HQ staff	Course	
			Other	
Q9	Have you been given training in fire scene examination? (Fire Investigation appropriate to your role) (Please tic		Yes	No
9a	If yes, please show what form of training? If "other" please specify	e.g. Shadowing (on-the-job) experience.	Experience	
		Unstructured training by member of FI Team	FIT	
		Structured course	Course	
			Other	
9b	Was this Fire Scene Examination training obtained from your FRS? (Please tick)		Yes	No
Q10	Have you been given training in photovoltaic electrical systems? (Please tick)		Yes	No
10a	Was this training received from your FRS? (Please tick)		Yes	No
Q11	Have you been given training in how to identify causes of fire potentially arising from a PV system? (Please		Yes	No
11a	Was this training received from your FRS? (Please tick)		Yes	No
Q12	Are you aware of a specific SOP issued by your FRS relating to PV systems? (Please tick)		Yes	No
Q13	Do you regularly use the IRS Guidance document when completing IRS?		Yes	No

Simon Smith. Prometheus Forensic Services. University of Kent. 2014/15

Fig 5 (iii) showing layout of page 1 of questionnaire [see appendix B4.2]

Level 1 Fire Scene Examiner Questionnaire Page 2

The next questions are to explore <u>your levels of confidence</u> in <u>your own</u> ability to establish the origin and cause of a fire.

	How confident or unconfident do you feel about each of the following? Please tick one option for each statement.	Not at all confident	Not Very confident	Neither confident nor under confident	Confident	Very confident
Q14	Identifying the cause of secondary (Code 3) fires?					
Q15	Identifying the cause of primary (Code 1) fires?					
Q16	Identifying the cause of fire to be an electrical systems failure?					
Q17	Identifying the cause of fire to be a solar panel system failure?					

Q18	Are you aware of how to seek assistance from a fire investigation team?	Yes	No

	Please indicate how likely or unlikely you are to request assistance from a specialist FI Team. Please tick one option for each statement.	Extremely unlikely	Unlikely	Neither likely nor unlikely	Likely	Extremely likely
Q19	If you are unable to determine the origin and cause of a secondary (code 3) fi					
Q20	If you are unable to determine the origin and cause of a primary (Code1) fire?					
Q21	If you felt the incident was of special interest (e.g. unusual fire development					
Q22	If you felt the incident was suspicious?					
Q23	If you felt the fire was electrical in origin but you were unable to determine the exact electrical component which had caused the fire?					

Q24	Please look at Photo No 1. Can you identify and name the various parts of the PV system shown?	Some	All	None

Simon Smith. Prometheus Forensic Services. University of Kent. 2014/15

Fig 5 (iv) showing layout of page 2 of questionnaire [see appendix B4.2]

Staff were given the questionnaire and asked to complete the dichotomous and Likert questions as appropriate. They were informed that on reaching question 24 they would be given a photograph to look at. The layout of the questionnaire was designed to ensure that subsequent questions did not bias the response to question 24 [see figs 5 (iii) and 5 (iv)].

On reaching questions 30, 31 and 32 [see fig 5 (v)] respondents were given three further photographs to look at [see appendices B4.2 and B4.3] and record their response to questions regarding those photographs. This staged handing of photographs to respondents was designated to further limit response bias to earlier questions and is one of the reasons the questionnaire was administered directly by the researcher face-to-face.

Level 1 Fire Scene Examiner Questionnaire Page 3

	If your answer to Q24 is "some" or "all" Please write a name, or very brief description for each.	
Q25	A,	Code
Q26	B,	Code
Q27	C,	Code
Q28	D,	Code
Q29	E,	Code

	Please look at Photos 2, 3 and 4. How confident or unconfident do you feel about being able to identify a cause of fire, sufficient for IRS purposes, from those images? Please tick one option for each statement.	Not at all confident	Not Very confident	Neither confident nor under confident	Confident	Very Confident
Q30	**Photo 2**					
Q31	**Photo 3**					
Q32	**Photo 4**					

Thank you for taking the time to complete this questionnaire am very grateful for your assistance

Simon Smith. Prometheus Forensic Services. University of Kent. 2014/15

Fig 5 (v) showing layout of page 3 of questionnaire [see appendix B4.2]

Seventy-five (75) requests were made for a questionnaire to be completed during January and February 2015. Sixty-nine (69) were completed giving the high response rate of 92%.

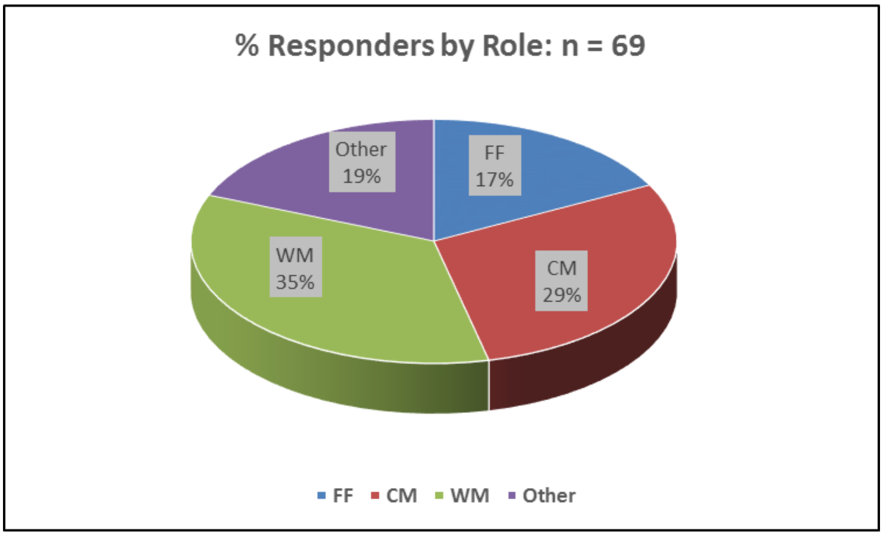


Fig 5 (vi) Percentage of questionnaire responders by role (Rank)

The majority of responders were of Firefighter (FF), Crew Manager (CM) or Watch Manager (WM) level. The remainder (Other) were Station Managers or Group Managers [fig 5 (vi)].

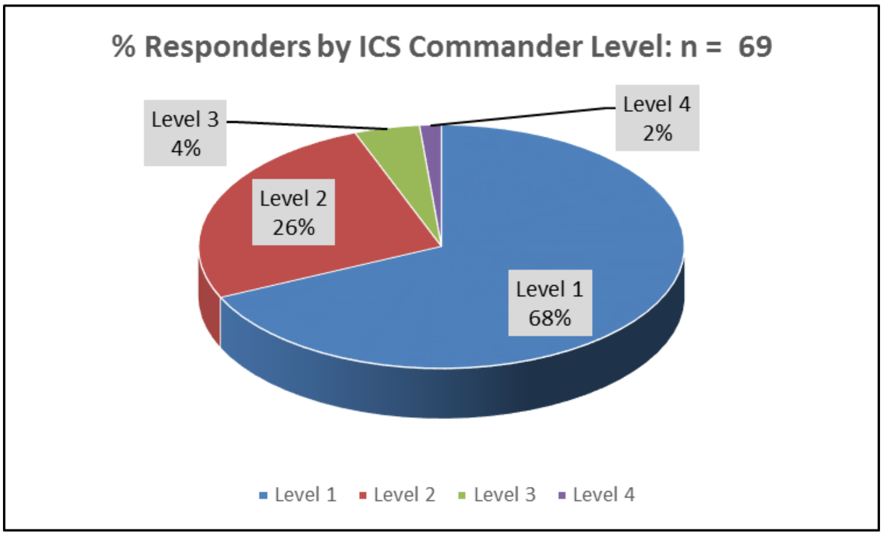


Fig 5 (vii) Percentage of questionnaire responders by ICS command level

It must be emphasised that notwithstanding their operational role, or command level (ICS level 1, 2, 3 or 4) [fig 5 (vii)], all the respondents were level 1 fire scenes examiners by virtue of the fact that none of them were trained fire investigators in the fire investigation team.

Questionnaire data was analysed using an Excel spreadsheet based on the questionnaire design and featuring auto calculation formulae [see appendix B4.1]. Analysis of the data shows that respondents had served an average of 19 years in KFRS, with an average of 9 years in their current role. 84% of respondents indicated they rode in charge of fire appliances and 87% indicated they had entered data into IRS. 78% of them felt they had been given training or guidance in the completion of IRS but only 42% felt they had been given training or guidance in fire scene examination appropriate to their role. This brings into doubt both the accuracy and reliability of IRS data as recorded by those not adequately trained.

Interestingly, although 71% of respondents were aware of the Standard Operating Procedure (SOP) produced by KFRS giving guidance on PV systems (KFRS 2013), only 29% indicated they felt they had received training in PV electrical systems, with this falling to only 10% for those who felt they had been trained to identify the origin of fire from a PV system. This can be contrasted with the view of the focus group on the difference between guidance and training discussed earlier. Organisationally it may be more cost effective to issue guidance in the form of an SOP, however operational staff indicated they did not feel this was sufficient for their needs. Also written guidance may not always be used by staff, as indicated by the low (29%) positive response to the question '*Do you regularly use the IRS guidance document when completing IRS?'*

The respondent was then required to turn the page and was confronted with a different style of questions in order to reduce response bias (Newing 2011 p.111). Pages two and three of the questionnaire were therefore used to ascertain the levels of confidence of level 1 FSEs in their own ability in fire scene examination, their willingness to seek assistance from a level 2 FSE and their ability to recognise PV as an origin of fire. The page two layout consisted of two blocks of Likert questions intersected with a dichotomous question on the awareness of the method of calling for assistance from the Fire Investigation Team [see fig 5 (iv) and appendix B4.2]. This layout was designed to prevent the respondent from simply following the vertical line of the Likert boxes and to cause a cognitive interruption, in order to further reduce response bias (De Vaus 2002 ch.7). As discussed earlier this page ended with question 24. From this point photographs were shown to the respondents asking for their views to be recorded on page three, based on those photographs. Therefore, the three pages of the questionnaire were so designed as to change response style, thereby limiting response bias (*ibid*).

5.7 Indicated confidence of level 1FSEs

Answers to questions 14 to 17 show the respondents have a tendency to confidence in their ability to ascertain the origin and cause of secondary or primary fires. However, this confidence falls with regards to electrical fires and falls even further to a high tendency of being not very confident with regards to identifying a PV system as a cause [fig 5 (viii)].

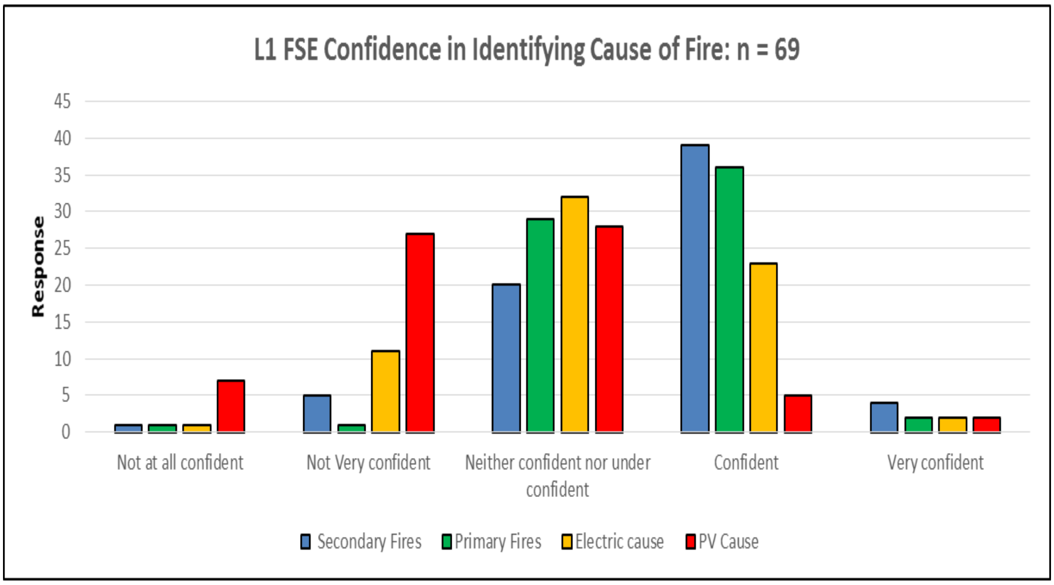


Fig 5 (viii) Level 1 FSE levels of confidence in their ability to identify the origin and cause of fire

Respondents were then asked to indicate if they were aware of how to seek assistance from the fire investigation team. 96% indicated they were. It may be that this figure could have been skewed by a positive response bias, as respondents may not be willing to indicate a lack of knowledge in this area to a former member of the KFRS FI team. Further independent research would therefore be required to verify this response.

Questions 19 to 23 then asked which type of incident the level 1 FSEs might call for level 2 FSEs to investigate. With the exception of minor (secondary) fires the results indicate there is a strong tendency for assistance to be sought across the board [fig 5 (ix)]. Again, more research would be required into this area in order to eliminate a positive response bias to these questions.

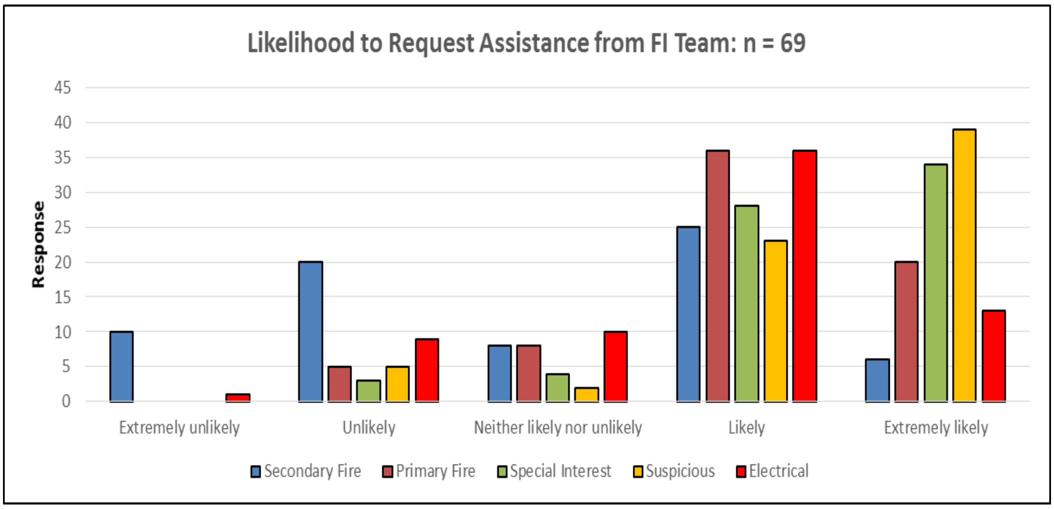


Fig 5 (ix) Level 1 FSE likelihood to seek assistance from the FIT (level 2 FSE)

The questionnaire then examined the respondents' confidence in recognising PV as a cause of fire. Firstly, respondents were shown a photograph of a part of a PV system [see Photo Q1] and asked if they could identify the various components in the photograph. Answer choice was '*some*', '*all*' or '*none*'. Only 6 respondents (9%) indicated they could identify all the components, with the overwhelming majority (80%) indicating they could identify some of them. 11% of respondents honestly indicated they could not identify any of the components in the picture [fig 5 (x)]. This gives confidence in the validity of the responses to the questionnaire.

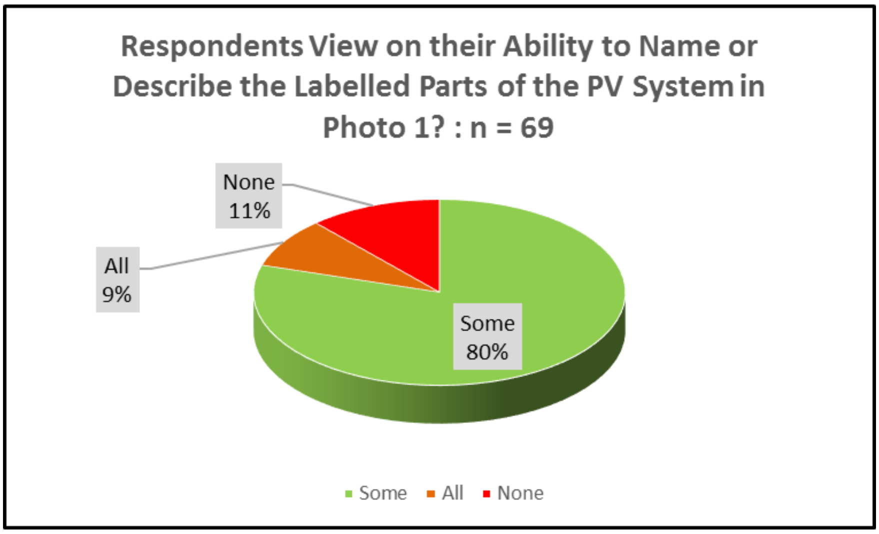
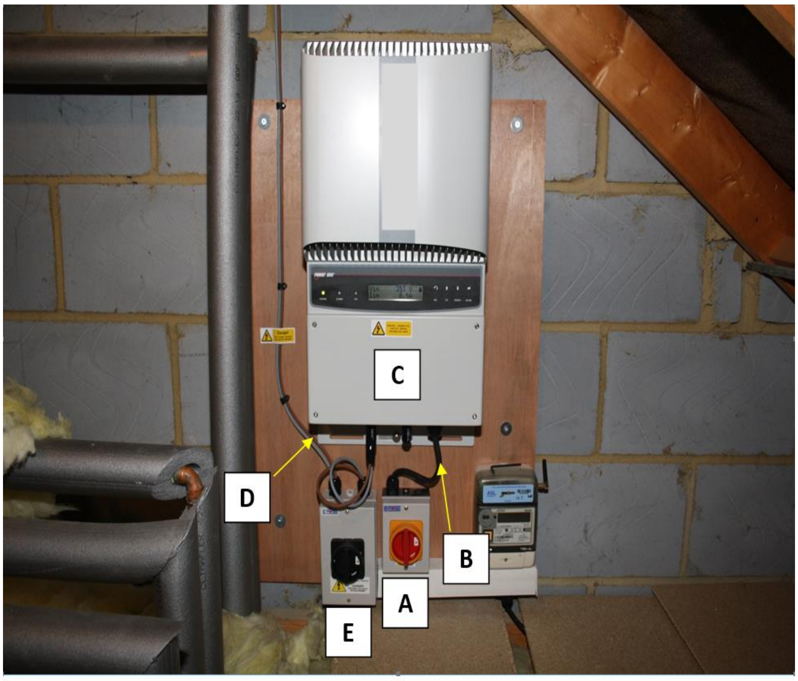


Fig 5 (x) Level 1 FSE view on ability to name selected PV components shown in questionnaire

Response bias to this question was then checked by asking the respondents to again change pages, to page three of the questionnaire, where they were asked to name or describe the components shown in the photograph in a free text entry box correlated against a letter label on the photograph [see photo Q1 below].



KFRS Photo

Photo Q1 Image of a PV string inverter and associated components as used during the questionnaire process (KFRS Photo)

Mixed methods analysis of these responses shows that those who said they could identify ‘all’ the components all did so correctly. Interestingly 7 of the respondents who stated they could only identify ‘some’ of the components could actually identify them all. This represents 13% of those who indicated ‘some’ and indicates under-confidence in those respondents.

The least likely of all the components to be correctly identified was item ‘E’ the DC isolator. We will see later that anecdotally this is the component which appears to have failed most frequently and led to fires originating from PV systems.

Respondents were then asked to look at photographs of three fires which had occurred in Kent where the origin had been attributed to a PV component (being the DC Isolator in all three cases). They were asked to indicate their levels of confidence in being able to ascertain to IRS requirements (the most likely supposed cause), the origin and cause of fire as shown in those photographs [see photo Q2 and appendix B4.2].

Photograph 2 for Questionnaire

KFRS Photo

Photo Q2 Image of a fire damaged string inverter and associated components as used during the questionnaire process (KFRS photo)

The data show that there is an indicated high tendency to lack of confidence amongst the respondents' view of their own ability in this area [fig 5 (xi)]. Only 28% responding as being confident or very confident.

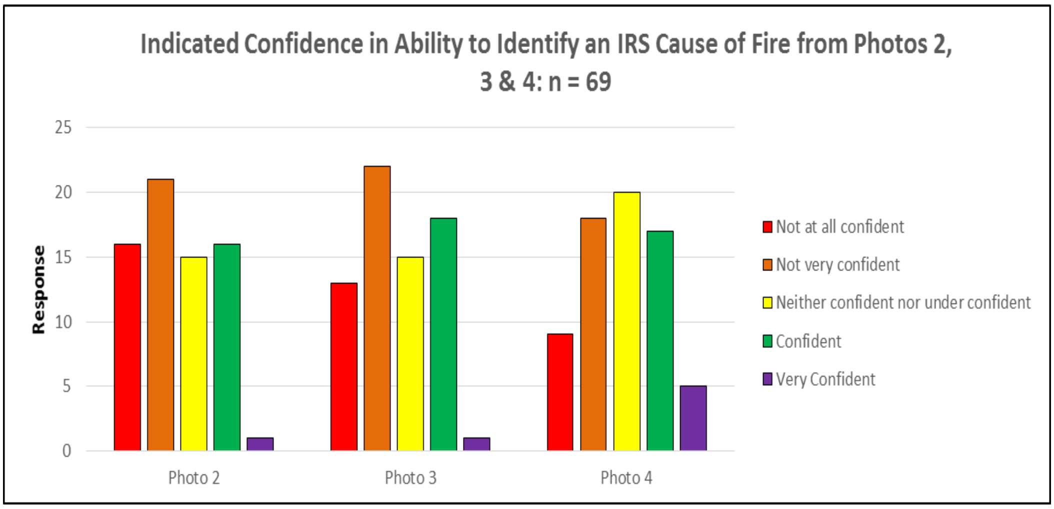


Fig 5 (xi) Spread of indicated self-confidence in ability of level 1 FSEs to identify cause of fire from photos 2, 3 and 4 in the questionnaire

Consideration was given to asking respondents what their IRS entries would have been given the circumstances outlined in the photographs. This was not carried out as such a question would probably have elicited a response biased answer (it must be PV electrical, for you are asking me about PV). Also IRS data entry is an electronic system and simulating this on paper was considered to be a difficult diversion to the data gathering process. Similarly, physically testing the responders' data entry skills using the actual KFRS system would have required a greater effort and time commitment on the responders' part and was considered to be a disincentive to obtaining the completion of as many questionnaires as possible.

5.8 Discussion regarding questionnaire analysis

The level 1 FSEs who completed the survey display a tendency to lack of confidence in their own ability in both fire scene examination, appropriate to their role, where electricity is considered to be involved and in the recognition of PV components. If possible response bias is ignored they do however support the focus group's view that level 1 FSEs are willing to seek assistance from their level 2 colleagues in the Fire Investigation Team. However, as discussed earlier, in order to seek that assistance they have to recognise the situation for what it is.

5.9 PV originated fires in Kent

KFRS data shows six incidents during the period 2009 - 2014 (the period for which data was available) where solar power systems were recorded as the cause of the incident. These six incidents had been attended by five different incident commanders. Having identified the supervisory managers, semi-structured interviews were carried out with them in order to establish which methods of fire scene examination they had used to come to their conclusions. All five requests were successful, including one for a then retired KFRS employee. Interviews took place in January and February 2015 at various KFRS fire stations across the county. The interviews were recorded digitally and the recordings transcribed by the researcher, being edited only for speech inconsistencies such as ‘err’ and ‘umm’ [see appendices B2.3].

The research reveals all five interviewed fire officers were whole time firefighters, as opposed to part-time or retained staff. They had served an average of twenty-seven years, with three of them having served over thirty years each. These long lengths of service, and therefore greater experiential learning, are believed to be an important factor in the positive identification of PV at these incidents, for all of the fire officers indicated they had identified the involvement of PV at their respective incident using a combination of all the information gathered during the incident command process…

> “*I observed smoke issuing from around the eaves of the property. It was light coloured smoke issuing from around the eaves of the property…dynamic risk assessment of the complete building I have to carry out a 360° reconnaissance of the property. So I can see what it was presenting before I committed crews to going into it... There were probably about a dozen solar panels on the front face of the roof of the property… The solar panels were on the other pitch of the roof, the one that faced the other way, so I didn't see them at first. When I did my 360* [*sic*] *of the building I realised that they were there…”* (KFRS Employees 2015).

…augmented by information from witnesses, *“…already been pre-warned by the turnout system that it was solar panels alight…The premises was occupied at the time… I was met by an engineer that was installing the system...”* Along with direct observation of the burn pattern after the fire had been extinguished, “*… when the fire was out, and the guys had pointed out that it was some sort of electrical installation on the wall in the loft. That was when I made the connection with the solar panels… obvious that the thing that had caused the fire were these boxlike structures on the inside wall of the gable end”.*

Four of the fire officers informed the fire investigation team of the incident they were attending, “*…fire investigation turned up and did a proper investigation of it. They confirmed to me that it was the electrical equipment that was responsible for taking the current out the panels, inverting it from DC into AC…”* two other incidents were considered too minor to justify calling out the team, *“…I could be pretty confident by tracing back the burn patterns as to where the fire initially started …Now the only reason I decided this was a possible cause of the fire, was a process of elimination, because there was nothing else there. Nothing.”*

A comparison of KFRS (2015) IRS entries for the 6 incidents known to have been recognised by KFRS L1 FSEs as originating from PV systems shows data to vary, with different choices being made as to the ‘best fit’ for data into the available subsets [see table 5 (i)]. The *‘Cause of fire’* data for four very similar fires coded *‘Stop code 1’* (all adjudged to have originated in a DC Isolator) were recorded the same; ‘*Fault in equipment or apparatus’*. However, the ‘*Ignition source’* differed for one of those four [see highlighted data in table 5 (i)]. One incident was recorded as a ‘*False Alarm Good Intent’* and therefore coded *‘Stop code 7’* (KFRS 2014). The data entry for one other *‘Stop code 1’* fire differed wildly from all the other entries. It is also not possible to identify incidents which originated from a PV system but have been misreported as originating from other causes, or as *‘unknown’*. This means it is difficult to compare data to discover a commonality of cause and supports the view that IRS data is not reliable for this area. Further research is required to ascertain the extent of this effect nationally and whether any of these effects are attributable to managerialism.

Date	Inc No	Stop code	Cause of fire	Ignition Source	Cause fee text
02/10/2011	209	7	N/A	N/A	Smoke from solar powered heating system
15/03/2012	1051	1	Fault in equipment or appliance	Wiring, cabling, plugs	Accidental - Isolator on D.C current side of installation from PV solar panel, failure.
30/07/2012	2280	1	Fault in equipment or appliance	Apparatus - batteries, generators	Accidental - Fault in electrical system
18/09/2012	1684	1	Fault in equipment or appliance	Apparatus - batteries, generators	Accidental - electrical fault in solar panel control system.
18/07/2013	1906	1	Combustible articles too close to heat source (or fire)	Other - solar lighting power converter	Accidental - Suspected conducted heat from solar power converter…
08/08/2013	714	1	Fault in equipment or appliance	Apparatus - batteries, generators	Accidental - Fire started within a faulty DC inverter box whilst under maintainence.

Table 5 (i) IRS data entries for KFRS attended incidents identified by L1 FSEs as being attributable to solar power systems during the period 2009 - 2014.

5.10 Discussion

This original social science based research has shown that a significant number of the level 1 fire scenes examiners, who took part in the research, are not confident in their ability to recognise fires originating from electrical fires *per se*, and specifically PV electrical systems. It shows that identification of the origin and cause of fires is currently dependent on experience and therefore a fire officer's length of service, and exposure to incidents during that service.

It is interesting that this appears to be the case for a developing problem such as fires from PV systems; for we have seen that PV solar power is an emergent technology, therefore the numbers of PV fire incidents only a decade ago would have been very small and FSEs would not have had the opportunity to gain much specific PV fire experience. It appears that an increase in general experience allows a L1 FSE to discount expected ‘normal’ causes and therefore attribute an incident to a PV cause.

“*Now the only reason I decided this was a possible cause of the fire, was a process of elimination, because there was nothing else there. Nothing.” (KFRS Employee 2015)*

The more experienced L1 FSE may also be open to requesting assistance without feeling threatened; this could be an example of experience combatting cognitive bias. Further research is required to confirm this.

However, numbers of all fire incidents are falling, thereby reducing available experience. It is proposed therefore that the competence and confidence of level 1 FSEs can be raised by better training, including observational learning. This will lead to more valid data in IRS and facilitate further investigations by appropriate levels of fire scene examiner.

Examination of available evidence indicates an area of interest for further research as being within the DC circuitry of PV systems and specifically the DC isolator. The next chapter describes possible electrical failure which may lead to ignition of PV components and illustrates expected early post fire indicators which may be seen following such a failure, thus enabling level 1 FSEs to recognise incipient fires originating from PV systems.

Chapter 6. Fire from Photovoltaic Electrical Circuits

6.1 Introduction

Fire scenes examiners seeking to identify the origin of a fire as being attributable to a specific section of a PV system have to recognise appropriate post fire indicators left behind after the event and examine them in conjunction with comparative witness testimony (Babrauskas 2003a; Babrauskas 2003b pp.10 -11; Daeid 2004 ch. 1; DeHaan, Kirk and Icove 2012 p.2). For level 1 FSEs physical evidence must be recognisable to the naked eye (Hobbs 2010). Research was therefore carried out to clarify expected post fire indicators which may identify early failure of part of a PV electrical circuit. Time limitation precluded research into all aspects of PV systems. It was therefore decided that building on the results in Chapter 5, experiments would be carried out on a DC isolator.

In order to establish a common cause of ignition a cold case (Green 2015) forensic review of documentary and photographic evidence appertaining to known PV system fires in Kent was carried out. Once the most probable cause of ignition of these fires had been established from qualitatively re-examining evidence, experiments were developed in order to quantitatively test hypotheses regarding possible sequences of failure which may have led to ignition. This can be seen to be approaching the ideal methodology of transdisciplinary research discussed earlier.

6.2 Cold case documentary examination

Although we have seen in chapter 5 there is anecdotal evidence for fires originating from DC isolators, the exact nature of the cause of ignition in the cases discussed had not been established by the attending fire officers at the time. For as discussed earlier they were not required to do so. Therefore, a cold case review (Green 2015) was carried out utilising available evidence from fires identified in chapter 5 as having originated from PV systems generating mains voltages, in order to confirm the origin of those fires and to assess a possible commonality of cause. This review consisted of an examination of photographs taken by KFRS staff at each fire scene, along with a review of appropriate IRS documentation and analysis of the transcript data collected for the research discussed in chapter 5. This examination revealed that in every case there is evidence of electrical arcing having occurred in the vicinity of the DC isolators. Although such arcing may be the cause of the original heating of PV system components to their ignition temperatures, arcing can also be caused as a consequence of a fire, as insulation is burnt off cables during fire development (Babrauskas 2003a).

In two of the cases examined, the fire was discovered by installers upon switching on the system, and it is therefore highly likely that instantaneous electrical arcing was the cause of the ignition in these cases [see Photographs CC1 and CC2]. This could have been caused by a poor contact in the terminal block or switch mechanism of the DC isolator. Alternatively, such arcing could be caused by rapid thermal degradation of the structural integrity of the electrical switchgear insulation, allowing the switch bridge mechanism to separate from the contacts. This could have been caused by internal heating of the switch gear; by either overload of the switch design current, or ohmic heating from a poor connection (Babrauskas 2003b p.549; Daeid 2004 p.81; DeHaan, Kirk and Icove 2012 Ch.10; ESFRS 2015; Hobbs 2010). Clarification of this could possibly be established by carrying out ‘cognitive interviews’ of witnesses to the actual event. Such interview techniques build a degree of trust between the interviewer and the witness, thereby allowing more details to be recalled (Fisher and Geiselman 2010). However, this was not possible as the only witnesses available for this research were KFRS staff, all of whom had attended the scene after ignition had occurred.

Photo CC1 Fire and firefighting media damage to Kraus and Naimer KG20 T104/D=P003KL51V DC isolator. Observed by witnesses to have been caused by immediate arcing (KFRS photo)

Photo CC2 Fire damage to inverter with integrated combined AC/DC isolator. Observed by witnesses to have been caused by immediate arcing (KFRS photo)

In two other cases a prolonged period of time had passed between the installation of the PV systems and the discovery of fire originating from those systems. This passage of time therefore precludes the possibility of an instantaneous arc being established on commissioning. The company installing the PV systems had fitted the AC and DC isolators, the inverter and the smart meter (along with the wiring required to connect these components) onto an engineered timber product backboard. This complied with the wiring regulations in force at the time of installation (BSi 2011). The wiring regulations were amended in 2015 to require that this type of switchgear should be contained in a non-combustible enclosure (BSi 2015 pp.36 & 75). However, the changes in requirements do not apply to the inverter or smart meter, as they are defined as appliances (BSi 2015 p.23). As changes to wiring regulations are not required to be addressed retrospectively (BSi 2015 p.4), many such installations may exist. The backboard assembly had then been fitted to a wall in the loft, and connected to the array of roof fitted PV modules and the mains circuits of the property. Photograph CC3, taken in an adjacent premises to that in which one of the fires occurred, shows an undamaged example of this type of system. It is believed that this system had been installed by the same company and at roughly the same time as those involved in fire.

Photo CC3 Undamaged inverter and associated switchgear on combustible backboard

(KFRS photo)

Photographs CC4 and CC5 show two separate fire damaged examples of this type of system.

Photo CC4 Fire damaged inverter and associated switchgear on combustible backboard

(KFRS photo)

Photo CC5 Fire damaged inverter and associated switchgear on combustible backboard

(KFRS photo)

In both cases the depth of char of the backboard and associated radiant heat damage post fire indicators, (DeHaan, Kirk and Icove 2012 pp.48 & 128) show the fire to have originated in the vicinity of the lower left hand side of the backboard. This can be seen to be where the DC isolator is fitted to the backboard, as shown in photograph CC1. Photograph CC6 shows beading of metal on the end of a copper conductor found on the floor under the left hand side of the backboard at one of the examined incidents.

Photo CC6 Evidence of line arcing in DC cabling (KFRS photo)

This post fire indicator is caused when an electrical arc is established. The beading is seen to be at the end of the conductor and therefore shows evidence of line arcing (Babrauskas 2003a). Microscopic analysis of the actual wires would be required to establish the exact nature of the arcing evidence. This was not possible for this research due to the passage of time after the event and the unavailability of physical evidence. However, photograph CC6 was enlarged and cropped [see photograph CC7]. The enhanced image shows splatter beads, as described by Babrauskas (*2003a*) on some of the broken wire strands. Possible evidence of parallel arcing can also be seen on the solidified melted strands adjacent to the main bead, where a clear demarcation of the roughly spherical beads is visible. As temperatures in excess of 1085ºC are required to melt copper this evidence appears indicative of arcing and not the melting of the metal by heat from the fire (Babrauskas 2003b pp.795-796). As stated above, microscopic analysis would be required to confirm if this is arcing evidence and if so is it attributable to the 'cause' of the fire or was it created as a 'victim' of the fire when insulation burnt off a live cable (Babrauskas 2003a). It is possible both occurred here, with an original arc fault causing a fire which subsequently burnt off the insulation allowing 'victim' arcs to be established.

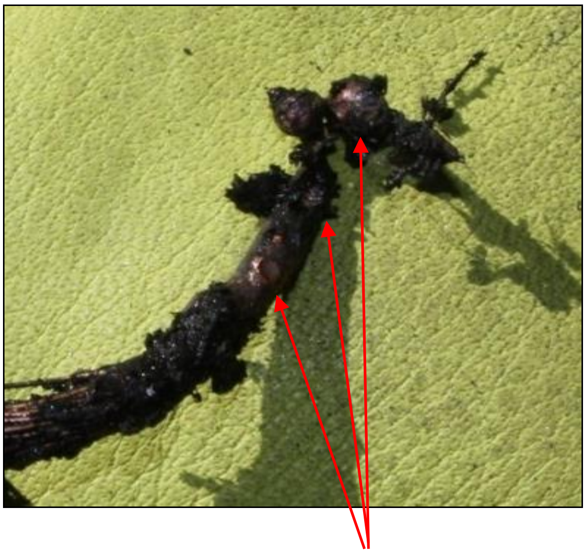


Photo CC7 Enlargement of Photo CC6 showing ***"cause or victim beading"*** *(Babrauskas 2003a) created from solidified globules of molten metal (KFRS photo)*

Photograph CC5 shows charring to have occurred in a line vertically up the left hand side of the said backboard. This could be evidence of arcing occurring up the length of the mounting board. This may have been caused by parallel arcing across the positive and negative supply cables, which can be seen to be closely mounted on the backboard in photograph CC1. This conclusion is based on the assumption that the cables would have been similarly mounted on all the units examined. Such evidence of possible parallel arcing does not however preclude the original source of heat as being generated by a line arc at a loose connection, or from heating at a high resistance connection. Again it was not possible to establish this due to the passage of time and unavailability of physical evidence. It is interesting to note that the occupants of one of the fire affected properties reported to the attending FSE that they had heard, what they described as "*animal scratching noises*" in their roof space before the fire*…"* [see appendix B2.3.4]. It is possible the sound they heard was caused by DC arcing rather than by animals. Further research is required to clarify this, for it is sometimes postulated that rodents may be the cause of some electrical arcing, as they are alleged to nibble insulation off conductors (Babrauskas 2003b P.787).

The limited nature of the available evidence precludes the exact cause of these fires from being established from the cold case review. However, the available evidence does indicate that the 'area of interest' (DeHaan, Kirk and Icove 2012 p.250) lies within the DC circuitry in the vicinity of the DC isolator.

Two possible hypotheses can therefore be formed as to the cause of fire in the examined cases where delayed arcing occurred: either the insulating material of the switch gear itself was raised to a temperature whereby the material itself pyrolysed and possibly ignited, allowing an arc to be established as the insulation was consumed, or the integral structure of the switchgear failed as the insulating material changed its phase state due to heating over a prolonged period of time, allowing an arc to be established.

To produce qualitative photographic evidence and quantitative data which could be made available to fire scenes examiners, it was decided to develop an experimental simulation of a poor electrical connection to a DC isolator to internally heat the thermoplastic switch gear insulation material to test if it was possible to:

- Raise the temperature of the insulation polymer to enable pyrolysis leading to combustion of the liberated compounds in their gas phase, or

- Raise the temperature of the insulation polymer to a point where phase change of the insulation may reduce the structural integrity of the switch gear, leading to the potential for an arc to be established.

Only one DC isolator was identified during the cold case review process; namely the Kraus and Naimer KG20 T104/D=P003KL51V model, rated at 16 A at 600 V (9.6 kW). This particular make and model of isolator switch was therefore chosen for the experimental section of the natural science research. The layout and nomenclature of terminals within this isolator are shown in fig 6 (i).

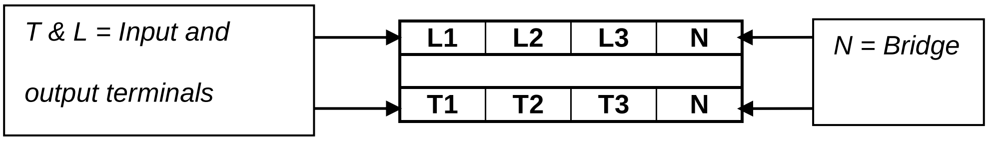


Fig 6 (i) Schematic of the layout and identification of terminals in the terminal block of Kraus and Naimer KG20 T104/D=P003KL51V DC isolator.

6.3 Preliminary experiments to show resistive heating.

A series of preliminary experiments was undertaken to establish the degree of heating caused by increased resistance in electrical connections to the identified isolator [see appendix B6]. Table 6 (i) lists the equipment used in these experiments.

DC Isolator Preliminary Tests Equipment and Instruments Used		
Equipment Description	**Manufacturer**	**Model**
DC Isolator rated at 16 A at 600 V	Kraus and Naimer	KG20 T104/D=P003KL51V
1 mm annealed copper wire	University Stock	N/A
Cabling. 4mm solar grade copper cable	Triple Solar	N/A
Continuity tester/multimeter	Digital	DT4000ZC
Differential Thermometer and assorted Thermocouples	Comark	2008
Differential Thermometer and assorted Thermocouples	Comark	N9008
Differential Thermometer Calibrator	Omega	CL23A
High Current supply rated at 20 V 20 A	Hochstrom-Netzgerat	521 55
Infrared Thermometer	Voltcraft	IR 650-12D
SLR Digital Camera	Cannon	EOS20D
Video Recorder	Sony	Handy Cam DCR=SR58

Table 6 (i) Equipment used in preliminary ohmic heating experiment

These experiments were limited due to the level of DC power from the available Hochstrom-Netzgerat high current supply 20 V / 20 A (400 W).

Fig 6 (ii) shows the electrical connections from the DC supply to the DC isolator switch.

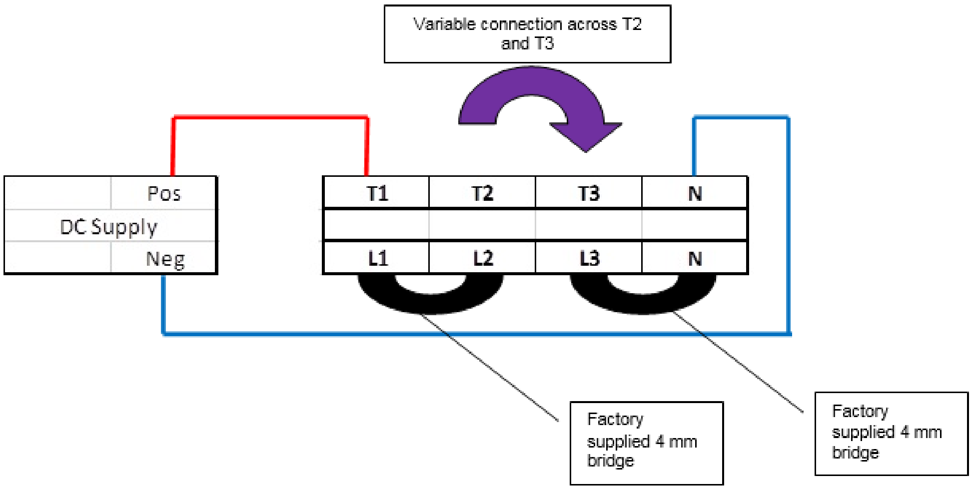


Fig 6 (ii) Electrical connections from Hochstrom-Netzgerat 400 W DC supply to terminal block. Red line shows positive connection; blue line shows negative connection. Purple arrow indicates the short circuit connection between terminals T2 and T3. This was varied during the series of experiments to simulate high resistance connections.

Full available power was applied from the DC supply, with the terminal block short circuited across terminals T2 and T3 [fig 6 (ii)]. Temperature readings were taken using a contact thermocouple connected to a digital thermometer and an IR thermometer. Data marked Temp 1, [blue line] on the following graph, indicates the surface temperature of the negative cable insulation adjacent to terminal T3 in the terminal block. Temp 2 [orange line], shows the surface temperature of the plastic switch gear housing immediately above terminal T1. These data were obtained using the contact thermocouple and digital thermometer. Infrared (IR) thermometer readings were taken of the surface of the terminal insulation plastic. These data are marked IR on the graph [grey line]. For experiment No 1, IR data are taken from the right hand edge of the exterior of the switch box. For experiments No 2, 3 and 4 readings were taken from the plastic of switch gear housing immediately above terminal T3. Fig 6 (ix) below shows the temperatures reached during an experiment with the terminal block using good electrical connections and with the full available power applied.

Experiment No 1 with 4mm PV cable & good connection				
Voltage (Volts)	0.3		Watts	6.2
Current (amps)	20.7		Room	20 deg C
Time interval	Time	Temp 1	Temp 2	IR
0	12:25	20.2	20.2	20.2
10	12:35	24.4	27	19
20	12:45	29.6	27	19
30	12:55	30.7	27.9	19.8
40	13:05	30.7	28.3	20.1
50	13:15	31.7	29.2	21.3
60	13:25	32.1	29.7	22
70	13:35	32.3	30.1	22

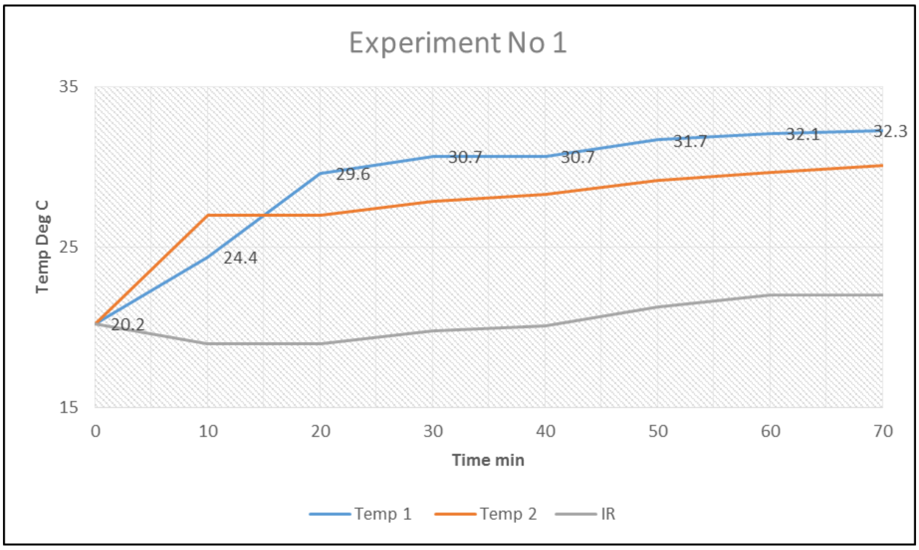


Fig 6 (ix) Temperature obtained by applying the available power to a good connection

Designers have to take this heating effect to terminal connections into account when designing appropriate switch gear. This is the reason switches have different electrical ratings (Pester 2014) and guidance is given on making connections (MCS 2012).

Terminal temperatures were taken again, using the same power supply but with the connection modified to reduce the area of electrical contact to a single strand of copper wire. A minor increase in terminal block temperature of 3.7^{o}C was observed, with equilibrium reached within 10 minutes. In order to attempt to further increase the resistance in the circuit, the 4 mm solar cabling used as the short circuit patch lead was then replaced with 1 mm annealed wire. Screwdriver tightened connections were made to bare wire, cleaned of the annealed insulation material in the terminals and the experiment re-run. A further increase in terminal block temperature to 72^{o}C was observed from this experiment. However, it was not possible to observe any physical changes in the insulation material during any of the experiments.

These preliminary experiments were therefore judged to be only partially successful, for whilst heating of the terminal block occurred, the DC electrical power supply available at the time was too low to do sufficient work on an electrical connection and cause the temperature within the switchgear terminal block to rise high enough to thermally degrade the switchgear materials. A number of options were considered regarding obtaining DC power at the values likely to be encountered in a domestic PV system. These included using power from domestic, or commercial (PV installers) PV systems, or the use of DC generators. However, following meetings with three owners of domestic properties fitted with PV systems and three installers of PV systems, risk assessments showed all of these options to be not safely viable. As it was also not possible to obtain a DC generator of the required output, it was not possible to recreate component overload, electrical arcs, or resistive heating of connections under safe controlled conditions. It was therefore decided to develop a series of simulation experiments under the safe conditions of a teaching laboratory.

6.4 Experimental heating research

Research was therefore carried out in a risk assessed teaching laboratory at the University of Kent to simulate heating of terminals by work done by electricity on those terminals, thus simulating an electrical fault within the isolator. It was hypothesised that this would enable the identification of post fire indicators likely to be observed in a DC isolator terminal block which had been indirectly heated internally, irrespective of the method of imparting that heat.

Table 6 (ii) lists the equipment used in this series of experiments.

Indirect Heating Experiments Equipment and Instruments Used		
Equipment Description	**Manufacturer**	**Model**
2.5 mm copper wire x 2	Kraus and Naimer	N/A
3.5 mm copper wire	University Stock	N/A
4 mm x 300 mm pure copper rod	Milton Keynes Metals	N/A
Attenuated Total Reflectance Infrared Spectroscope	Shimadzu	A21374902172
Balance	Ohaus Pioneer	3DP/PA 143
Bunsen Burner x 2 (Mains gas)	University Stock	N/A
Clamps and stands	University Stock	N/A
Continuity tester/multimeter	Digitek	DT4000ZC
DC Isolator rated at 16 A at 600 V	Kraus and Naimer	KG20 T104/D=P003KL51V
Differential Thermometer	Comark	2008
Differential Thermometer	Comark	N9008
Differential Thermometer Calibrator	Omega	CL23A
Gas tight syringe (2.5mL).	Supelco	SGE
Multi-function meter	Megger	MFT1710
Nylon 11 sample bag 200 mm x 300 mm	Supplied by Kent Police	N/A
SLR Digital Camera	Cannon	EOS20D
Smartphone	Motorola	Moto G
Test tube heater block	Stuart	SBH200D

Table 6 (ii) Equipment used in indirect heating experiments EX0 – EX3

Experiments were designed using heated copper to conduct heat into the terminal, thus simulating the heating of a terminal by work done from a high resistance connection. This enabled observations to be carried out of chemical changes to terminal block insulating material, caused by the indirect heating of a terminal within the block. Due to time restrictions and to maximise the gathering of available data it was decided to carry out parts of this section of the natural science research jointly between the author and Miss Charlotte Moss (a fellow MSc student at the University of Kent). By utilising the same materials, the researchers were able to also identify the composition of some of the pyrolysis products emanating from the insulating polymer heated in the experiments whilst simulating field conditions. The author led the development and use of a test rig to enable physical and chemical changes caused by heating the isolator terminal block to be examined, and appropriate data and samples to be collected [see appendices B6 and B7]. Moss led the development of a *'Simple Method to Identify the Flammable Thermal Decomposition Products from* [the] *nylon 6,6'* insulation material [see appendix B8] which culminated in a separate thesis [see appendix B8.3] (Moss 2015).

A preliminary experiment [see appendix B7.2] was carried out to confirm data received from the DC isolator manufacturer on the composition of the plastic used in the terminal block. A simulation test rig was designed and an experiment carried out in order to identify whether the rig performed to a satisfactory standard [see appendix B7.1]. Following these preliminary experiments, a series of three developmental experiments were conducted using progressively modified test rigs, in order to gather data on the decomposition of the insulating polymer due to internal heating [see appendices B7.3 – B7.8]. Experiments were then conducted to analyse pyrolysis products observed to have emanated from the insulating polymer [see appendix B8.3] (Moss 2015).

6.4.1 Preliminary experiments

Five further Kraus and Naimer DC isolators, type T04/D-P003DE-14H406, were bought online [see photo P1 and appendix B7].

Photo P1 Kraus and Naimer DC isolator, type T04/D-P003DE-14H406

Correspondence was entered into with the manufacturer of the identified DC isolator (also known as a disconnector). A datasheet was provided by them showing the materials used in the construction of the isolator (Kraus & Naimer Limited 2015).

An Attenuated Total Reflectance Infrared (ATR IR) spectrometer was used to confirm the insulating material used for the manufacture of the switchgear. The material was observably coloured blue due to a commercial decision by Kraus and Naimer to ensure product identity (Kraus & Naimer Limited 2014) however, the exact nature of the pigment used was not revealed by the manufacturer due to commercial confidentiality (Kraus & Naimer Limited 2015).

Shavings were taken from the insulating material making up each of the terminal blocks used for experiments EX0 – EX3 (see appendix B7) and tested in the ATR IR. The results of these tests were then compared against different polymer databases within the ATR IR to obtain a match.

Although it was possible to obtain an excellent match above 1200 cm^{-1}, significant additional peaks to the database spectrogram were noted in the sample below 1170 cm^{-1} [see fig 6 (x) and 6 (xii)].

No.	Peak	Intensity
1	530.42	70.079
2	555.50	76.124
3	576.72	70.032
4	659.66	75.426
5	682.80	71.049
6	756.10	81.106
7	779.24	73.119
8	1049.28	80.900
9	1076.28	74.843
10	1147.65	73.361

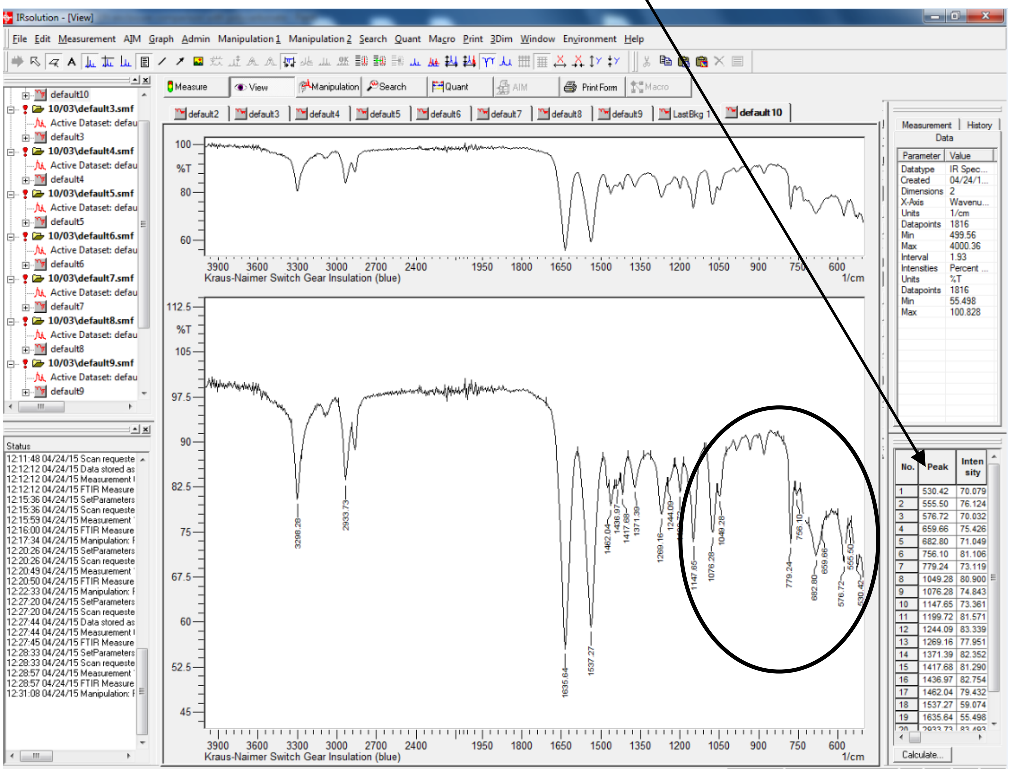


*Fig 6 (x) Adapted screenshot of labelled ATR IR data (including enlargement of peak list), showing significant additional peaks (**circled**) between 530 – 1148* cm^{-1}

The additional observed peaks may represent chemicals added to the nylon 6,6 used in the switchgear, such as the colour pigment(s). Fire retardant chemicals can also be added to nylon products, by either incorporating retardant additives at the compounding stage, or bonding fire-retardant groups on the polymer chain, or the surface of the polymer. However, the addition of fire retardant chemicals alters the properties of nylon, including stability and electrical performance (Levchik & Weil, 2000). Correspondence with the manufacturer of the identified DC isolator (Kraus & Naimer Limited 2015) did not reveal that fire retardant chemicals had been added during the manufacturing process. However, it is possible that the extra peaks observed in the ATR IR spectrograms may be indications of fire retardant chemicals in addition to pigments. Further research is required to confirm this.

It can also be seen that, although at the same frequency and observably similar in shape, some of the peaks in the spectrogram for the sample appear less strong than those for the database reference. This is probably due to the known properties of reflectance IR spectroscopy, as compared with transmission spectroscopy (the available library spectrogram is labelled as being obtained by the transmission method) [see fig 6 (xi)]. Lower peak intensity is expected the higher the wave count from reflectance, rather than from the transmission methods (Setnička n.d.; Shimadzu 2016).

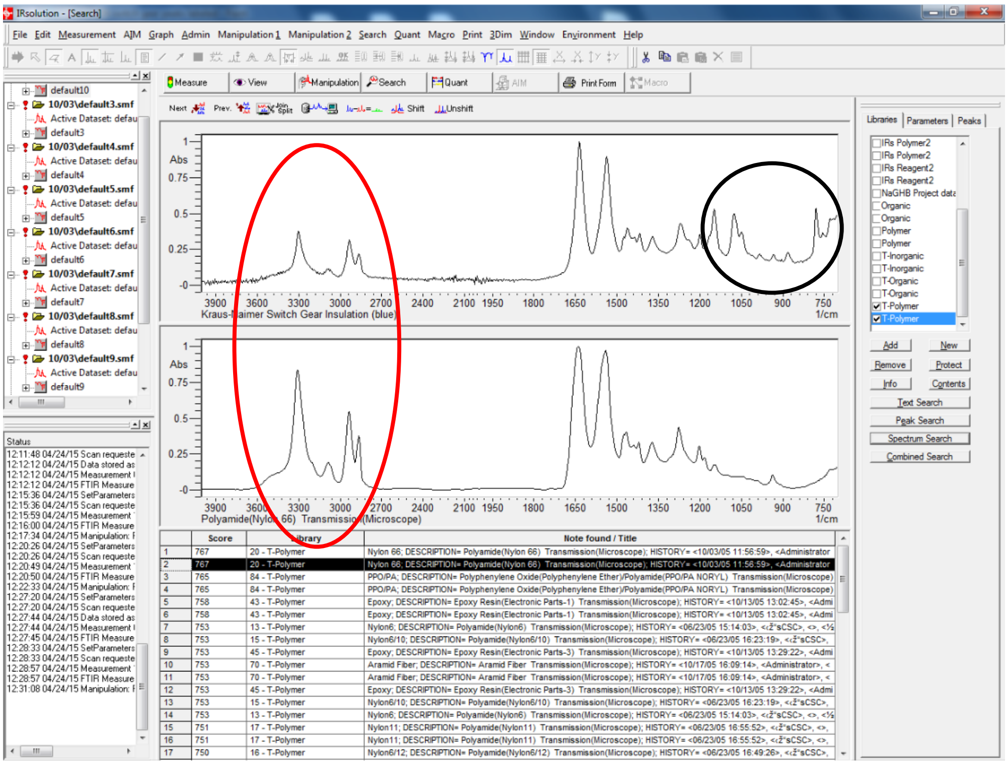


Fig 6 (xi) Adapted screenshot of ATR IR data indicating insulating plastic as nylon 6,6. Top line shows sample spectrum with additional peaks ***circled****, bottom line shows database comparison. Peak abundance value differences (****circled****) can be observed between 2800-3600 cm^{-1}*

Time restrictions precluded further experiments to ascertain the composition of any additional chemicals. Therefore, as this experiment was solely carried out to confirm data received from the manufacturer, it was considered that a qualitative interpretation of the IR spectra (Coates 2000) was sufficient for these purposes. These results were therefore considered to indicate that the insulating material in the switch gear terminal block was nylon 6,6 (with additions) confirming the data received from the manufacturer [see fig 6 (xi) and appendix B7.2].

Nylon 6,6 (polyhexamethylene adipamide) consists of carbon chains with amide groups (Mark 1998 p.189) and is created by a condensation reaction between hexamethylenediamine and adipic acid, both 6 carbon monomers, hence nylon (aka polyamide or PA) 6,6 (Antron 2013;

Invista.com 2014; Braun & Levin 1987). Nylon 6,6 is widely used in industry due to its strength, rigidity and good electro-insulating properties (Levchik & Weil 2000). Nylon 6,6 enters the glass transition stage at 50ºC (T_g) and melts at 255ºC (T_m) (BPF 2015; Invista.com 2014; Polymer Science Learning Foundation 2005; Thanki and Singh 1998).

Nylon is one of the earliest produced synthetic polymers and has been used extensively for fibre, film or plastic applications, including electrical insulation, furniture manufacturing and clothing. The most widely produced nylons are nylon 6 and nylon 6,6 (Levchik & Weil, 2000). Nylon has therefore been studied extensively with regards to its toxicity and performance when heated. As long ago as the 1950's Achhammer *et al* (1951) and Straus & Wall (1958) analysed nylon 6,6 heated in a vacuum to 400ºC. Both found a range of hydrocarbons were produced. Huffman & Peebles (1971) heated nylon 6,6 to 350ºC in a vacuum. They found the major products to be CO_2, NH_3, and H_2O, along with a variety of hydrocarbons.

Braun & Levin (1987) reviewed previous studies of the decomposition of nylons by the application of heat, in order to assess the toxicity of combustion products of nylon for the Centre for Fire Research at the National Bureau of Standards for the USA. This review found that pyrolysis products from nylon do not differ greatly by nylon type, nor is the experimental atmosphere (air, inert gas or vacuum) a major factor in the formation of product. This research did show that experiments carried out in air produced less hydrocarbons and more CO, CO_2, H_2O, NH_3, HCN and NO_2. The research acknowledged that many previous experiments had heated nylon to decomposition in the absence of oxygen, either in a vacuum (Achhammer *et al* 1951; Straus & Wall 1958; Huffman & Peebles 1971) or by pyrolysis-GC with nitrogen (Senoo *et al* 1971) and that this can appear not to be relevant to a 'real' fire situation where atmospheric O_2 would be expected to be freely available (Braun & Levin 1987). Michal *et al* (1981) experimented with nylon in air (although nylon 6,6 was not specifically studied) and found a number of hydrocarbon products from their experiments with nylons 6, 7, 8 and 11.

It was therefore decided to carry out indirect heating research using the supplied switchgear with Moss' pyrolysis experiments also conducted using cuttings and shavings taken from the edges of the same switch gear (Moss 2015) thus ensuring consistency between the two researchers projects.

One DC isolator was dismantled to identify the working parts and the location of those parts within the encasing plastic insulating material [see photo P2].

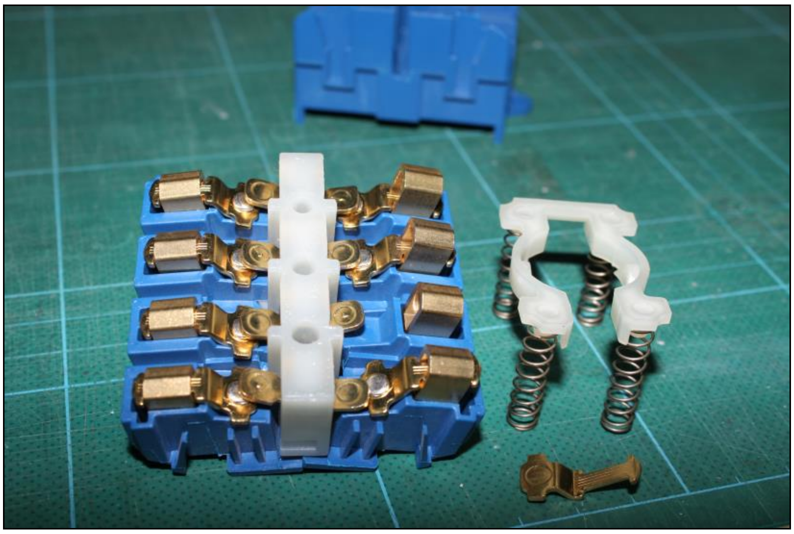


Photo P2 Dismantled DC isolator showing terminal block and switch bridges

A preliminary heating experiment was then carried out to test the proposed method [see Appendix B7.1]. The terminal block was removed from its enclosure for the experiment and held in a clamp in a fume cupboard. A 3.5 mm copper wire was clamped into the electrical connection for terminal T2 and heated using a Bunsen burner. Heat from the Bunsen flame was conducted along the copper wire to heat the terminal block from the inside, in the vicinity of terminal T2. The experiment was partially successful in that the terminal block displayed post fire indicators of internal heating of the insulating polymer in the vicinity of terminal T2. However, the insulating material became increasingly less viscous during the period of heating through its glass transition phase. This allowed the heated wire to fall due to gravity [photo P3].

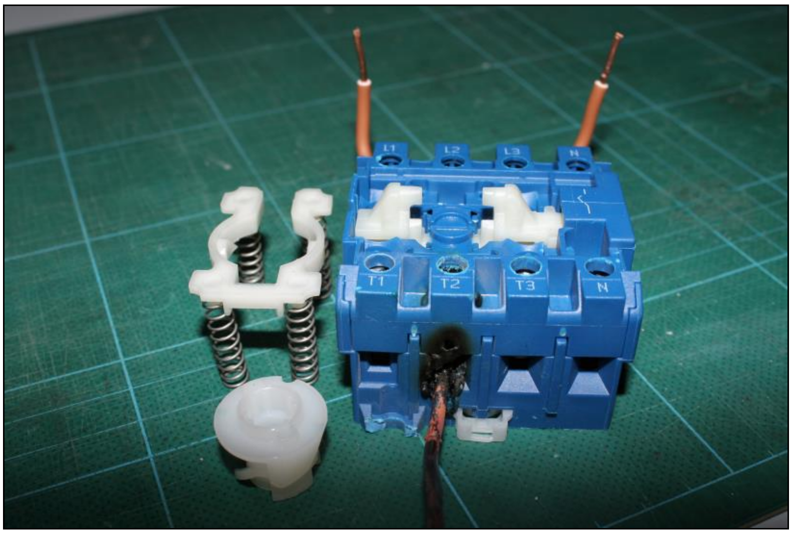


Photo P3 DC isolator at end of prelim heating experiment showing evidence of charring to terminal T2 and evidence of movement of the heated wire through the polymer

The proposed test rig was modified following observations from the preliminary experiment and a series of method developmental heating experiments was undertaken to create internal heating of the terminal block.

6.4.2 Heating experiments

The test rig was modified to hold the terminal block in the lower half of its designed enclosure in order to reduce the cooling effect from the surrounding atmosphere. This lower half of the enclosure was held in a clamp in a fume cabinet. In order to maximise heat transfer into terminal T2, which is designed to receive a 4 mm connection, a 4 mm x 300 mm copper rod was fitted into the terminal electrical connection clamp and used to conduct the heat from two Bunsen burners into the terminal. The lower half of the isolator enclosure was modified to allow the copper rod to pass through it, whilst minimising heating to the structure of the enclosure [fig 6 (xii) and photo E1].

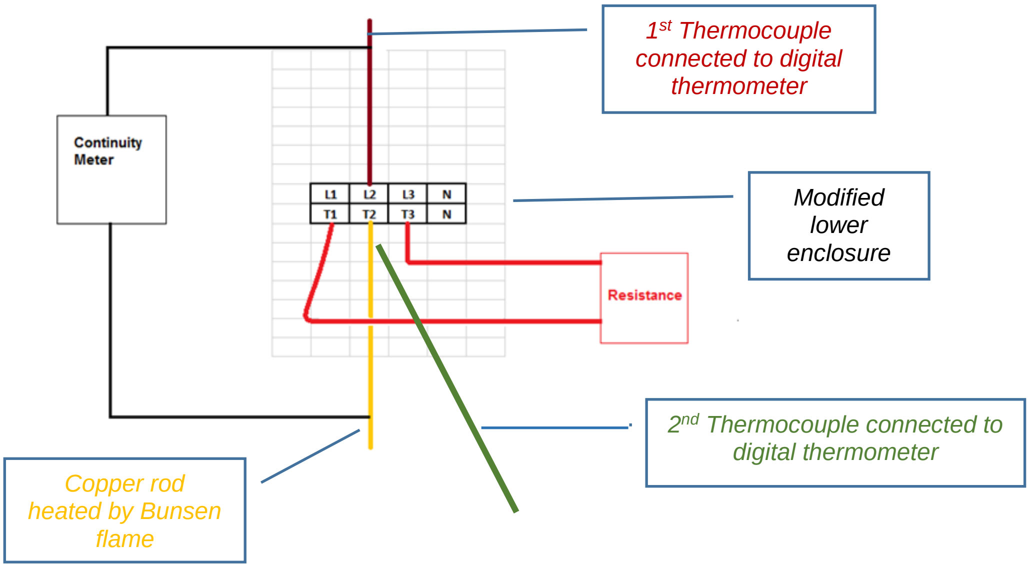


Fig 6 (xii) Diagram of test rig set up for heating experiments.

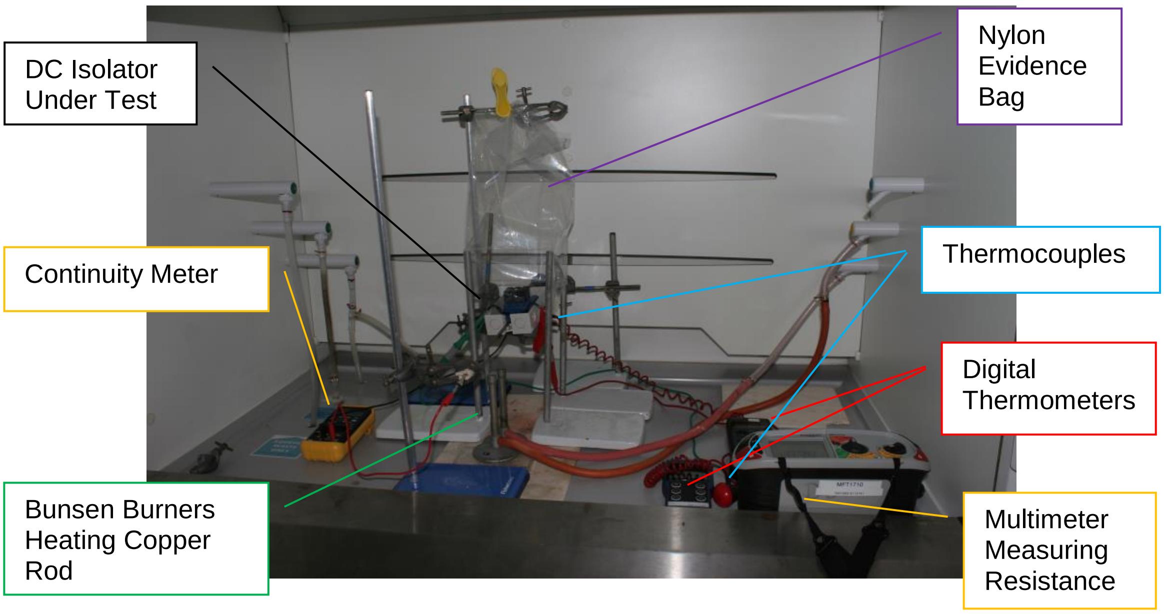


Photo E1 Set up of test rigs for experiments EX1 – EX3

In order to prevent gravity causing the heated rod to fall during the experiment (as the insulating material entered its glass transition phase), the opposite end of the rod was held in a clamp. Thermally insulating material was used to reduce the amount of heat conducted into the clamp from the rod (Schroeder 2000 p.38) [see photo E2].

Photo E2 Copper rod conducting heat into terminal T2 of experiment EX2

The following data were recorded:

- The temperature of the input terminal T2
- The temperature of the corresponding output terminal L2
- The electrical resistance across the heated terminals.

From observations of the preliminary heating experiment a hypothesis was formed that the lowered viscosity of the insulating material caused by heating, may allow movement of metal contacts in the insulating material and therefore cause a break in the circuit in the switch. Electrical conductivity was therefore tested across the switch using a continuity meter connected between the end of the copper rod held in the clamp and a thermocouple clamped into terminal L2. The continuity meter was set to emit sound whilst there was a continuity of circuit.

The test rigs were weighed to ascertain any change in mass during the experiments. The total mass of the test rigs was measured with the copper rod in place. This introduced an unmeasured variable, as the metal of the rod would be expected to gain mass during the experiment, as oxides formed on the surface of the metal. It was not possible to remove the rod after the experiment without causing damage (and therefore loss of mass) to the heat affected insulation material.

In order to collect pyrolysis product potentially emanating from the test rig, and then test those vapours using field conditions, a nylon 11 bag (as used by Kent Police for fire debris evidence collection) was positioned over the rig [see photos E1 and E2]. It was intended that this bag would collect vapours rising from the test rig in convection currents and that evolved pyrolysis compounds would either remain in the bag as vapour, or condense onto the inside of the bag. The bag was sealed at the end of the experiment by swan neck sealing and fastening with a cable tie [see photo E3]. This is an accepted forensic field technique for the collection of hydrocarbon samples (such as ignitable liquids) from fire scenes (FSS 2010 p.65; Daeid 2004 ch. 5; DeHaan, Kirk and Icove 2012 p.569). A sample of the head space from the bag was then removed using a gas syringe and analysed as part of Moss' project utilising Gas Chromatography Mass Spectrometry (GC-MS). This is a technique used to sample suspected hydrocarbons (ignitable liquids) collected from fire scenes (Daeid 2004 ch.5 & ch.6; DeHaan, Kirk and Icove 2012 ch.14).

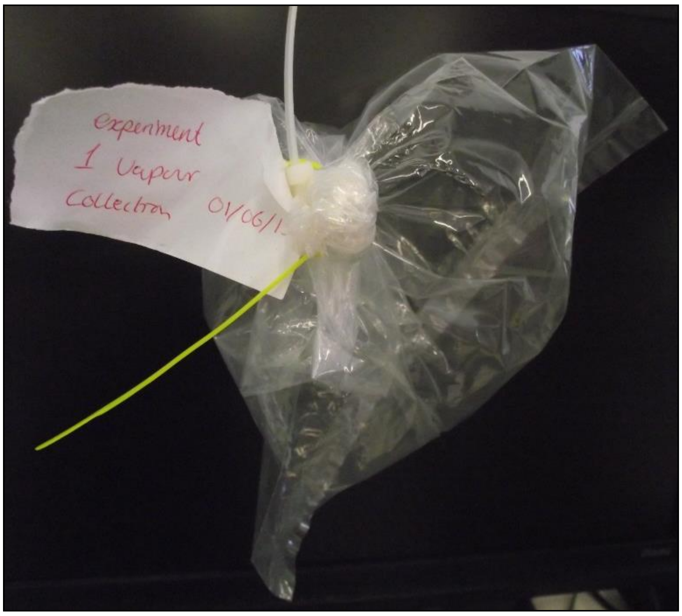


Photo E3 Nylon 11 evidence bag sealed by swan neck sealing. Moss photo

Due to the relaxation time required for the thermocouples to reach thermal equilibrium (Schroeder 2000 p.2), and to enable the recording of readings from portable digital thermometers and a portable multi-meter, it was decided a 1 minute time frame would be used to collect data and to record data every 5 minutes. The experiments were run for approximately three hours until thermal equilibrium was considered to have been reached [see appendix B7.8].

The temperature of terminals T2 and L2 was seen to alter consistently across all three experiments, with the temperature of terminal L2 noted to be lower than T2 in all three. It was also noted that for all three experiments the temperature of terminal L2 fell as contact between the terminals was lost [fig 6 (xiii)]. The temperature readings for terminal T2 in experiment EX1 can be seen to fluctuate [blue line in fig 6 (xiii)]. This was considered to be due to the difficulties in the application of the flat contact thermocouple used to take the reading. The experiment was adjusted to improve constancy of temperature readings by changing the method of recording the temperature of terminal T2, from the use of a flat surface contact thermocouple (as used in experiment EX1), to a needle probe thermocouple for EX2 and EX3. The use of an IR thermometer was considered, however, it was found not to be possible to obtain consistent readings using the hand held IR instrument. Consistency of temperature readings improved for experiment EX2 and improved further for experiment EX3 as the author's skill in the use of the instrumentation improved.

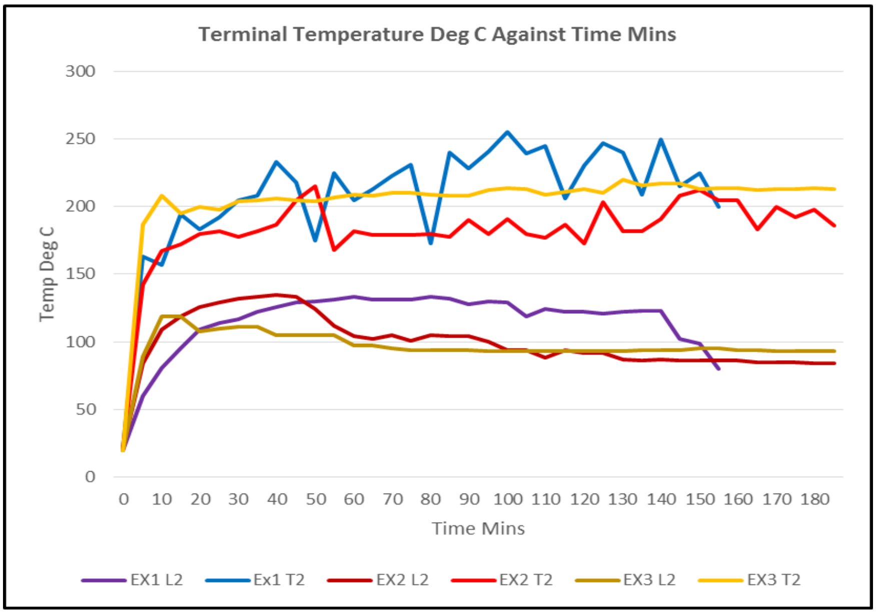


Fig 6 (xiii) Temperatures of terminals T2 and L2 for experiments EX1, EX2 and EX3

Electrical resistance across terminal block insulation was measured using a Megger multi-meter set to read MΩ and connected across the heated terminals [photos E4 and E5]. For experiment EX1 resistance was measured between terminals L1 and L3. This was altered to terminals T1 and T3 for subsequent experiments following comparison of the amount of heating damage caused to the insulating material in the regions of terminal T2 and L2 during experiment EX1.

Photo E4 Measuring instruments as used for all experiments

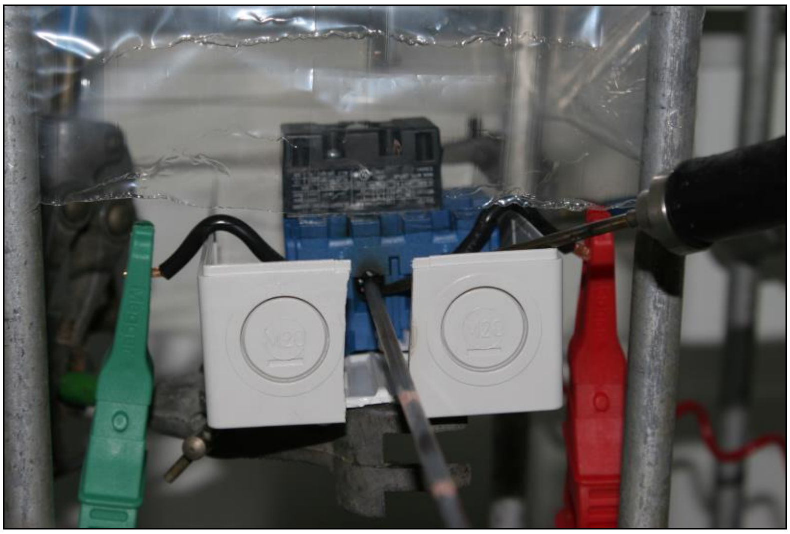


Photo E5 Electrical contacts used to measure resistance across terminals T1 and T3 and use of a needle probe thermocouple to measure the temperature of terminal T2 during experiment EX2

Resistance was observed to fall as the temperature increased during all three experiments and then was observed to return to initial levels [fig 6 (xiv)].

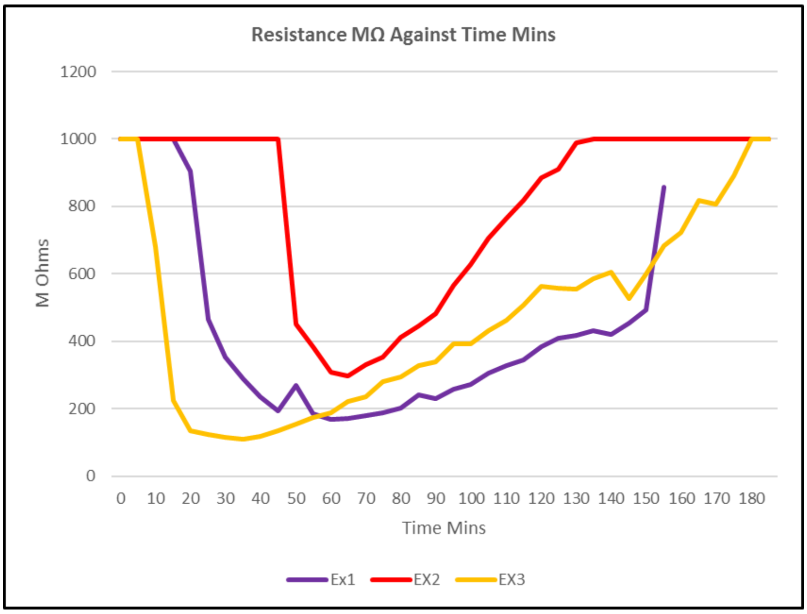


Fig 6 (xiv) Electrical resistance of insulation material as compared to time for experiments EX1, EX2 & EX3

Further research is required to ascertain the reason for this change in electrical resistance. It is hypothesised that this effect may be a feature of the insulation material passing through its glass transition phase [fig 6 (xv)].

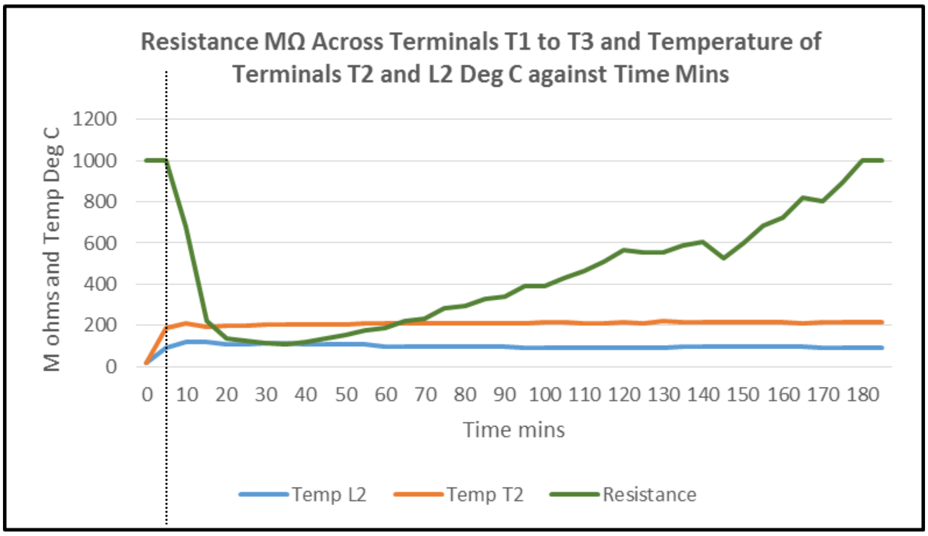


Fig 6 (xv) Electrical resistance of insulation material (nylon 6,6) as compared to temperature and time for experiment EX3 vertical dashed line showing initial fall of resistance correlating to T2 temperature of 208°C

It should be noted however that the lowest observed resistance of 109 MΩ for experiment EX3 is above the minimum Portable Appliance Test (PAT) regulations requirement of 2 MΩ for 230 v AC power (Burns 2011). Further research is required, regarding possible semiconductor ohmic heating effects on insulation displaying this fall in resistance due to heating in this type of isolator, when operating at designed levels of DC electrical power.

Significantly, it was observed that electrical continuity was lost across the switch bridge between terminals T2 and L2 during all three experiments. The times of this varied depending on the set up of the test rigs [see appendix B7.8]. In experiment EX1 the thermocouple inserted into terminal L2 was unsupported. It was seen to fall due to gravity as the integral structure of the terminal block altered, thereby breaking the continuity across the switch. It is postulated that this occurred as the insulation material became less viscous during the glass transition phase 50°C (T_g) – 255°C (T_m)

(Invista.com 2014). This caused the experiment to be terminated at 155 mins. Test rigs for experiments EX2 and EX3 were therefore modified by holding the L2 terminal thermocouple in a clamp to ensure support throughout the experiment. It was noted that continuity between terminals T2 and L2 again failed during these experiments. It is postulated that this was caused by the anti-arcing springs in the design of the isolator applying pressure to the switch bridge, thereby causing the switch to move slowly away from the terminal contacts as the insulation material became less viscous in the glass transition phase. The continuity meter's sound was heard to intermittently fail and re-sound as the contact was broken and re-made several times, before finally breaking contact altogether. This is indicative of arcing to occurring between the contacts.

Terminal blocks were dissected following their respective experiments and the insulation material adjacent to the metal contacts examined. In each case the insulating polymer showed signs of progressive thermal decomposition, from black char immediately adjacent to the metal components of the heated terminal, to lesser charring and melting observed away from the terminal [see photos E6 – E9].

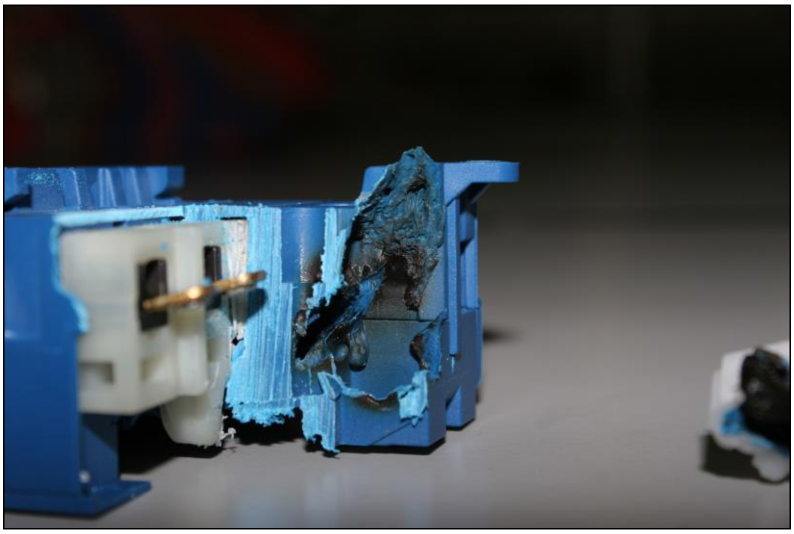


Photo E6 Dissected terminal location T2 from EX1

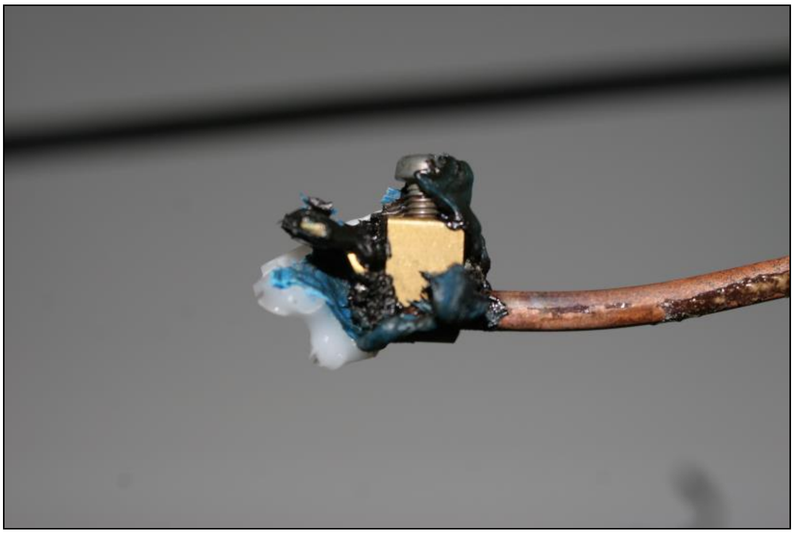


Photo E7 Removed terminal T2 from EX1

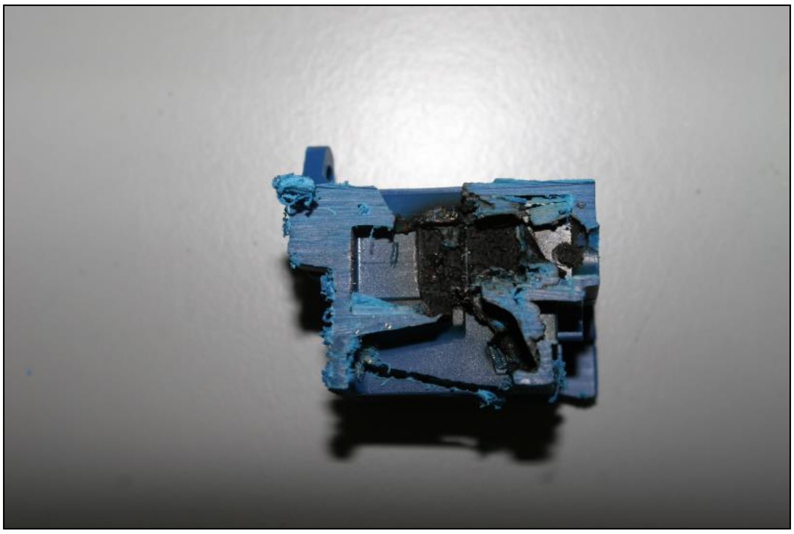


Photo E8 Dissected terminal T2 from EX2

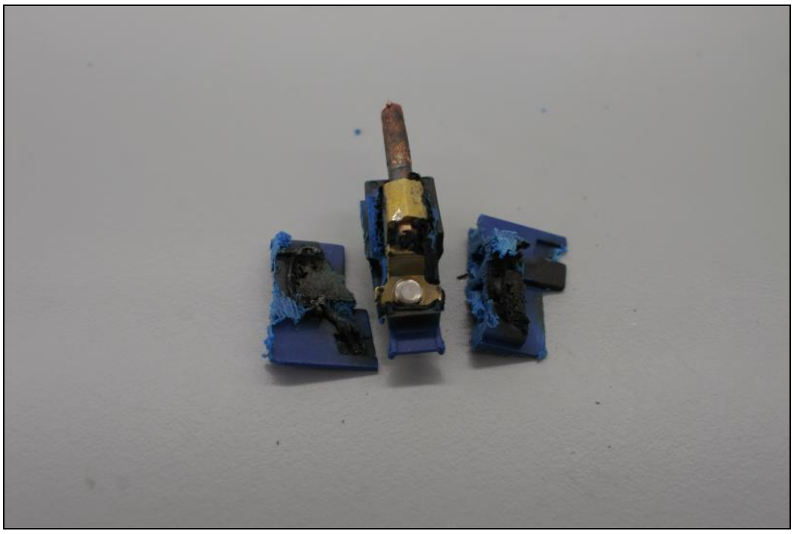


Photo E9 Dissected terminal T2 from EX3

This observable progressive charring is explained by considering the relatively low thermal conductivity (0.33 W m^{-1} K^{-1}) of nylon 6,6 as discussed in chapter 2. As heat is unable to pass into the bulk of the insulating material quickly, the localised heated area chars. This implies the temperature gradient (Nave 2012) from the area adjacent to the heated terminal to within the terminal block, could prevent the bulk of the material from reaching pyrolysis temperatures before phase changes occur. Further research is required to confirm this. Further research is also required to identify the extent to which the observed carbonisation may allow electrical tracking to occur at the levels of electrical power likely to be encountered in a domestic PV system.

Total mass loss was not measured for experiment EX1. There was a net loss of approximately 0.5 g from experiments EX2 and EX3. This indicates that some material had vaporised during these experiments. However, no visible pyrolysis product was observed emanating from any of the test rigs and the experiment to collect vapours from the test rigs was unsuccessful, with Moss' (2015) GC-MS analysis of the nylon 11 bag headspace showing no hydrocarbons collected from any of the rig experiments.

A series of experiments was then carried out to ascertain the nature of pyrolysis products evolved from filings and cuttings taken from the dismantled nylon 6,6 terminal block insulating material when heated. Moss was attempting to develop a simple method of identifying pyrolysis products emanating from nylon using Gas Chromatography allied with Mass Spectrometry (GC-MS). By using the same materials as the Smith led experiments it was hoped to show that GC-MS methods, as used to identify ignitable liquids recovered from fire scenes (Daeid 2004 pp.163-170) could be used to confirm the presence of flammable hydrocarbons in the pyrolysis products from heated nylon, as found in the DC isolator switchgear. For the GC-MS analysis section of the laboratory research Moss carried out the GC-MS analysis, Smith supplied samples to her and acted as her assistant, working under her direction. GC-MS details, including those for the column and settings can be found in Moss' thesis (Moss 2015 pp.14-20) [see appendix B8.4].

In order to supply Moss with gaseous samples for GC-MS analysis, five samples of 0.1 g of shavings of nylon 6,6 were taken from the terminal block of an isolator and placed in test tubes. The tubes were sealed using 100 mm x 100 mm nylon 11 bags and a cable tie. These tubes were heated over a Bunsen flame until visible pyrolysis vapour was observed to evolve from the shavings. The experiments were run for qualitatively progressive times, with the colour of the evolved product being the deciding factor [photo E10].

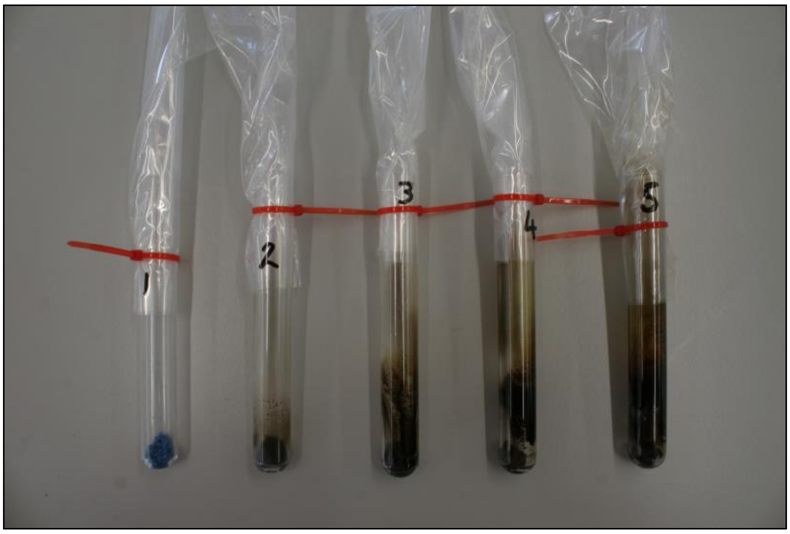


Photo E10 Evidence of progressive evolution of pyrolysis vapour from heated insulation polymer (nylon 6,6)

Experiment 1 was ended when light blue pyrolysis product was seen to evolve. Experiment 2 when yellow vapour evolved. Experiment 3 when brown vapour evolved and greater darkening of the inside of the tube was apparent. Experiments 4 and 5 were ended when progressively darker deposits were observed on the inside of the tubes.

1.5 ml of vapour was then removed from the headspace of each sample and directly injected into a GC-MS. Results were compared against a database to identify molecules and isomers in the samples.

A further sample of 0.1 g of nylon 6,6 insulating material was sealed in a tube as described previously, placed in a 'black body heat' test tube heater and heated to 200^{o}C (maximum setting) for 180 minutes. It was not possible to observe pyrolysis product emanating from this material. This material changed colour from its blue dyed designed colour (Kraus & Naimer Limited 2015) to green, but remained as a granulated solid. It was possible to separate the grains after the experiment, indicating that the material had not melted during the experiment and subsequently solidified [photo E11]. The green colour and granular nature of the material heated to 200^{o}C can be observed in the lower tube. Headspace GC-MS analysis of this sample revealed no hydrocarbons present.

Photo E11 Comparison of insulation polymer (nylon 6,6) heated by Bunsen flame until pyrolysis product was observed to evolve (upper tube) and that heated by black heat to 200^{o}C (lower tube)

This can be compared to the upper tube (marked 1 in photo E11) containing granulated polymer heated over a Bunsen flame until visible blue pyrolysis product was seen to evolve. The polymer is seen to be partially granulated after heating but adhering to the bottom of the tube where the material had melted and solidified. The material is observed to be still coloured blue in the photograph. As discussed earlier, due to commercial confidentiality, it is not known which chemicals had been used to colour the nylon in the switchgear. As the sample changed colour to green when heated to 200ºC it is possible that the blue pigment in the nylon switchgear may be volatile at low temperatures and therefore add to the evolved products. Further research is required to ascertain the extent to which this is the case.

GC-MS analysis of possible pyrolysis products evolving from the nylon used in the switchgear was then carried out. Two of the aims of Moss' research were to develop a method to:

- *'…determine the thermal decomposition products of nylon 6,6 samples …in conjunction with fellow researcher Mr Simon Smith's research…'*
- *'Assess the viability and accuracy of the developed method by determining whether the products found are likely to be the products of nylon 6,6 thermal decomposition' (Moss 2015).*

The GC-MS method was chosen as it is widely used in the detection of ignitable liquids recovered from fire scenes (Moss 2015). GC-MS analysis has the advantage of being three dimensional, allowing for gas chromatography retention time and abundance to be allied to mass charge ratio (Daeid 2004 p.163; Koussiafes 2015). However, the two aims [above] could be contradictory, for if the developed method was not accurate, or viable, then it would not be possible to reliably determine nylon 6,6 pyrolysis products.

Moss (2015 p.53) states in her thesis that she believes the interpretation of GC-MS results improve with experience. Furthermore, the interpretation of spectrograms can be considered to be a qualitative rather than a quantitative skill (Coates 2000; Koussiafes 2015; Lentini 2013 p.178). An additional problem with GC-MS is the fact the results vary depending on the equipment and settings used (Daeid 2004 p.169). The remote library data (NIST98) as used by Moss would most probably not have been captured by a machine with the same settings, or column, leading to possible inconstancies and requiring chromatogram and spectrogram interpretation by a researcher (Koussiafes 2015). The GC-MS internal data base also failed during the research (Moss 2015 p.44) possibly introducing further inconsistences to be taken into consideration.

This is illustrated by photo E12, a screen shot of the NIST database suggesting the pyrolysis products from sample 2, eluted from the column at 0.893 min to be atmospheric nitrogen (N_2).

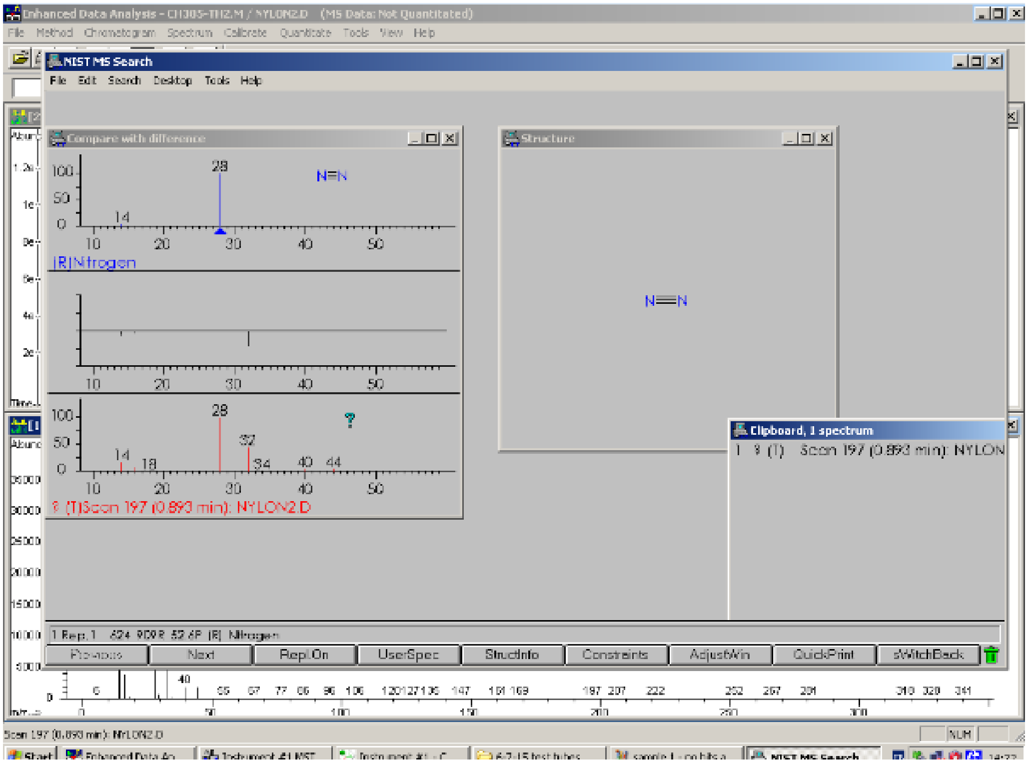


Photo E12 Screen shot of Moss' GC-MS analysis comparison with NIST database suggesting atmospheric nitrogen for a scan of the pyrolysis products from sample 2 (Moss 2015)

The atomic weight of nitrogen is 14 amu, meaning that of atmospheric molecular nitrogen (N_2) is 28 amu. This accounts for the database suggestion. However, the atomic weight of carbon

(12 amu) added to that of oxygen (16 amu) also gives a m/z of 28 (Chang 2013 p.81; Ebbing 1999 pp.52, 56 & 90). This means the data from the sample could have been inappropriately interpreted as N_2 and could actually be CO, which is a known pyrolysis product of nylon (Braun & Levin 1987). Furthermore, when using MS the heaviest detected ion is usually considered to be the molecular ion, therefore the Ion at m/z 44 could be CO_2 [12 amu + (16 amu x 2)]. The very process of ionising an injected sample in GC-MS causes the sample to fragment (Daeid 2004 p.163; Koussiafes 2015) potentially giving the return at m/z 28 [as observed in the NIST standard shown in fig 6(xvi)], suggesting CO may have been produced as a fragment of CO_2, or there has been an incomplete separation of gasses. CO_2 is also a known pyrolysis product from nylon (Braun & Levin 1987).

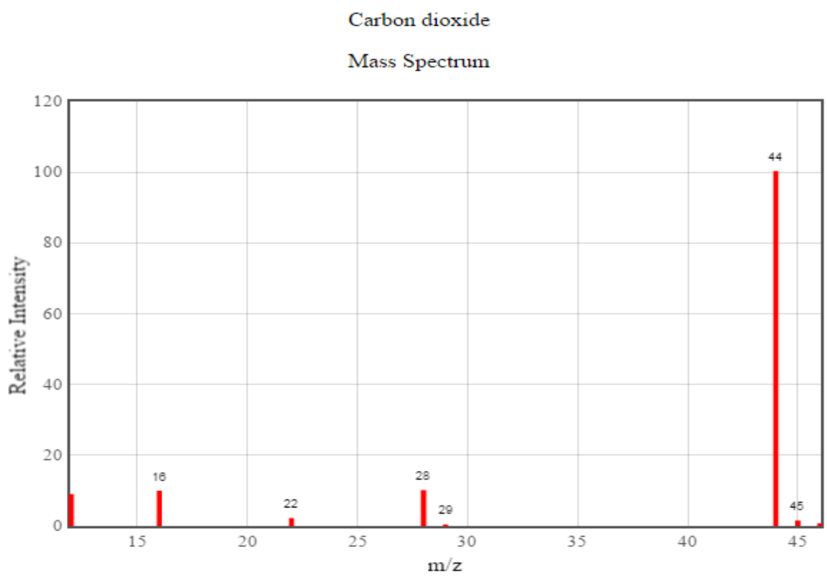


Fig 6 (xvi) Mass spectrum for CO_2 (NIST 2016)

However, the abundance peaks at m/z 44 and m/z 28 for the sample (as shown in photo E12) are observably opposite to those in the standard shown in fig 6 (xvi).

By adding the GC retention time to the discussion we can see that the elution of pyrolysis product in sample 2 (suggested as atmospheric nitrogen) was at about 0.89 min [red line added to photo E13].

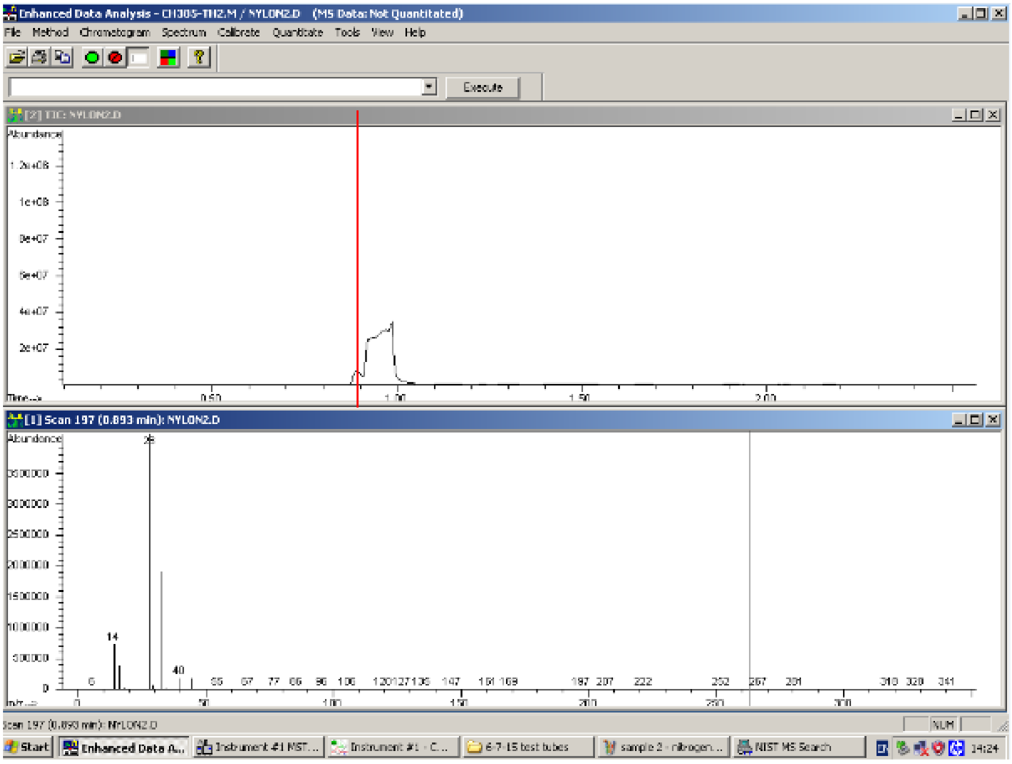


Photo E13 screen shot of GC-MS analysis showing peak at approximately 0.89 min (indicated by author's red line) taken to indicate atmospheric nitrogen (Moss 2015)

However, the peak at 0.89 min is not present in a previous air sample (see photo E14) indicating the hit at 0.89 min in photo E13 is not atmospheric nitrogen, for nitrogen is a major constituent of atmosphere and would be expected to be within the band of returns approximately (0.91- 1.25 min) shown in photo E14.

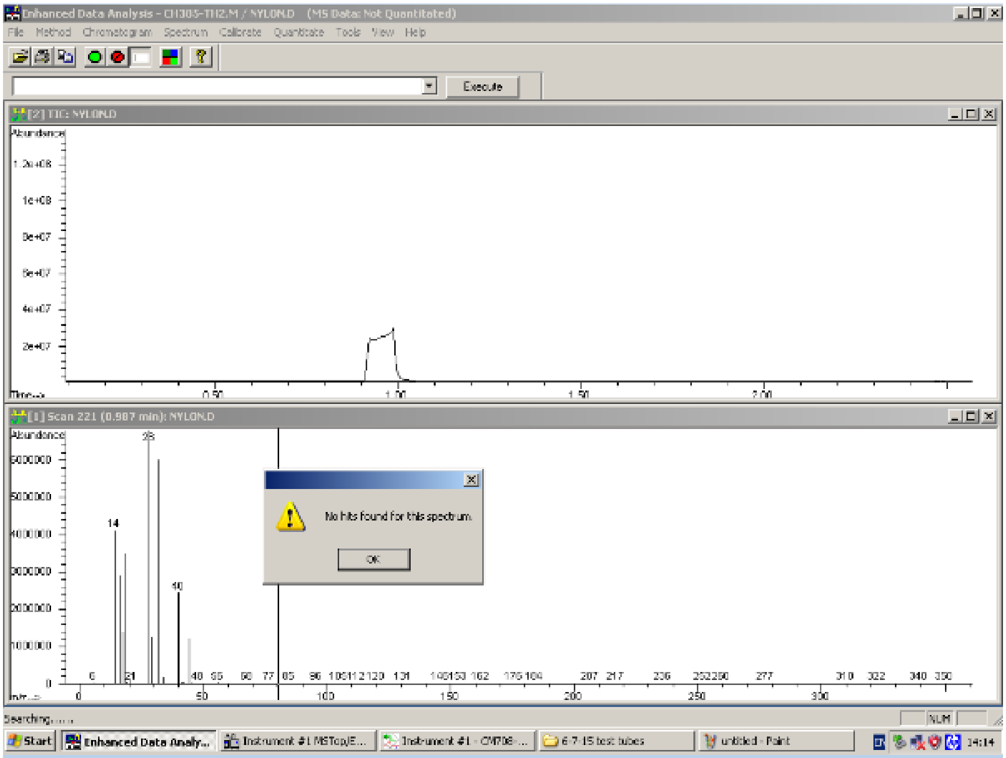


Photo E14 screenshot of analysis of GC-MS showing retention time and abundance of air sample. The peak before 0.9 mins is not present (Moss 2015)

Several improbable pyrolysis products were identified (Moss 2015 pp.45-47). This could be attributed to sampling techniques or user error on the part of the researchers. For example, Methylcyclobutane (C_5H_{10}) and 4,4-Dimethyl-2-Oxetanone ($C_5H_8O_2$) are identified as evolving from sample 5 [see appendices B8.2.47, B8.2.54 and figs 6 (xvii) and 6 (xviii)].

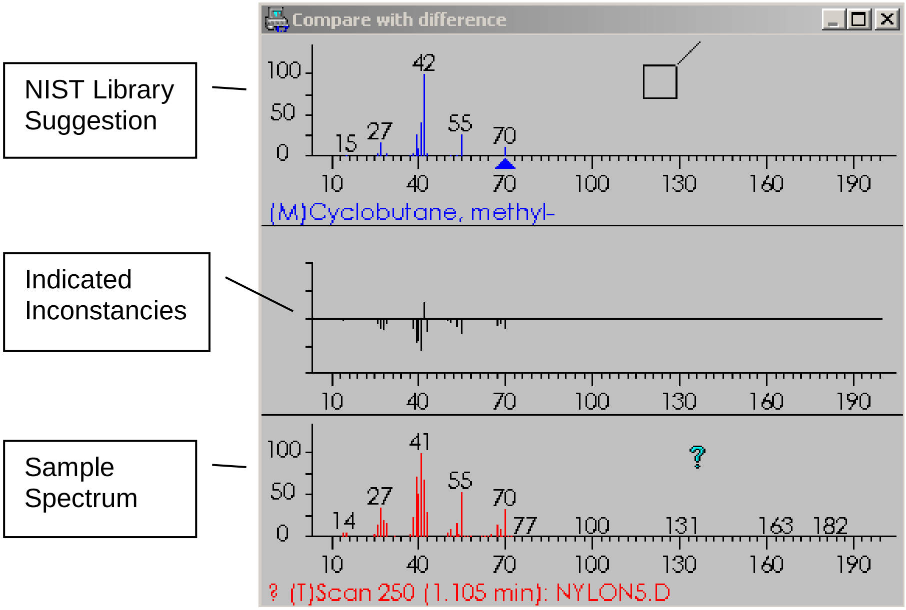


Fig 6 (xvii) Methylcyclobutane suggestion from NIST database showing structure and comparison with sample data taken at 1.105 min. Adapted from Moss (2015)

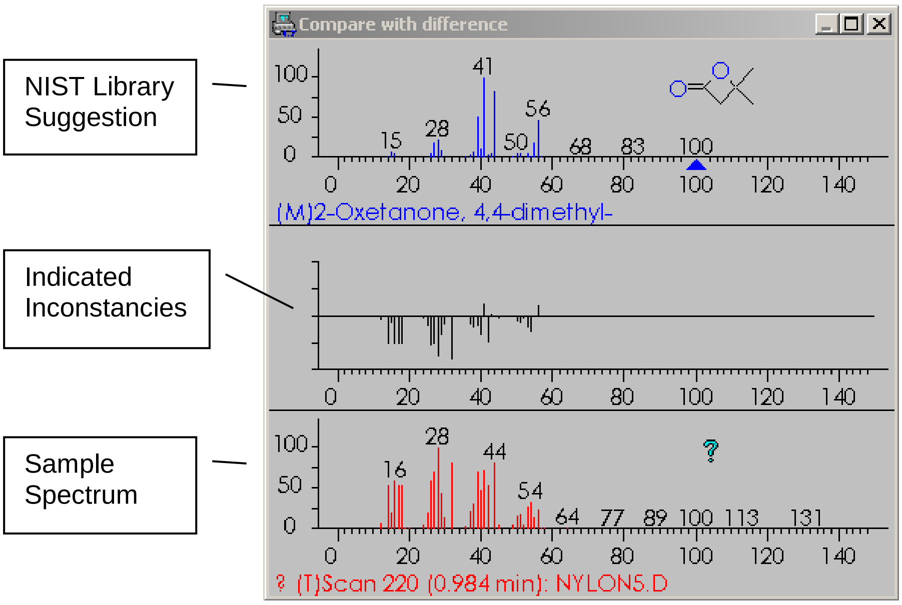
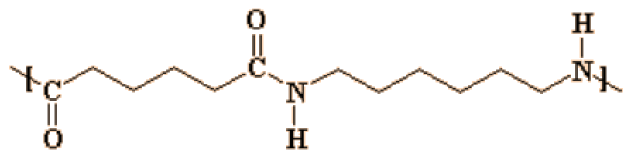


Fig 6 (xviii) 4,4-Dimethyl-2-Oxetanone suggestion from NIST database showing structure and comparison with sample data taken at 0.984 min. Adapted from Moss (2015)

Both of these molecules have strained four member rings, making them implausible products of the pyrolysis of nylon which is a linear chain molecule [see fig 6 (ix)]. Furthermore, the fragmentation pattern for 4,4-Dimethyl-2-Oxetanone as seen in fig 6 (xviii) is a very poor match to the library spectra suggestion.



nylon 6,6

Fig 6 (ix) nylon 6,6 linear structure, adapted from Polymer Science Learning Foundation (2005)

The GC-MS method developed by Moss to identify pyrolysis products from the nylon switchgear needs to be used with caution, as comparisons with library data should only be considered as a suggested guide and not definitive. For as Koussiafes (2015*) states "it is not acceptable to make a final, conclusive identification… based solely on a search of an externally generated library"*. To be certain, direct comparisons with the suggested products would have to be made using the same GC-MS, column and settings.

However, on reviewing the available mass spectrometry data, the library match for benzene [appendix B8.2.39] appears to show good correlation with the sample [see photo E15].

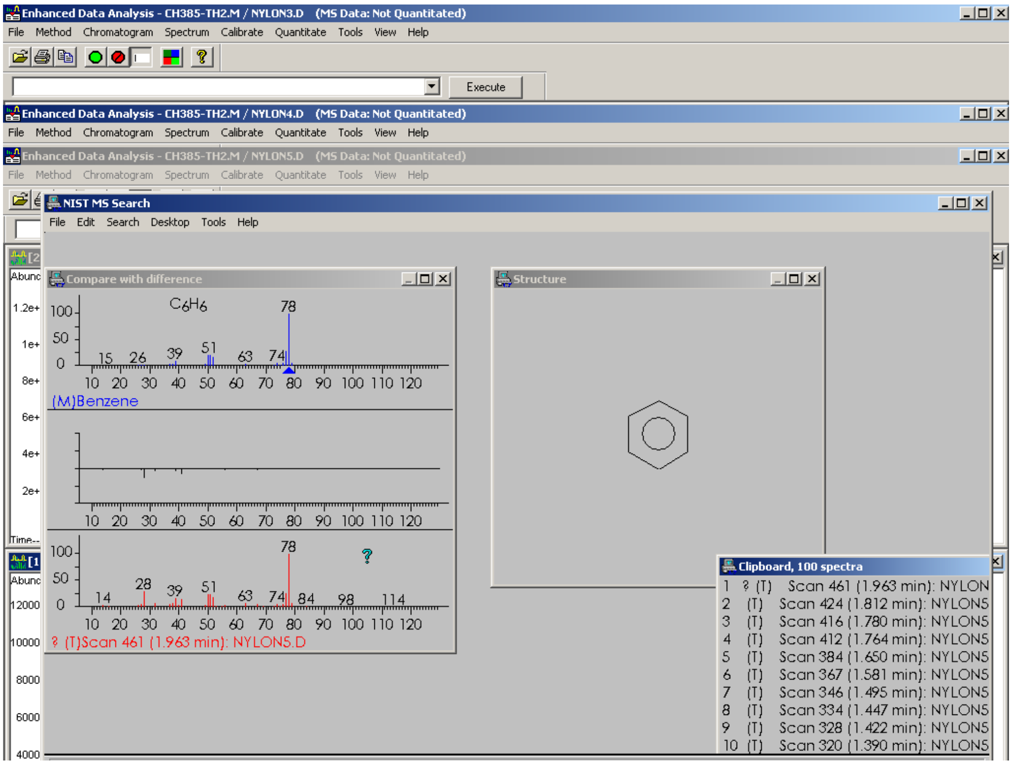


Photo E15 Screenshot of GC-MS analysis showing a good correlation between sample and library spectra for Benzene (Moss 2015)

Nitrogen and oxygen would be expected to be found in pyrolysis products evolved from nylon 6,6 for as discussed earlier nylon contains those elements. Moss (2015 p.49) believes several products containing nitrogen and oxygen were identified and attributes this to the presence of those elements in both the nylon, and the air the pyrolysis (and possible partial combustion) took place in.

Moss' research does therefore indicate that a variety of flammable hydrocarbons are probably evolved (along with carbon monoxide and carbon dioxide) when nylon 6,6 making up the switchgear is heated to above 200ºC. It is interesting to note that Moss suggests many hydrocarbons listed from previous studies which could be identified using her method [see table 6 (iii)], as the method employed by the author to capture the pyrolysis product from the nylon shavings exposed the samples to heat whilst in air, contrary to the methods used by the majority of previous researchers, and neither Smith or Moss could be considered as skilled in GC-MS laboratory analysis.

Product	**Reference for Study in which Product was Previously Located**
Benzene	Achhammer *et al* 1951, Straus & Wall 1958, Senoo *et al* 1971, Christos *et al* 1977, Michal *et al* 1981
Butadiene	Michal *et al* 1981
Butene	Straus & Wall 1958, Achhammer *et al* 1951, Michal *et al* 1981
Carbon Dioxide	Straus & Wall 1958, Achhammer *et al* 1951, Huffman & Peebles 1971, Christos *et al* 1977
Carbon Monoxide	Achhammer *et al* 1951, Christos *et al* 1977
Cyclohexene	Michal *et al* 1981, Achhammer *et al* 1951, Straus & Wall 1958
Cyclopentanone	Christos *et al* 1977, Ohtani *et al* 2011, Michal *et al* 1981, Achhammer *et al* 1951, Straus & Wall 1958, Huffman & Peebles 1971, Lattimer & Montaudo 2002
Cyclopentene	Michal *et al* 1981
Heptadiene	Michal *et al* 1981
Heptene	Michal *et al* 1981
Hexadiene	Straus & Wall 1958, Michal *et al* 1981
Hexane	Michal *et al* 1981, Achhammer *et al* 1951
Hexene	Michal *et al* 1981
Methane	Achhammer *et al* 1951
Methylcyclopentene	Michal *et al* 1981
Pentadiene	Straus & Wall 1958, Achhammer *et al* 1951, Michal *et al* 1981
Propene	Achhammer *et al* 1951
Toluene	Christos *et al* 1977, Michal *et al* 1981

Table 6 (iii) Table of results of GC-MS analysis, listing pyrolysis products suggested by Moss which had previously been found by historical researchers. Adapted from Moss (2015)

If known ignition data are considered for examples of possible pyrolysis products from nylon as suggested by Moss and identified in previous research fig 6 (xviii), then a potential fuel source can be identified.

Substance	MIE in air mJ	Flash Point Deg C	Auto Ignition Temp Deg C	Lower Flammable Limit vol %	Upper Flammable Limit vol %
Benzene	0.55	-11	580	1.3	7.9
Butadiene	0.13	-76	335	2	12
Butene	N/A	-73	325	1.7	9.7
Carbon Dioxide					
Carbon Monoxide	N/A	N/A	588	12.5	74
Cyclohexene	N/A	-20	310	1.2	10.1 e
Hexane	0.29	-23	220	1.2	7.4
Methane	0.3	-188	640	5	15

Fig 6 (xviii) Known ignition data for examples of pyrolysis products identified by previous research (non-hydrocarbons highlighted; N.B. CO_2 is non-flammable).

Adapted from (Moss 2015; Explosion Solutions.co n.d.; Babrauskas 2003b pp.1024-1055)

6.5 Discussion

Developmental experiments have allowed a test method to be identified and improved on, in order to observe the effects of heat applied internally to a Kraus and Naimer DC isolator (type T04/D-P003DE-14H406) terminal block, in the vicinity of terminal T2. This simulates the effect of work done on terminal T2 by a poor electrical connection. Should such work done on that terminal generate heating to the temperatures identified in this series of experiments, then it is reasonable to conclude that similar effects would be observed.

The most significant of the observed effects is the possible creation of conditions for arcing within the switch gear terminal block, for it is known that such an arc would generate sufficient radiated heat to cause pyrolysis of the adjacent switchgear insulation polymer. Alternatively, should an arc be established, radiated heat from the DC arching could ignite the isolator enclosure, which was identified as polycarbonate by the manufacturer (Kraus & Naimer Limited 2015), or the substrate a DC isolator was mounted on. Further research is therefore required to ascertain the combustibility of the plastic enclosure.

This developmental experimental research could be improved by the use of integrated instrumentation capable of taking simultaneous readings, thereby enabling data to be collected at equal time intervals and more accurate comparisons to be made. Furthermore, the introduction of electrical power at levels likely to be expected across the switch would enable data to be collected relating to the observation of arcing.

The series of method developmental experiments for the GC-MS analysis of products evolved from heating of electrical insulation as used in a Kraus and Naimer DC isolator, (type T04/D-P003DE-14H406) terminal block, has suggested that should a terminal block be heated to above 200^{o}C and pyrolysis occur, a wide range of hydrocarbons and CO may be evolved. Further research is required to ascertain the exact temperatures at which pyrolysis of nylon 6,6 as used in this terminal insulation occurs. However, it is reasonable to postulate that ignition of any evolved hydrocarbon vapours and CO gas could result if they were exposed to an ignition source (such as an electric arc above the MIE for the evolved product) in the presence of sufficient oxygen.

Chapter 7 Conclusion

This research has followed the principles of transdisciplinarity, blending both social science and natural science methods. To be fully successful this research would have to be seen to have merged natural science and social science techniques into a single transformative methodology, transcending disciplinary boundaries. This has been achieved and is most apparent as applied to the cold case review carried out for this research. Here, data gathered from social science style interviews and use of documentary analysis has been blended with an applied knowledge of the natural sciences of chemistry and physics, to form a conclusion as to a possible common point of failure for a PV system which may develop to fire. Transdisciplinarity would have been further enhanced if the researcher had been able to attend a PV related fire scene(s) during the research period to gather and carry out laboratory analysis of physical evidence from an actual fire(s).

This research clarifies that unlike traditional mains voltage systems, circuits in PV systems can carry high DC voltages (usually into the roof spaces of properties for domestic use) and that these DC circuits cannot be switched off, or fuse protected. It explains differences in wiring circuitry and identifies major components likely to be used to harvest solar energy and convert it to usable mains voltages. The research also shows that although a significant number of fires have been identified as originating from PV systems, doubt exists as to actual numbers, or whether there is a commonality of cause of fire, for this research clarifies that national fire data does not specifically record PV as an origin, or cause of fire.

This research identifies that although a greater range of local data is collected by KFRS, quality of that data varies depending on levels of training and experience of the person examining the fire scenes. By using the social science techniques of qualitative, quantitative and mixed methods analysis, the research demonstrates that a significant number of operational fire managers feel they have not received sufficient training to recognise a fire as originating from a PV system and that they therefore feel they do not have the skills, or confidence, to do so. It does show a high degree of trust has been placed on calling for assistance from higher level FSEs within the KFRS. However, this research also exposes that for this to occur a lower level FSE has to recognise the problem and refer it up the line. Reliance of fire service management on issuing guidance regarding this issue is revealed to be flawed, with a high percentage of staff shown to be not using, or indeed even aware of such guidance. This lack of knowledge, competence and/or confidence by L1 FSEs in the area of PV, could prevent further examination of fire scenes by level 2 or 3 FSEs leading to a possible trend being missed.

Using transdisciplinary forensic cold case analysis techniques this research has clarified data from fires which have been attributed to PV systems in Kent. This analysis has indicated that there is a probable common point of origin for those incidents, with the area of interest being within the DC circuits, and centred on the DC isolator. This research has shown that the main cause for the origin of fire at the examined incidents is most likely to be DC arcing and that such arcing could be caused by poor installation, poor construction, electrical overload or design limitations.

The aforementioned contextualising research then led to the development of a natural science based method for laboratory examination of post fire indicators of the early stages of internal heating of a terminal block in a DC isolator. This developmental research revealed that charring and phase changes occur to electrical insulation material in the close vicinity of a terminal heated to between 200ºC and 255ºC. It is postulated that heating to within this temperature range could be sufficient to cause arcing to occur, leading to rapid further heating and therefore fire development (dependent on the rate of heat conduction through the material as considered against the rate of phase change). It is also interesting to note the changes to the electrical insulation properties of the insulating material when it was heated to approximately 200ºC. Further research is required to ascertain the extent (if any) to which this may add to internal heating of the terminal block from semiconductor ohmic loss.

This laboratory based research therefore builds on the previous contextualising research and brings the project as a whole closer to the concept of forensic transdisciplinarity. By recognising the social science based research outlined in chapter five and the cold case review in chapter six as the application of inductive social science grounded theory research (where the researcher starts with an open mind and a blank sheet, then collects data whilst looking for answers arising from those data) (Newing 2011 pp.243 & 246) two hypotheses may be formed as to possible mechanisms of failure which may lead to arcing in a DC isolator for a PV system (see section 6.2).

If laboratory based natural science research provides a possible answer to the identified problem and evidence from this research is communicated to level 1 FSEs, then the loop will be closed and the concept of total transdisciplinarity will be achieved.

First hypothesis:

> ***Ignition of insulating material within the terminal block of the switch occurs leading to arcing, as the insulating material is consumed.***

It is possible that combustion of insulation material could occur leading to arcing as the fire progresses and consumes the insulation. However, it has been shown that temperatures in excess of 200^{o}C are required to pyrolise the tested insulating polymer (nylon 6,6). Pyrolysis products observed to have evolved from the insulating material have been shown to be flammable hydrocarbons and CO. However, heat introduced onto the terminal block (by work done on a poor electrical connection for example) has to create suitable conditions for pyrolysis product to be evolved, and for those products to be subsequently ignited. As the ignition temperature range (piloted and auto) of nylon 6,6, as listed by Babrauskas (2003b p.1067) is 420-500ºC, it is thought improbable that this could be caused by ohmic loss heating from a poor electrical connection.

Further research is required in order to clarify this, using levels of electrical power designed to be applied to a PV DC isolator to ascertain the heat yield from work done on a poor electrical contact at those levels. However, given the evidence outlined in chapters 5 and 6 it is thought improbable this is the correct hypothesis for the origin of the examined fires.

Second hypothesis:

> ***Internal heating of a terminal block causes the insulating material to lose its intrinsic mechanical supporting characteristics, allowing an arc to occur.***

Experimental research has revealed that internal heating of a terminal connection can lead to changes of the phase state of the insulating material, causing failure of structural integrity and therefore allowing an arc to be established. It is felt that this is the most significant observation from the experimental stage of the research. It was noted the lowering of viscosity of the insulating polymer heated into its glass transition temperature region (T_g) seemed to allow the springs in the switchgear assembly of the examined isolator to slowly separate the electrical switch bridge from its contacts. This slow separation is the opposite from that required by design, and would inevitably lead to arcing across the switch when carrying the designed DC current. It can be postulated that such an arc would create sufficient heat to vaporise the insulating polymer and ignite the evolved products. It is therefore surprising an insulating polymer with such a low T_g was used in the construction of this type of electrical switchgear.

Again, further research incorporating designed electrical power levels is required in order to develop the methods identified in this research, using voltages high enough to establish an arc and test this hypothesis. Further research into the behaviour of other makes, models and types of DC isolator is also required to establish if there is a common problem. However, it is believed this is the most likely hypothesis for the origin of the examined fires.

7.1 Summary

This research has revealed:

- It has not been possible to ascertain if fires recorded as originating within Photovoltaic (PV) solar systems are proportionate to fires arising from other electrical circuits, for national and local fire data are exposed as not reliable for this area.
- There is a wide inconsistency in the ability and confidence of fire scenes examiners in Kent in recognising the origin of fires which should be attributed to a PV system and that this appears to vary in proportion to the experience of the examiner.
- PV solar systems offer a different risk 'of fire', and 'from fire', due to the different nature of the installation, type, and voltages of electricity used. Being high voltage DC (which cannot be switched off while light shines on the solar modules) rather than mains voltage AC.
- The point of failure of a PV system for fires in Kent over a five year period as most likely to be within the DC circuits and most probably in the area of the DC isolator.
- Two hypotheses can be developed as to a possible mechanism of failure leading to ignition.
- Expected observable post fire indicators likely to be associated with those mechanisms of failure.

7.2 Future research and recommendations

The author proposes the following areas for further research:

7.2.1 Social science based research

- **Data from other FRS.** Local fire data collected and collated by other UK fire and rescue services could be examined for consistency.

- **Data from PV Industry.** Data from the alternative energy industry and the Microgeneration Certification Scheme could be compared and contrasted with improved fire data to establish frequency of PV fires.

- **Government Data.** Government departments such as DECC and DCLG (Home Office from April 2016) (Gov.UK 2016) could compare and contrast data to establish frequency of PV fires, in a similar way to that collected and collated for crime, by the Home Office from the police and DCLG from the fire service.

- **International Data.** Fire data from other countries which use PV systems could be examined to establish commonality.

- **Verification of this research**. Data collected by the author from KFRS should be independently verified.

7.2.2 Natural science based research

- **Expansion of Dataset.**

- Experiments should be carried out on other makes and models of DC isolator.

- Experiments should be carried out using DC power at designed levels.

- Experiments could be carried out to ascertain the combustibility of plastics used for DC isolator enclosures such as the Kraus and Naimer KG20T104/D=P003KL51V DC. However, it should be noted changes in wiring regulations from 2016 require such switchgear to be enclosed in non-combustible materials (BSi 2015 pp.36 & 75).

- **Verification of this research**.

- Experimental data collected by the author should be independently verified.

7.2.3 Transdisciplinary research

- The principles of transdisciplinarity should be applied to the examination of fires scenes. Something the author fully intends to do.

7.3 Recommendations

In the interests of safety and to allow for more accurate determination of the origin of fire originating from PV systems:

- Consideration should be given to amending Approved Document B of schedule 1 of the Building Regulations to require that smoke detection be fitted to roof spaces, or similar compartments, containing PV system components such as isolators, inverters and/or DC connectors.

- Outcomes of this research should be spread widely to the fire investigation fraternity, specifically:

    - Presentations to conferences attracting a wide audience of fire scenes examiners.

    - Wider circulation of sections of this research in fire industry publications.

- Further training in fire scene examination should be carried out for all levels of fire scenes examiner, including the demonstration of expected early stage post fire indicators from internal heating of components.

- '*PV equipment'* should be added as a data sub set to the national IRS data set as a source of ignition.

- National and local inter-government department data should be standardised and shared, especially between DCLG [Home Office from April 2016] (Gov.UK 2016) and DECC.

- The use of an insulating polymer with a T_g as low as 50^{o}C as a structural part of a DC isolator should be discontinued.

- PV components should be mounted on non-combustible materials.

- Obvious standardised signage should be fitted externally to buildings where DC PV solar power is used.

7.4 Post Script

Although not the focus of this thesis, it is noted that during interviews conducted for this research KFRS staff raised concerns regarding the additional imposed weight loading of PV modules on buildings, especially during firefighting operations. The reader may be interested to note that the author is involved (2016) in research into this and other related PV fire hazards being carried out by BRE Global Ltd (BRE 2016).

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Appendices

This research is an example of forensic transdisciplinary methodology and therefore a wide range of differing types of data have been gathered and integrated to form conclusions. These include social science based data such as interview transcripts and questionnaire data, along with natural science based experimental and literature review data, including forensic science based document examination and cold case review data.

Data integrated to form conclusions have been made available in appendices. However, in the interests of resource limitation and economic efficiency only one appendix has been printed and all other appendices are only to be found saved in various electronic formats on the enclosed CD-ROM.

Photographic Images

Unless otherwise indicated, all photographs in this thesis have been taken by the author and are copyright Prometheus Forensic Services Ltd.

All photographs can be found on the enclosed CD-ROM.

Appendix A.

An Explanation of Phase Change and Glass Transition

The known universe is created of matter and energy which can be interconverted as denoted by Einstein's famous equation: $E=mc^2$ (Nave 2012). Chemically, matter is subdivided into separate elements as represented in the periodic table. This table starts with the lightest element, hydrogen, then progresses through to very dense, heavy radioactive elements such as uranium. The smallest part of an element which still displays the properties of that element is called an atom. Atoms can be joined together by electrostatic force, or by the sharing of electrons in a process called bonding (Ionic, Covalent or Metallic), to create compounds. Two or more elements can co-exist in a mixture, or, if they react with each other, they can form different types of bond, to create compounds (Chang 2013 ch.2; Ebbing 1999 p.11; Housecroft and Constable 2010 p.31).

When above absolute zero (0 K or approximately -273^{o}C) particles which make up matter (molecules or atoms) are in a constant state of movement, dependent upon their energy levels (temperature) and the pressure applied to them. They vibrate in solids, are free to flow around each other in liquids, and are free to move in any direction in gases.

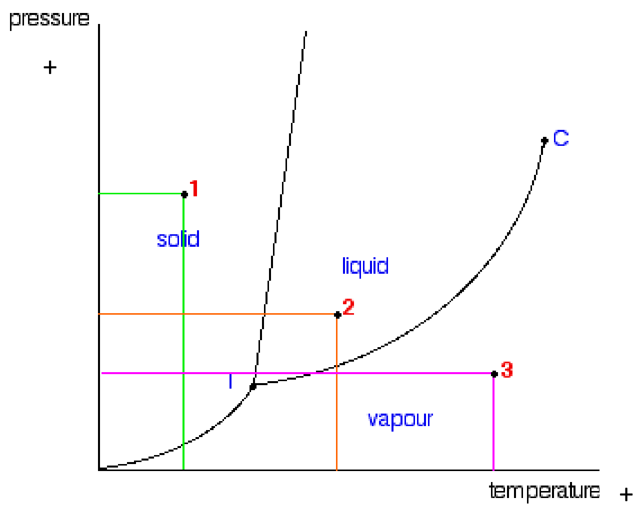

Fig 2 (viii) Phase change diagram adapted from (Chang 2013 p.506)

This vibration (kinetic energy) is therefore responsible for the phase state of the matter, solid, liquid or gas. For example at the temperature and pressure shown at point 1 in Fig 2 (viii) [above] the substance is a solid. If the pressure applied to the matter decreases, or heat energy is transferred into matter (thereby raising the temperature of the substance), the particles which make up that substance become 'excited'. They start to vibrate more, until they reach an energy state where they are able to loosen the bonds between them and flow over and around one another. This increase in temperature causes the substance to change its phase state from a solid to a liquid, as indicated in the region shown at point 2 in Fig 2 (viii). Or to put it more simply the substance melts.

If more heat energy is transferred into the substance the particles continue to become excited. Eventually the energy in the substance overcomes the forces bonding the particles one to another and they separate, changing the phase state to a vapour, (or gas) as indicated in the region shown at point 3. The magenta line in the graph indicates that at the given pressure the substance would have changed through all three phase states (solid, liquid and vapour) to reach point 3 due to increasing temperature. The difference between a vapour and a gas is also dependent upon temperature and pressure as indicated by point C (the critical point) in fig 2 (viii), for at temperatures above the critical point vapours of a substance cannot be liquefied by increasing the pressure and liquids have different properties, being referred to as super critical liquids (*ibid*).

Matter in its solid state can be either crystalline or amorphous depending on intermolecular bonding; whether molecular, covalent, ionic or metallic. Molecules in crystalline matter are bonded one to another in a three dimensional lattice. Those in amorphous matter are attracted one to another in no particular order, therefore amorphous solids could be considered to be extremely viscous liquids. Glass is an example of this type of state. A third type of solid, usually formed by rapid cooling, thus preventing molecular bonds from forming, displays the properties of both crystalline and amorphous matter, depending on the temperature of the matter. These solids are referred to as semi-crystalline (Chang 2013 p.478; Glot, Golotina and Shardakov 2015).

Synthetic polymers (plastics) can exist as any one of these three types of solid (Amin and Amin 2011).

Synthetic plastics fall into two basic types, thermo-setting plastics which cannot be softened or melted by the application of heat, and thermo-plastics, which soften with the application of heat (Amin and Amin 2011). The temperature between which materials such as a thermo-plastics start to soften (or vitrify) but before melting occurs, is referred to as the glass transition temperature. This is indicated with the symbol (T_g), for the lowest temperature at which glass transition occurs.

Fig 2 (ix) [below] shows the relationship of the heat capacity between the glass transition temperature (T_g) and the melting temperature (T_m) of crystalline, or vitreous (glassy state), glycerol (McKenna and Simon 1998). The graph shows the difference in the amount of heat being absorbed by the different states of the material between the T_g and T_m points. This energy is being used to change the phase state of the material.

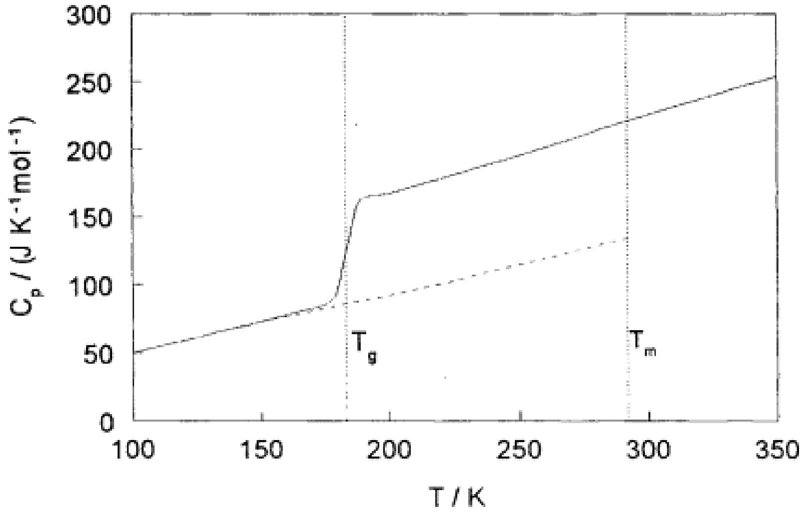

Fig 2 (ix) Heat capacity of glycerol as a function of temperature for the liquid and for the glassy state (solid curve) and for the crystalline state (dashed curve). The glass transition temperature (Tg) and the melting point (Tm) are indicated by vertical dashed lines (McKenna and Simon 1998).

Appendix B Electronic Data File CD-ROM

List of electronic appendices

1. Documents

1.1 Form FDR1

1.2 FRS Circular 1/2006 The Investigation of Fires where the Supposed Cause is not Accidental

1.3 KFRS IRS guidance doc v3

1.4 MoU KFRS Kent Police KFRS Fire Investigation

2. Focus Group and SS Interviews

2.1 Plans

2.1.1 P1. Outline for focus group meeting

2.1.2 P2. Outline for SS interviews with supervisory managers

2.1.3 P3. Outline for SS interviews with IRS team

2.2 Notes

2.2.1 IN1. Redacted Peregrina notes

2.2.2 IN2. Redacted Moss notes

2.3 Transcripts

2.3.1 Transcript T1 Incident Redacted

2.3.2 Transcript T2 Incident Redacted

2.3.3 Transcript T3 Incident Redacted

2.3.4 Transcript T4 Incident Redacted

2.3.5 Transcript T5 Incident Redacted

2.3.6 Transcript T6 Group Interview Redacted

2.3.7 Transcript T7 Focus Group Redacted

3. NVivo Appendices

3.1 N1. Competence

3.2 N2. Confidence

3.3 N3. Experiential learning

3.4 N4. Fire from PV FSE capability Nodes

3.5 N5. ICS procedures

3.6 N6. ID of PV as cause

3.7 N7. Information from third parties

3.8 N8. Knowledge

3.9 N9. Length of service of PV id ICs

3.10 N10. Level 1

3.11 N11. NVIVO screenshot

3.12 N12. Organisational attitude to training

3.13 N13. Reporting

3.14 N14. Training in IRS

3.15 N15. Training in scene examination

3.16 N16 NVivo Word Tree. Knowledge

3.17 N17 Word Frequency Query ICs who identified PV originated fires in KFRS

4. Questionnaire

4.1 Q1 FSE Questionnaire analysis tool

4.2 Q2 Level 1 FSE questionnaire Excel vrs

4.3 Q3 Photos for Questionnaire

4.4 Q4 Questionnaire screen shot

4.5 Completed Questionnaires 00 - 19.

4.6 Completed Questionnaires 20 - 45.

4.7 Completed Questionnaires 46 - 69.

5. *Cold Case Review Photos*

6. Prelim Electrical

6.1 DC isolator prelim tests

6.2 Prelim electrical experiment data 15.01.15

7. Heating Lab Experiments

7.1 EX0 Prelim Heating

7.1.1 Isolator heating data prelim

7.1.2 Prelim heating tests on K&N switchgear polymers

7.2 IR Tests

7.2.1 IR tests on K&N switchgear polymers

7.2.2 Screenshots of IR spectrograms

7.3 Prep of Ex1 Ex2 and Ex3 tests on K&N Switchgear Polymers

7.4 EX1 01.06.15

7.4.1 EX1 heating test on K&N switchgear polymers

7.4.2 EX1 Isolator heating data

7.5 EX2 08.06.15

7.5.1 EX2 heating test on K&N switchgear polymers

7.5.2 EX2 Isolator heating data

7.6 EX3 15.06.15

7.6.1 EX3 Heating test on K&N switchgear polymers

7.6.2 EX3 Isolator Heating Data

7.7 Heating experiments photos (All)

7.7.1 Prelim and set up photos

7.7.2 EX1 Photos 01.06.15

7.7.3 EX2 Photos 08.06.15

7.7.4 EX3 Photos 15.06.15

7.8 All EX Data

8. Pyrolysis

8.1 Pyrolysis experiments photos

8.2 GC-MS results from test tubes

8.3 Moss Project Thesis