

**THERMOCHEMISTRY OF GRENFELL TOWER FIRE DISASTER:
Catastrophic Effects of Water as an ‘Extinguisher’ in Aluminium Conflagrations**

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SYNOPSIS: We review the thermochemistry of combustion reactions involved in the Grenfell Tower fire that occurred during the early hours of 14th June 2017. London Fire Brigade (LFB), having advised all the occupants to stay in their apartments, attempted to extinguish the fire with water. The Grenfell Tower 24-storey block had recently been re-clad with an insulation to meet energy saving targets. It comprised an aluminum exterior façade, and a polymer composite thermal insulator ‘sandwich filler’, mainly polyethylene, with narrow air gaps in between polymer and aluminium sheets. The renovated window frames were also made of aluminum coated with a powdered polyester. Here, we highlight the scientific thermochemical reasons why water should never be used on aluminum fires; not least because a mixture of aluminium and water is a NASA rocket fuel! When the plastic insulation initially catches fire and burns with limited oxygen (O_2 in air) to carbon (C), seen as an aerosol (black smoke) and black residue, the heat of reaction melts the aluminum (Al) and increases its fluidity and volatility, hence also its reactivity, whence it rapidly reacts with the carbon product of polymer combustion to form aluminum carbide (Al_4C_3). The heat of formation of Al_4Cl_3 is so great that it becomes white hot sparks like fireworks. At very high temperatures, both molten Al and Al_4C_3 aerosol react violently with water to give alumina fine dust aerosol (Al_2O_3) + hydrogen (H_2) gas and methane (CH_4) gas, respectively, with white smoke and residues. These highly inflammable gases, with low spontaneous combustion temperatures, instantaneously react with the oxygen in air accelerating the fire out of control. Adding water to an aluminum fire is like adding “rocket fuel” to the existing flames. The timeline of events and photographic evidence corroborates this scientific explanation why a 4th-floor kitchen-appliance fire became a major tower-block inferno within 12 minutes of applying water as a would-be extinguisher. A CO_2 -foam/powder extinguisher, as deployed in the aircraft industry against aluminum+plastic fires by smothering, might have contained the fire in its early stages.

Key words: Grenfell Tower, aluminium fires, plastic fires, heat of combustion, $Al+H_2O$ reactions

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BACKGROUND

A well-known adage in the advice we are given in the event of a kitchen fire is “never put water on burning liquids!”. There are several good reasons for this longstanding rule of engagement in the health and safety of professional fire-fighting literature. In the case of fires involving pans of hot cooking oil, for example, the main reason is that the heavier water with the lower boiling point would immediately vaporize and spray the burning oil all around, thereby spreading the fire out of control. Fires are classified according to the rules for extinguishing them; inflammable liquids are class B [1]. These fires involve liquids like cooking oil, gasoline, diesel fuel, alcohol and molten plastics, all of which emit flammable vapors at the liquid surface. It is these vapors that burn, not the liquid. If the surface of the liquid is static, the area is the smallest it can be. If the liquid is disturbed, it increases the surface area and amounts of flammable vapors released, and the extent of fire. That is the main reason never to pour water on stove-top cooking oil fires. Successful class B extinguishment is accomplished by starving the fire of oxygen, i.e. by smothering.

If the fire involves an aluminium pan, there is another good reason not to put water on it. A kitchen fire caused by leaving an aluminium pan of food, which partially burns to carbon, on hot stove can also lead to a catastrophic conflagration. If the aluminium melts and reacts with the carbon it becomes aluminium carbide (Al_4C_3) which, when dry, is a harmless, yellowish brown powder. Aluminium carbide, however, reacts with water to give aluminium hydroxide ($\text{Al}(\text{OH})_3$) plus the well-known natural gas fuel, methane (CH_4). At high temperatures the reaction speed increases, the products are alumina (Al_2O_3) + CH_4 . The reaction rate becomes fiercely fast, as the highly inflammable methane adds fuel to the flames, releasing more energy to further increase the temperature.

The chemistry of metallic carbides reaction with water is well established. Molten aluminium in contact with hot carbon readily forms aluminium carbide which reacts with water to give off 3x equimolar amounts of methane (CH_4) gas. In the case of calcium carbide (Ca_2C) the gas produced is acetylene (C_2H_2), which combines with oxygen (O_2) in air to produce the hottest known flame, as used in oxyacetylene welding. The controlled application of water to calcium carbide has long been a source of heat or light in the antique carbide lamps. This general chemistry between many metallic carbides and water is one means of storing very high energy gaseous fuels, such as methane, acetylene and hydrogen. It was first reported in Nature as long ago as 1896 [2].

QUOTE: “The construction of the electric furnace by M. Moissan in 1893, in which the heating power of the electric arc was directly utilised, by extending the upper limit of working temperatures, fused aluminium takes up carbon readily with formation of the crystalline carbide Al_4C_3 , and the oxides of many other metals furnish similar crystalline compounds when heated in the electric furnace with an excess of carbon. The behaviour of these substances with water furnishes the most convenient mode of classification. Of those reacting with water, the carbides of lithium, Li_2C_2 , calcium, CaC_2 , strontium, SrC_2 , and barium, BaC_2 , furnish pure acetylene; of aluminium, Al_4C_3 , and of beryllium, Be_2C , pure methane; of manganese, Mn_3C_2 , a mixture of equal volumes of hydrogen and methane; whilst the metals of the cerite group give crystalline carbides of the type RC (CeC , LaC , YC , and ThC), all of which react with cold

water, forming a complicated gas mixture containing hydrogen, acetylene, ethylene, and methane.”

Thus, we have known for at least 120 years that when the predominant materials are molten aluminium, and molten polymers, the combustion intermediate aluminium carbide is produced. High temperature aluminium carbide reacts instantly with water to produce copious quantities of highly inflammable methane gas, the common natural gas combustion fuel that can even be explosive. The spontaneous combustion temperature of methane is 570°C. Temperatures around Grenfell Tower would reach excess of 2000°C. The otherwise slower burning aluminium-polymer cladding needed nothing more than cold water to turn what was a domestic fire, manageable by smothering containment, and evacuation, into the catastrophic inferno that was the Grenfell disaster (Figure 1).



Figure 1.

Burning Grenfell Tower at the height of the conflagration; the black smoke at the top is combustible material burning without water; the whitish gas is mainly alumina dust from the reaction of Al and/or Al_4C_3 and steam, as the water still being applied: note the intensity of the conflagration where the water hits the building, and the associated whitish clouds around it.

Many reports in the media have already suggested that the cladding used for the Grenfell Tower refurbishment contributed to the rapid spread of fire. Online U-tube film footage shows flames shooting up the side of the building and sheets of flaming material ‘raining’ down. There has been a great deal of speculation as to why the fire spread so rapidly. The fire broke out on a warm night. Windows were open with curtains blowing in the breeze, which would have contributed to the rapid spread of fire within the building. There were chimney ventilation effects from the cavities, etc., etc. Notwithstanding all of these observations, the basic reason that the fire spread out of control in just a few minutes is that water was sprayed upon a combination of burning molten plastic and aluminium.

Interestingly, NASA scientists recently test launched a rocket with a new fuel propellant formulated by mixing aluminum powder and water (powdered ice), called ‘ALICE’ [3]. Thermochemical engineers have known for years that aluminium reacts exothermically with water, giving off hydrogen gas plus heat energy. While solid aluminium requires excess heat to ignite the reaction with water, nano-aluminium has much greater surface area and will react with water at around 650°C, i.e. as the aluminium begins to melt. At this temperature, the nano-aluminium with water can be ignited with a small flame. The same applies to molten aluminium when sprayed with water.

The US Defence Agencies have applied considerable resources to research fire hazards. While some of that work is classified, much is available in the open-access scientific literature. For example, Zabel’s group at the Southwest Research Institute at San Antonio, Texas, has

compiled a comprehensive military handbook [4] that addresses, *inter alia*, the kind of special particulate-loaded fire extinguishers needed to fight aluminium fires. The US Air Force uses Al₂O₃ powder-based extinguishers. It has also been documented how various aluminium composite formulations can be used to very effectively burn through the armour plating of combat vehicles [5]. The special hazards of aluminium-based fires are well-known to the aerospace research community. This information, however, needs to more widely disseminated throughout the civilian fire-fighting community. We should point out here that our focus is on addressing the root scientific cause of the Grenfell conflagration so that the lessons learned may help avoid similar disasters in future.

In the following sections we review (i) the properties of the combustible construction materials (ii) the thermochemical reactions involved, and (iii) the evidence that the water caused the acceleration of the conflagration from the timeline of events, and (iv) a brief survey of previous similar disasters recently, with lessons that evidently have not yet been properly learned and instigated by the fire-fighting authorities. We conclude the article with vivid warning: the 9/11 collapse of the world trade center twin towers illustrates the potential dangers of automatic tower block sprinkler systems in fires where aluminium is present in the combustion mixtures.

CLADDING AND WINDOW MATERIALS

High-rise buildings are designed to contain fires within the flat where they may break out. The basic reason why people are told to stay-put inside their flats is that there is a presumption the building construction materials and the application of water hoses, if need be, will prevent fire spreading. The original Grenfell, cladding when the building was constructed in 1970 was precast ceramic panels to window height with single-glazed aluminium framed windows above. The thermal insulation of this type of façade is poor, but the fire resistance is good.

Grenfell Tower was upgraded using funding from the ECO (Energy Company Obligation) a UK-government energy efficiency programme. The cladding thermal insulation was ‘Reynobond Celotex RS5000’ insulation panel and cladding. Its core material is mainly polyethylene. There was a 50mm gap between the insulation and cladding. The cladding was available in two variants. The plastic construction choice enables a rigid yet lightweight panel, but it poses a greater fire hazard.

The new facade windows in Grenfell Tower window frames were made from polyester (PMMA- polymethyl methacrylate) powder coated aluminium.

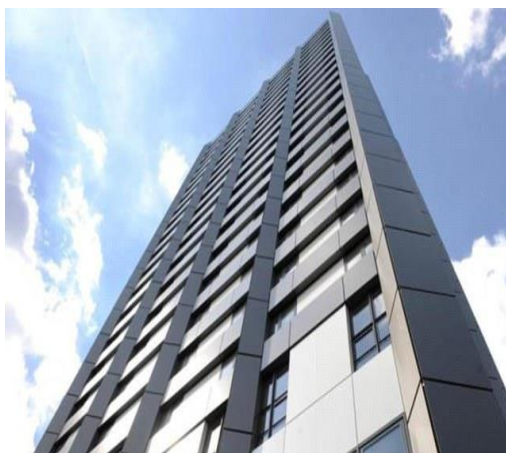


Figure 2.

Aluminium Composite Material (ACM) panels are commonly used for cladding buildings, typically as a form of rainscreen as part of a double-wall construction. The cladding itself prevents significant amounts of water from penetrating into the wall. Thermal insulation, air-tightness and structural stability are provided by the inner part of the wall construction.

ACM (aluminium composite material) cladding consists of two panels of aluminium bonded to either side of a lightweight core of an insulating material such as polyethylene (PE). The aluminium rain screen is fitted over the cladding insulator panels to protect the insulation from the weather and provide a decorative finish. This is separated from the insulation by a 50mm wide cavity.

The insulation plastic was a thick layer, 100 mm to 150 mm. Although porous, therefore, still quite sufficient per unit area of the building surface, ready for the fire to develop. The outer aluminium panel would be cooler than the building wall when the fire starts, so the molten plastic would preferably stick to the aluminium creating favourable conditions for production of Al_4C_3 , with the chimney draft created in the space between the burning plastic and the building wall, hence bringing in more air and propelling the fire upwards.

Since polyethylene-cored plastic foam cladding panels was used alongside aluminium sheets, and with a few millimetres of air in between, it is hardly surprising an external fire took hold so quickly. The aluminum facing is resistant to the surface spread of flame, but this would be of little use where the intensity of the fire would quickly melt the thin aluminum, which has a relatively low melting point (660°C). Cavities in buildings can contribute to the spread of fire as these function like a chimney drawing flames upwards. Thus, once the fire took hold at the window of 4th-floor flat 16, all that was needed to spread a firestorm upwards and out of control, with the liberation of flammable gases hydrogen and methane, was a relatively small amount of water. Copious amounts of hot hydrogen and methane gases liberated when water hits Al or Al_4C_3 go upwards by convection and thus accelerate the propagation of fire towards the top of the building by bringing live flames to new quantities of plastic and aluminium. In effect water added to such fires is literally “adding fuel to the flames”.

COMBUSTION CHEMICAL REACTIONS

Combustion of plastics

Polyethylene gets hot slowly as its specific heat is relatively high ($1900 \text{ J}\cdot\text{K}^{-1} \text{ kg}^{-1}$) and its thermal conductivity is relatively low (0.45 to $0.52 \text{ W}\cdot\text{m}^{-1} \text{ }^\circ\text{K}^{-1}$). Figure 2 illustrates how solid polyethylene burns with a slow and steady blue flame. The flash point of high density polyethylene is 340°C , the autoignition point is 380°C . The flame spreads slowly along the surface melting the solid polyethylene to liquid as it spreads. The melting point of polyethylene is 100°C to 135°C , depending on the density. Molten polyethylene in the laboratory (Figure 3) drips flaming drops, but in a contained environment, for example, sandwiched between aluminium sheets, with an air cavity, the whole sample would quickly become liquid.

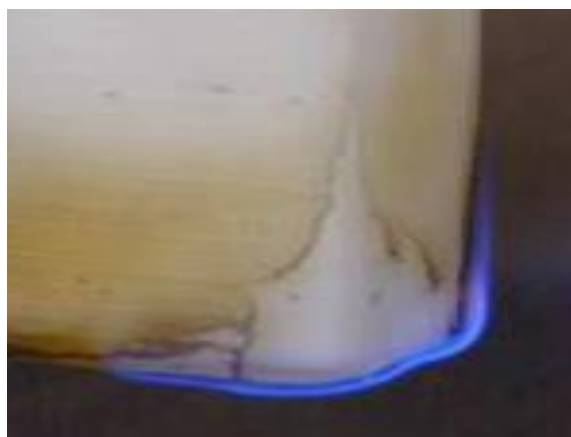


Figure 3.

Initial stages of burning a sample of polyethylene (PE); solid PE burns only after it has been melted at the surface by a contiguous flame; it is the vapor at the surface of the molten plastic that combines with oxygen of the air during combustion; the rate of combustion can accelerate if the surface area of a molten plastic is dispersed, for example, by the addition of water.

When bulk polyethylene burns rapidly with a limited supply of oxygen, the combustion produces clouds of black carbon aerosol fumes. Any containment or fire control system should allow for the low melting point of polyethylene. The following combustion reaction occurs when PE solid melts, and then liquid, polyethylene burns in air, with limited oxygen diffusion to the molten polymer /air interface, i.e. at the flame



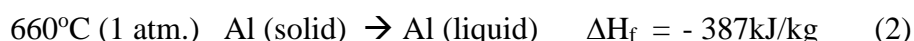
The combustion product carbon can take the form of both a solid residue and a black aerosol smoke. Some of the carbon burns to carbon dioxide (CO₂) and carbon monoxide (CO) gases. Flame temperatures are estimated to be between 1000 and 1500°C. The heat of combustion is taken from Walters and Hackett [6]. Their experimental results were compared with thermochemical calculations of the net heat of combustion from oxygen consumption and the gross heat of combustion from group additivity of the heats of formation of products and reactants. The gross and net heats of combustion calculated from polymer enthalpies of formation and oxygen consumption thermochemistry were all within 5% of the experimental values from oxygen bomb calorimetry. The net heat released by combustion per gram of oxygen consumed is $13.1 \pm 0.8 \text{ kJ/gO}_2$ for all polymers tested, including polyethylene. Using this average result, and chemical equation (1), we very roughly estimate that the burning polyethylene yields an amount of heat for every kilogram of burned polyethylene

$$1000 \times 13.1 \times 8/7 = 15 \text{ MJ/ kg.}$$

where 8/7 is the molecular weight ratio of oxygen to ethylene (32/28).

Reaction molten aluminum with water

The melting temperature of aluminium at 1 atm. with latent heat of fusion (ΔH_f) is:



and the boiling point of liquid aluminium is 2470°C. We do not know that the fire reaches this high temperature, but it may be possible.

Thermochemistry of Grenfell : Public Inquiry, London: 1st August 2018

The mean heat capacity (C_p) of solid aluminium over its range of existence from say 25°C to 660°C at 1 atm. is $\langle C_p \rangle = 0.96$ kJ/(kg.°C). Thus, we can calculate the total energy required to heat, and then to melt, 1 kilogram of aluminum is $635 \times 0.96 + 387 = 997$ kJ of heat. This amount of heat is produced in the combustion of around 67 grams of polyethylene!

It is well known in the energy industry that over the entire temperature range of its existence, aluminum reacts spontaneously with water to produce hydrogen [7]. The reaction at all temperatures is exothermic with a very large heat of reaction (see Table 1).



The first reaction forms the aluminum hydroxide bayerite ($\text{Al}(\text{OH})_3$) and hydrogen, the second reaction forms the aluminum hydroxide boehmite ($\text{AlO}(\text{OH})$) and hydrogen, and the third reaction forms aluminum oxide and hydrogen. All these reactions are thermodynamically favorable from room temperatures upwards. All are also highly exothermic. From room temperature to 280°C, $\text{Al}(\text{OH})_3$ is the most stable product, while from 280-480°C, $\text{AlO}(\text{OH})$ is most stable. Above 480°C, alumina Al_2O_3 is the most stable product; Al_2O_3 becomes increasingly more thermodynamically favorable than the hydroxide $\text{Al}(\text{OH})_3$ at elevated temperatures.

Table 1: Thermodynamic data for the aluminum-water reaction to form alumina.

T(°C)	ΔH kJ/mol H ₂	ΔS J/K	ΔG kJ/molH ₂
0	-272	62.1	-289
100	-275	51.1	-294
1000	-366	-51.6	-304

The thermodynamic parameters high temperature Al_2O_3 reactions are reproduced from reference [6] in Table 1 at three temperatures up to 1000°C. The tabulated values are per mol H₂ produced. The enthalpy (ΔH) is highly exothermic at all temperatures, with a very high value of -366 kJ/mol H₂ at 1000°C. Over this temperature range the entropy change (ΔS) goes from positive to negative reflecting that water becomes steam above 100°C. The Gibbs free energy of the reaction (ΔG) is decreasing sharply as temperature increases, thereby driving the reaction rate faster. The hydrogen is liberated will spontaneously burn in the air to water plus additional large amounts of energy. At 1000°C, for example, the heat of combustion of hydrogen is of the order 1 MJ per mole of oxygen.



‘ALICE’ is an acronym for a fuel used in the aerospace industry comprising a mixture of aluminum powder and water, in the form of ice for safe storage. The mixture reacts by equations (3) and (4) to produce huge amounts of energy. It is used by NASA as a rocket launch propellant when burned at high temperatures around 1000°C [3].

Formation of aluminium carbide

Aluminum carbide is a linear chain-configuration molecule (**Figure 4**) with conjugated double and/or triple delocalised pi-bonds.

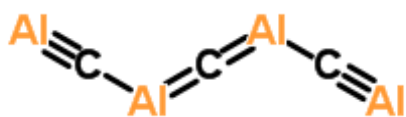


Figure 4.

Molecular structure of aluminum carbide

The heat of formation of Al_4C_3 at around 1330°C is a massive 1275 KJ per mole [8]; this enormous amount of energy released when Al_4C_3 is formed, can be compared with the heat of formation of water vapor at 1 atmosphere pressure from the explosive reaction of hydrogen with oxygen, 241.8 KJ per mole of water.

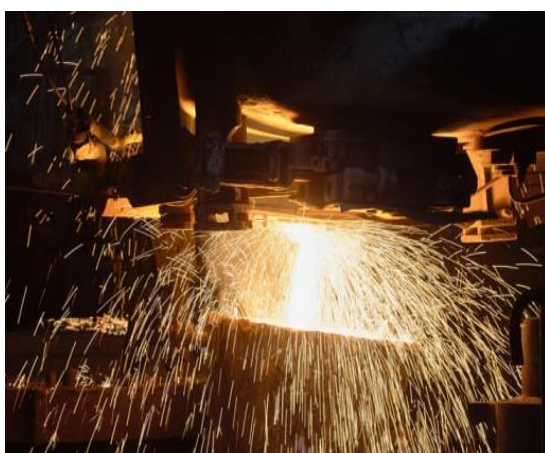
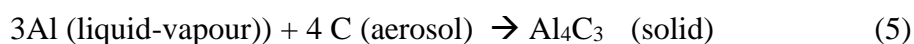


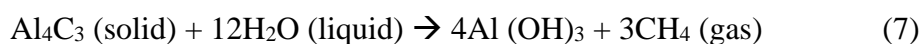
Figure 5:

Interaction of vaporized aluminum with carbon at a temperature of 1800°C in an electric furnace produces aluminium carbide (Al_4C_3) commercially; the heat of formation of Al_4C_3 is so great that it takes the form of white hot liquid sparks like fireworks.

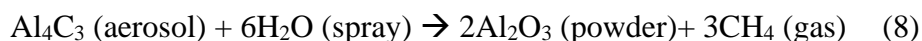
When the reaction temperature in the electric furnace reaches above $\sim 1800^\circ\text{C}$ aluminium carbide plus unreacted oxygen (equation 6) is the stable product rather than alumina plus reactant carbon (equation 5)



Hydrolysis is a reaction that takes place between a substance and water, as a result of which the substance and water break down, and new compounds form. Al_3C_4 is a salt-like carbide, which is essentially the product of the displacement of the hydrogen atom in methane by metal atoms. During hydrolysis, reverse displacement takes place easily, and methane forms. The hydrolysis of aluminum carbide is an irreversible reaction with a large negative Gibbs free energy of reaction at all temperatures. This reaction is often used as a simple method of obtaining methane in the laboratory; hydrolysis of Al_4C_3 at low temperatures gives aluminium hydroxide.

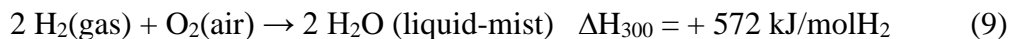


whereas at the high combustion temperatures above 1000°C the solid product is alumina



Combustion of hydrogen and methane

The combustion reaction of hydrogen with oxygen is highly exothermic with a heat liberated of 572 kJ per mole of hydrogen.



Hydrogen gas forms explosive mixtures with air in concentrations from 4–74%; although the spontaneous combustion temperature (585°C) is higher than some hydrocarbon fuels, such as methane, it is much more dangerous as the auto-ignition energy barrier is extremely small; explosive reactions may be triggered by a spark, simply low heat, or even sunlight.

The auto-ignition or spontaneous combustion temperature of methane in the presence of oxygen-air is 537°C, so the CH₄ then further fuels the conflagration with the exothermic combustion of the fuel gaseous methane, which can also be explosive in its reaction with oxygen under certain conditions.

Figure 6 explains how amounts of reaction heat can be approximately estimated from bond energy tables; the stronger the chemical bonds of the product, like water and CO₂, the greater is the release of energy on combustion.

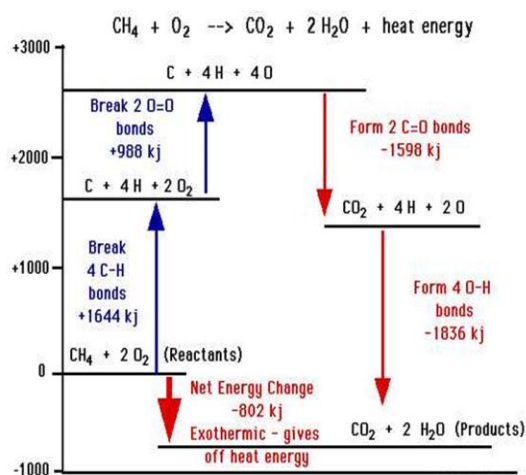
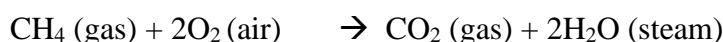
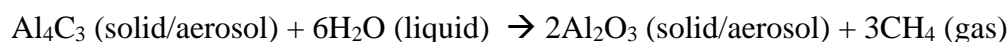
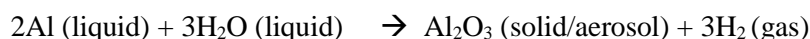
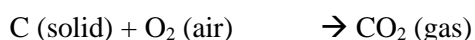
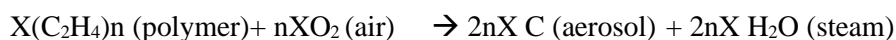


Figure 6.

Heat of combustion energy of methane obtained from standard tables of bond energies explains how it originates; equations (5) and (7) show that 1kg of aluminium can combine with carbon and water to produce 30 moles of CH₄ which reacts with oxygen in air to liberate to the environment 0.8 x 30 = 24 Mega-Joules of heat energy.

Overall reactions



Thermochemistry of Grenfell : Public Inquiry, London: 1st August 2018

A crude estimate of the heat balance with excess water, and oxygen surface-limited combustion of polyethylene to melt the aluminium, for the overall combustion of a mixture of aluminium and water is of the order + 20 Mega-Joules of energy liberated per kg of aluminium at around 1000°C.

TIMELINE EVIDENCE

- 12.56 am Fire alarm was raised in a 999-call by resident of the 4th floor flat 16 on NE corner.
- 1.00 am First fire fighters arrived.
All residents still in building advised by London Fire Brigade (LFB) HQ to “stay in apartment”.
- 1.02 am Flames reported “flickering” out of window of flat 16 on 4th floor.
- 1.07 am Fire crew outside the building prepare to tackle the flames coming out of flat 16 with a water hose.
- 1.12 am Fire officer reported “the external cladding is on fire with sparking and spitting”: requested additional water pumps be applied.
[The “sparking and spitting” is the evidence for the reaction intermediate aluminium carbide as shown in Figure 5]
- 1.14 am Firefighters with breathing equipment gained entrance to flat 16 and tried to extinguish the fire, where it started in the NW corner 4th floor apartment, both inside and out, 20 minutes after the fire brigade were alerted, but the cladding was already alight. Simultaneously, fire fighters began pumping hosed water into the building, initially around the source of the fire, i.e. around 1.15pm to 1.20pm from street level.
[At this stage the fire might have been contained by smothering with a specialist foam as used in aircraft fires: Note: extinguishers for metals like aluminium use fine powders like sand, salt, and even alumina (Al₂O₃) powder to reverse the reaction]
- 1.15 am A member of fire-fighting team that entered flat 16 reported:
(i) “the water we put on the fire just turned to steam” [the heat liberated by the Al + H₂O reactions is so great that it instantly boils any excess water]
(ii) “residents from flats above were coming downstairs with “streaming eyes and coughing” [this is symptomatic of an acidic alumina dust resulting from Al + H₂O reactions also reported by WTC 9-11 victim survivor: 7]
(iii) “the water jets are having no impact”,
(iv) “external cladding was becoming more involved at a rapid rate”
- 1.21 am Fire in flat 16 reported to have been “extinguished”.

Thermochemistry of Grenfell : Public Inquiry, London: 1st August 2018

Reports of “hot molten droplets from above with heavy smoke”.

- 1.26 am Cladding external fire had reached 23rd Floor on NE corner sides; the fire escalated 19 floors within 12 minutes of the first application of water ‘extinguishers’.
- At this stage, firefighters were instructed to reach the 24th -storey roof and pour water down the outside of the building from above in the hope of extinguishing the flames.
- 1.48 am Fire fighters inside trying to rescue trapped persons on 16th floor report “black smoke” within apartments.
- 1.53 am Fire has reached the top and begun to spread sideways in both directions from the SE corner on the east and south sides.
- 2.47 am “Get out now” advice issued to persons still alive in the building. Nearly two hours after the first instructions given to all those that communicated with the fire service, to “stay put”, the advice from LFB was reversed.
- 4.00 am Both flame fronts have now encompassed the entire building and converged at the top level 23.

PREVIOUS ALUMINIUM FIRES

There have been several previous high-profile tower-block fires, all associated with the use of water as an ‘extinguisher’ on aluminum-polymer clad buildings, although still not recognised as the cause of rapid conflagration by the various authorities involved.

Garnock Court, Ayrshire (1999)

This was the tower-block fire which first raised concerns over polymer and aluminium cladding on high-rise buildings. Witnesses told how the flames leapt up yellow-coloured cladding on the corners of the block, taking just five minutes to spread to the top. The blaze prompted a parliamentary inquiry into tower-block cladding, which recommended a much tougher testing regime, and the use of non-combustible materials. One witness reported “there were parts of the cladding dropping on to the first appliance that “could not be moved as it was supplying the fire fighters with water.” A subsequent Parliamentary enquiry concluded, when fire spreads externally via the cladding, guidance for this type of fire might not be adequate to prevent the conflagration. It further concluded cladding systems should be required either to be entirely non-combustible, or to be proven through full-scale testing not to pose an unacceptable level of risk in terms of fire spread.

Lakanal House fire (2011)

Six people died in this Southwark London tower block fire, but with many injured; the fire started as an electrical fault. A coroner’s report in 2013 found problems with fire safety including the buildings fire resistance. London Fire Brigade also opened an investigation into the fire; the report revealed that Lakanal House had been identified as being at risk of enabling a fire to spread if one should occur in one of the flats. Although it was originally reported that

Thermochemistry of Grenfell : Public Inquiry, London: 1st August 2018

some of the windows made of plastic (U-pvc), windows in the block were in fact made of aluminium. An inquest into the deaths at Lakanal House "found the fire spread unexpectedly fast, both laterally and vertically, trapping people in apartments, with the exterior cladding panels burning through in just four and a half minutes". As in the case of the Grenfell Tower fire 6 years later, the official advice was for people to remain in their homes in the event of a blaze. The inquest concluded that years of "botched renovations" had removed fire-preventative material between flats and communal corridors, allowing a blaze to spread, and that the risk of rapid conflagration was not identified in any of the safety inspections.

Lacrosse tower in Melbourne (2014)

The Lacrosse multi-storey apartment block caught fire in Nov. 2014 in the dockland area of Melbourne, Australia, resulting in a rapid conflagration in a similar manner to London's Grenfell Tower. It was believed to have started when a cigarette burning on an eighth-floor balcony of the residential tower sparked a fire that raced up the aluminium-clad walls to the 21st floor within 11 minutes. A post-incident report said aluminium composite panels that were not approved for external use on a high-rise building in Australia, and that they were the direct cause of the "speed and intensity of the fire spread". A closer investigation of the pictures, and timeline of events, bear a remarkable similarity to the Grenfell Tower disaster. This suggests that the Lacrosse fire also erupted when water was first applied to extinguish the embryonic flames.

Dubai fires (2012 -2016)

There have been 5 well-publicised aluminium cladding fires in the city of Dubai since 2012. Dubai is renowned for its shiny rocket shaped sky-scraper tower blocks that characterise the city skyline. The first aluminium cladding fire was in 2012, when the 40-storey Al Tayer Tower residential block erupted in flames, and later the same year, another residential block, 37-storey Tamweed Tower, went up in flames. In another Dubai fire, known as the Torch Tower blaze in March 2015 a 79-storey residential and office block, also quickly and dramatically, went up in flames. Fortunately, just before the Torch Tower fire, the authorities had put in place a protected access and evacuation system, so that the fire fighters were able to use this safety-lift to get rescue forces up to the area of the fire and safely evacuate all the occupants. The latest Dubai fire was a 75 storey residential tower just 1 year before Grenfell in July 2016.

The most dramatic of all the Dubai tower-block fires, however, was on New Year's Eve 2015 at the Address Downtown Dubai Hotel, which stands adjacent to Dubai's tallest skyscraper, and indeed, also the world's, tallest building the 850m high Burg Khalifa. Dubai's relatively modern tower blocks are all fitted with sprinkler systems to protect apartment fires from escalating and to allow evacuation. The Address Hotel fire coincided with the beginning of the New Years Eve fireworks celebrations from the Burj Khalifa super-tower. According to Dubai Civil Defence record of events, sprinkler systems in the fire at Address Downtown Dubai Hotel ran out of water 15 minutes into the breakout of fire.

Was this a blessing, we ask? The extent of the Dubai Address Hotel blaze was beyond the capacity of regular sprinkler systems to cope with; it was mainly an external fire across more than 40 floors. Compared to Grenfell, the fire spread was relatively slow, with no fatalities. Everyone was evacuated, leaving just 15 people with minor injuries, and one person suffered

a heart attack. When the firefighters reached the Address Downtown Hotel, they were swiftly able to clear 3,000 people.

Perhaps the reason for the damage-limited conflagration, and successful evacuation, can be explained to some degree by the fact that, owing to pressure on the fire safety systems that day, the Dubai Address Hotel tower building sprinkler system exhausted its water supply within 15 minutes of the start of the fire. There was also no water available for the fire fighters' hoses! Putting water sprinklers in aluminium clad tower blocks could exacerbate the risk of non-survival in similar conflagrations to Grenfell, rather than offer any more protection to residents.

CONCLUSIONS

The interior of flames from burning molten plastic can reach temperatures between 1000°C to 1500°C giving off a black smoke which is a carbon aerosol, and black carbon residues. At temperatures at, or near, burning molten plastics, aluminium becomes molten (above around 700°C), highly fluid, highly volatile, and highly reactive. The aluminium can react directly with carbon aerosols and residues to produce aluminium carbide. The heat of formation of Al_4C_3 is so great that it appears transiently as white-hot liquid sparks, like magnesium oxide in fireworks, as reportedly seen by the firefighters and observers nearby.

When water is added to aluminium carbide, methane is produced along with alumina dust and steam and carbon dioxide, also a white smoke. When water is sprayed on to hot molten aluminium, hydrogen gas is produced along with alumina as a white dust, and steam or water vapour. All the evidence shows that both these reactions would have played a major role in the rapid spread of the conflagration.

Without more forensic evidence than available here, we are unable to say with any certainty to what extent the aluminium burned directly with water via reaction equation (3) producing hydrogen, or reaction equation (8) producing methane. Whichever of these two reaction mechanisms prevailed, however, the result would be the same; a rapid catastrophic spread of the conflagration, as both H_2 and CH_4 are highly inflammable, and, under certain conditions, explosive, gaseous fuels. The Gibbs energy changes for both these reactions are extremely large and negative, thus both reactions will undoubtedly occur if the reactants are present. Moreover, the overall products of aluminium combustion with water are gases that are removed rapidly from the reaction mixture by convective forces, thus driving all reaction pathways to rapid completion.

We therefore conclude that the application of water to extinguish aluminium fires is worse than futile; it accelerates the conflagration and can be explosive. This is the scientific explanation of the ferocity and speed of the spread of Grenfell Tower fire that caused it to reach the top of the building in less than 15 minutes, and to eventually encircle the entire building whilst water was continuously being directed onto the flaming building from various directions.

Finally, in support of this conclusion, we cite the thermo-chemical explanation of the world's greatest ever tower-block disaster: the collapse of the New York World Trade Centre twin towers on September 11th-2001 after being hit by aeroplanes (Figure 7). The total collapse was inexplicable at the time of the subsequent official forensic investigations and for several years after.



Figure 7.

Black and white smoke billows up as the first of the two WTC towers collapses; the burning kerosene fuel, and burning plastic, is characterised by black smoke (2nd WTC: carbon aerosol and water vapor); the burning of aluminium and water reaction gases is characterised by white smoke (1st WTC: alumina dust and water vapor); hydrogen liberated in the Al + water reaction ‘explodes’ as the first twin tower collapses amidst plumes of white smoke.

Senior scientist Christian Simensen of SINTEF Materials and Chemistry (Norway) has presented the only plausible scientific explanation of what really caused the collapse of the twin towers when they were attacked by the aircraft, at an international materials technology conference [9].

When the aircraft became jammed inside layers of building debris, the mainly aluminium bodies rather than the buildings themselves absorbed most of the heat from the burning aircraft fuel. The vast amount of heat would melt all 30 tons the aluminium of the aircraft fuselage and increase the molten aluminium temperature. The fluidity, i.e. reciprocal viscosity, of liquids increases exponentially with temperature; molten aluminium above 1000°C is more fluid than water, and highly volatile. The aluminium poured downwards within the tower blocks through staircases and gaps in the floor, undergoing the chemical reaction with water from sprinklers. All floors of the twin towers 80 storeys were equipped with an automatic water sprinkler system in case of fire, triggered by rise in temperature. A mix of sprinkler system water and hot molten aluminium from the aircraft hulls reacted to produce hydrogen [equation (2)] that caused the explosions heard by hundreds of surviving witnesses at the scene. The vast pressures, created by the explosions of the hydrogen conflagration, caused the rapid collapse of the structures. White smoke is the compelling evidence (Figure 7).

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attn. Mr. Mark Fisher (Secretary)

Sir Martin Moore-Bick (Chairman)

Grenfell Tower Inquiry, Holborn Bars, 138-142 Holburn, LONDON EC1N 2SW

Dear Sir,

Please find attached a pdf documented review of the chemical reactions that were responsible for the rapid acceleration of the Grenfell fire, titled: "Thermochemistry of the Grenfell Tower Fire Disaster: Catastrophic Effects of Water as an Extinguisher in Aluminium Conflagrations" written by Dr. J. F. Maguire and myself. We are both longstanding Fellows of the Royal Society of Chemistry, and as such bound by the RSC Code of ethical conduct and professional standards.

Thermochemistry of Grenfell : Public Inquiry, London: 1st August 2018

The review is published with DOI: 10.13140/RG.2.2.24909.33763 and can be accessed on Researchgate

https://www.researchgate.net/publication/326782413_Thermochemistry_of_Grenfell_Tower_Fire_Disaster

Please note that we have been objective in this analysis and avoided political statement. The plans to install water sprinkler systems in all similar towers where there is a risk of aluminium fires however, as set out by the Mayor of London, for example, need to be re-thought with some expediency and at least reconsidered with more circumspection in the light of the thermochemical combustion reactions involved. Please note the evidence we cite in the attached, from similar fires in Dubai, and also the 9/11 WTC twin tower collapses were caused by the reactions between water from sprinkler systems and molten aluminium.

Yours sincerely,



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