Scientific Research Publishing

Journal of Modern Physics, 2025, 16(11), 1734-1760
https://www.scirp.org/journal/jmp
ISSN Online: 2153-120X
ISSN Print: 2153-1196

Physics of Combustion: Scientific Inquiry into Grenfell Fire Root-Cause Mechanisms

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How to cite this paper: Maguire, J.F. and Woodcock, L.V. (2025) Physics of Combustion: Scientific Inquiry into Grenfell Fire Root-Cause Mechanisms. *Journal of Modern Physics*, **16**, 1734-1760.
https://doi.org/10.4236/jmp.2025.1611080

Received: October 8, 2025
Accepted: November 25, 2025
Published: November 28, 2025

Abstract

Grenfell Tower in London* was destroyed in the early hours of 14th June 2017 by a conflagration that started as a small domestic fire in a refrigerator in the kitchen of an apartment. Seventy-two people died. Questions, why and how this tragedy happened, with a well-developed London fire-fighting infrastructure, prompted the UK government to launch a public inquiry. A Judge with a team of lawyers was commissioned to establish the reason why a domestic apartment fire, flickering from a 4th floor kitchen window, began to spread rapidly less than two-minutes after first fire engines arrived, to an inferno reaching the top floor in 20 minutes. The inquiry collected 1100 statements and took 7 years to complete. Interim and final inquiry reports, resting on expert-witness testimony, found that the rapid spread of the fire was "caused by the polymer insulation in the aluminium cladding". An extensive public final report concludes with a nebulous distribution of culpability amongst a plethora of manufacturers and suppliers of the aluminium cladding, and various national and local unnamed government officials. Here, we address the research problem of identifying the underlying combustion physics factors that can explain all the experimental observations as they unfolded in a scientific timeline. We apply the scientific method using the laws of thermodynamics and known chemical kinetic combustion mechanisms that contradict the "expert witness" evidence. Our principal findings are that the *prima facie* scientific evidence for the rapidity of conflagration was a fierce reaction to the first application of water to extinguish an aluminium fire. As the number of fire engines pumping water escalated around the towerblock, so did the fire. Water is the catalyst for both the initiation and propagation of highly exothermic oxidation reactions of aluminium. It reacts ferociously with molten aluminium and can be explosive. The implications are that, to avoid future catastrophes, water must not be used as a would-be extinguisher on Al-clad building fires. Such fires are readily suffocated at early stages with CO_2-foam or powder extinguishers. Our scientific inquiry complements the UK Public Inquiry final report by analyzing and revealing the root cause of the disaster.

Keywords

Combustion Physics, Tower-Block Inferno, Aluminium Cladding, Aluminium Fire, Aluminium-Plastic Extinguishers, Water Catalyst, Stay-Put Drill, Grenfell-Inquiry Fallout

1. Introduction

1.1. Grenfell Inquiry Reports

A scientific review that discusses the reason for the Grenfell tower block catastrophe and a history of similar disasters, was presented at the Joint European Thermodynamics Conference (Barcelona May 2019), peer-reviewed by five leading thermochemists/physicists, and published in the Proceedings, in thermodynamics journal Entropy [1]. Its content had previously been submitted to the Grenfell Inquiry [2] in London on August 1st, 2018 [3]. There is a consensus, of professional chemists and physicists, qualified in thermodynamics, that the Grenfell Tower fire spread suddenly, on arrival of fire engines, rapidly, and catastrophically, because of the ferocity of the oxidation interaction between hot molten aluminium (Al) and oxygen (O_2 in air), with the water. The would-be extinguishant acted as the catalyst to accelerate the fire, when it was sprayed upon the embryonic flames, flickering from a kitchen window, and molten aluminium [4].

The Grenfell Inquiry Interim Report resulted in immense financially disastrous fallout since its publication on 30-Oct.2019 with millions of Al-clad apartment block residents being unable to sell, mortgage or indeed even afford to insure their properties, and not least, sleep rest-assured that they are safe in their homes. This situation arose because the interim findings, as reported in the news media, blamed Al-cladding manufacturers. Such conclusions imply that all other Al-clad properties are at similar risk. The timeline of “key events” in the interim report, however, are contradicted by a scientific timeline that identifies the key event being the application of water on the embryonic plastic fire and continued application to fuel the combustion of aluminium cladding with water the catalyst [3] [4].

If the Grenfell Inquiry [5] had adopted the scientific method of investigation, the true cause of rapid progression of a kitchen fire to tower-block inferno, the thousands of similar tower-block apartments should not be deemed to be in jeopardy, and the plight of many thousands of flat owners would not become a fallout disaster affecting millions of people. Notwithstanding the Al-plastic cladding, another disaster like Grenfell could not happen without the water plus molten aluminium combination. Given appropriate fire-fighting technology at-the-ready, all modern apartment buildings that contain advanced materials like metal alloys, with plastics throughout, not just exterior cladding, ought to be rendered perfectly safe, insurable, mortgageable, and saleable.

Al-cladding suppresses an otherwise dry plastic fire. Hence the dense black smoke of a low-grade smoldering fire with a temperature that arrests at the melting point of aluminum. It is only when the water is added that the fire accelerates rapidly into an inferno. Aluminium cladding on buildings will act as a fire retardant, provided that a molten state or its carbide do not contact with water. It is the water that caused the rapid conflagration, and not the cladding *per se*.

There are two fundamental causes of the Grenfell human tragedy. The scientific timeline [4] also exposes the fateful "stay-put" policy that currently still applies to similar clad multistorey apartment and office tower blocks in the UK. It further shows that, were it not for the "stay-put" instructions, all the Grenfell residents could have been evacuated in a few minutes, using standard fire-drill procedures, before the LFB even attempted to extinguish the kitchen fire in a 4th floor-apartment. Al-clad tower-blocks can indeed then be simply rendered "perfectly safe", with two conditions. (i) Water must never again be used as an extinguishant of Al-plastic fires instead of inert foam or some other suitable extinguishant, and (ii) the "stay put" policy must be abandoned with standard fire-alarm and evacuation fire drill being reinstated for at-risk buildings.

We also have a UK Government's response to the interim report of Grenfell Inquiry, (published 21/1/2021). There is nothing in it to alleviate the fallout effect, quite the contrary.

https://www.gov.uk/government/publications/grenfell-tower-inquiry-phase-1-report-government-response/grenfell-tower-inquiry-phase-1-report-government-response

The Inquiry preliminary report, and government response, and media reporting of it, in October 2019 are the main cause of the plight of the million residents of aluminium-clad tower blocks. Given all that we now know, neither the Inquiry Interim report, nor the Government's response, make any reference to catastrophic use of water as an extinguisher, or the urgent need to abandon "stay-put" policy. This failure to establish and report the scientific truth, serves only to exacerbate the plight of millions of Grenfell-fallout victims, not just in the UK but around the world. Grenfell is international news [4].

The Grenfell Inquiry final report, including "expert witness" evidence [5], was published on 4th July 2024 to coincide with the day of the UK General Election. The report, as with the interim report, makes no reference to its original objective assignment, *i.e.* to deliver the truthful reasons for the disaster. The Inquiry report does not reassure the mortgage banks, insurance companies, and, not least, the millions of leaseholders and their families now living in Al-clad buildings that they may rest-assured safely without fear of another similar tragedy to Grenfell. Accordingly, the "stay-put" fire drill that resulted in loss of 72 lives, has remained in place. The official fire drill policy as set out by the Association of Chief Fire Officers and can be found on their website. https://www.nationalfirechiefs.org.uk/Stay-Put-position. Eight years on from the Grenfell fire, there needs to be more awareness of the underlying physics of the Grenfell Tower tragedy.

The Grenfell Inquiry timeline of "key-events" [3] [4], shows that the stay-put instructions to residents were maintained whilst the LFB's heroic frontline firefighters, who ought to be completely exonerated of any blame, were being instructed by their commanders to spray ever more water onto burning or charred plastic and molten aluminium.

Our research objective is essentially the same as that of the Grenfell public inquiry: to establish the relevant scientific facts and root cause of the rapid escalation. There are no hypotheses in our analysis except the refrigerator kitchen fire that started it. There are no hypotheses, in our thermodynamic and kinetic analysis underlying the scientific investigation and findings. We can, however, hypothesise on the basic reason for the refrigerator fire in the kitchen escalating suddenly from fridge to the whole kitchen, following a well-documented evidence of a minor explosion. This is not mentioned as a key event in inquiry report [5]. We hypothesize that it may not have happened if the apartment had been equipped with a 5 kg CO_2-foam hand extinguisher for the smothering of an embryonic kitchen fire.

1.2. 1st Key-Event Kitchen-Fire Hypothesis

The 1st "key event", not explained by either of the two Grenfell Inquiry reports, was a minor explosion. The lone resident of flat 16, and hence a principal witness, Mr. B. Kebede, said an explosion caused the fridge fire to spread within the kitchen. There is no explanation of this key event in the Inquiry report. It could be the result of aluminium foil in contact with burning plastic producing aluminium carbide. or it could have been an electrical fire, molten copper plus plastic explodes with water. All metals used in construction and appliance manufacturing industries (Al, Pb, Cu, Fe, and various alloys, are highly exothermic oxidation reagents; all melt at temperatures below those reached in burning plastic flames (>1000˚C), and all these molten metals can be explosive with cold water.

A plausible hypothesis is conjectured as follows: resident of 4th floor apartment is awoken by a fire alarm to find his flat filled with black acrid smoke emanating from his fridge. He pulls the plug to turn off the electrical supply to the fridge and opens the widow to let the smoke out and fills a saucepan with water and throws it on the fridge. Note that if this indeed was the occupant's reaction, it would be perfectly rational, *i.e.* what any thoughtful person would do in the circumstances. When the water hits the fridge, however, there is a methane explosion that spreads burning droplets of plastic combustibles around the kitchen, including inflammable window curtains. The resident evacuates and calls the fire brigade on 999.

Evidently, after giving his statement, with no mention of water on the fridge, Mr. Kebede placed himself beyond jurisdiction, perhaps fearing that he might be held in some measure responsible and/or be used as a scapegoat. It was of paramount importance to question him under oath with a view to establishing the truthful sequence of events at the outset. There is no record of this explosion as first key-event [5].

1.3. 2nd Key-Event: Initial Application of Water

The 2nd and most crucial "key-event", to ascertain the truthful reason of rapid conflagration, is the first application of water to the fire at the window of the apartment. We know to within a minute, the point in time; 1.09 am. We have photographic evidence of this key event from news media and witness accounts from LFB firefighters at the scene. The 999 call to report a fire in Flat 16, floor 4 Grenfell Tower was timed at 12.56 am. At 1.00 am the first fire fighters arrived. All residents within the building were advised by London Fire Brigade (LFB) "stay in apartment". At 1.02 am flames reported "flickering" out of window of flat 16 on 4th floor. At 1.07 am the first fire crew arrive outside the building to contain flames coming out of flat window with a water hose at 1.08 am.

Figure 1. Photographic evidence of fire in flat 16 of Grenfell Tower at 1.08 am 14-06-2017: the recently refurbished window frames were made of polyester-coated Al.

Neither the GI Interim Report key-event timeline, nor the GI Final Report, makes any mention of the time at which water was first sprayed onto the fire. The evidence confirms that it was very near the time of this first photo (**Figure 1**) taken at 1.08 am, *i.e.* seconds before water was first sprayed from the hose onto the flames at 01.09 am [3] [4]. With immediate effect, fire breaks out of flat 16 into exterior cladding and spreads rapidly upwards along east facade as water from hoses continues to fuel the burning plastics and ferocious oxidation of the molten aluminium. In ignoring this key event, the Grenfell Inquiry report is, *de facto,* implying that the simultaneous application of water, which is not mentioned in its timeline as a "key event", at 1.09 was just a coincidence; but was it?

1.4. Methods

Here we report and extend the "scientific method" that implies a platform of rules of investigation of experimental evidence, that has been refined and developed by leading scientists for more than 350 years since Newton [6]. Science seeks the truth, the whole truth and nothing but the truth. Without a much-improved scientific understanding of the fundamental nature of fire in high-rise buildings and other structures of the built environment it is not clear, following the Grenfell Inquiry, how we might even begin to mitigate, ultimately eliminate, future disasters of this type depicted by Grenfell Tower tragedy (**Figure 2**) from ever happening again.

(a) (b) (c)

Figure 2. (a) Tower-block inferno 2017: this is not just burning plastic insulation within the cladding: the reaction of extinguisher water on molten Al evidenced by white alumina smoke, as water hits the façade, is so violent it can be explosive. (b) Aftermath evidence: the excess hose-piped water has acted as a coolant to maintain a line of unreacted solid Al-cladding all around the lower floors of the building: hydrogen-unsaturated polymer insulation burns partially to carbon black; the Al has "disappeared" as alumina white smoke. (c) Memorial site 2025: presently scheduled by UK government for demolition and clearance, with many hitherto unanswered questions, some essential scientific forensic evidence will be lost forever.

Our methodological approach here is to review the evidence and to advance what science is already known. We use root-cause analysis methods, with scientific thermodynamic data analysis, and reaction kinetic analysis from timeline evidence, to establish without reasonable doubt, the root cause of why the exterior cladding fire erupted suddenly, burned so fiercely, and accelerated so rapidly. As discussed above, it is in this area that the Grenfell report is, at best, ambiguous with evidence of obfuscation of scientific truth emerging. It is not plausible to simply claim that just because the science may not be 100% firmly established by consensus with "expert witnesses" with various agendas, that it is not sufficiently established truth to make important inferences. We use the word "obfuscation" because the Grenfell inquiry was made fully aware of the potential for such fires to escalate out of control for reasons we research here, since 2018 [1]-[4]. We revisit the role played by water catalysis pathways in more detail, paying special attention to the application of classical thermodynamics and established knowledge of combustion chemical kinetics and fluid mechanics transport phenomena.

The remainder of our combustion physics inquiry is set out as follows. Section 2 places our analysis of the GI Final Report within the context of a well-reported recent history of tower-block with aluminium cladding fires, from which many lessons have already been learned. This essential historic knowledge (more than 100 references in Wikipedia "Grenfell Fire", however, has no reference or mention in the Grenfell final inquiry report [5]. Section 3 reviews the thermodynamic Gibbs energy differences that drive the mechanisms for the oxidation combustion reactions of aluminium with water as the catalyst. Section 4 provides a scientific analysis of how fires expand. Section 5 concludes with a simple summary of scientific explanation of Grenfell tragedy, and what we believe to be major scientific issues that need to be further investigated to enhance the safety of the Al-clad tower block environment.

2. Recent history of Aluminium Fires

2.1. Dubai Tower-Block Fires (2012-2016)

There were 5 well-publicized and well documented, aluminum cladding fires in the city of Dubai between 2012 and 2016. Dubai is renowned for its shiny rocket shaped sky-scraper tower blocks that characterize 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.

Figure 3. Dubai's Downtown Address Hotel, New Year celebration fire (December 31st 2015).

The latest Dubai fire was a 75-storey residential tower just 1 year before Grenfell in July 2016. There was a scientific lesson to be learned. This was the most publicized and dramatic of all the Dubai tower-block fires. It was on New Year's Eve

2015 at the Address Downtown Dubai Hotel, which stands adjacent to Dubai's tallest skyscraper, also still the world's tallest building, 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 (**Figure 3**) coincided with the beginning of the New Year's Eve fireworks celebrations from the Burg Khalifa super-tower. According to Dubai Civil Defense 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 evacuate 3000 people.

2.2. Aluminium Roof Fires

There have recently been many press headlines on an increasing number of fires of high-profile buildings with aluminium roofs. There are countless common house fires and large building fires but more recent fires such as the Brazil National Museum 2018 (**Figure 4**) and Notre Dame, Paris (**Figure 5**).

Figure 4. The National Museum of Brazil fire (2nd Sept. 2018).

Figure 5. Fire at Notre Dame in Paris (15th April 2019).

The cause of the fire that destroyed the national Museum of Brazil is unknown but has been attributed to an electrical fault (a somewhat generic cause in fire forensics) or maybe a "sky lantern" that drifted on to the roof.

From the publication of our first reports [1]-[5] serious fires continue to erupt around the

world. The Parisian fire fighters had the good sense to divert water from the roof to the masonry thus saving the superstructure of the building. The fire broke out as the roof was being renovated but we do not yet have a forensic report as to what happened. If aluminum was being used to replace lead over ancient wood the Notre Dame fire may well have an origin similar to the Grenfell Tower

2.3. Aluminium Marine Fires

A high-profile example of marine aluminium fire was on the US aircraft carrier Bonhomme Richard which, during the latter stages of a renovation costing some $3B, caught fire in San Diego harbor (12 July 2020) and burnt for four days (**Figure 6**) despite the best efforts of a fleet of fire tenders and helicopter fire drops. It was a total loss and was later towed out into the Pacific Ocean and sunk. On might ask, "so what was special about these fires?"

The super structure used large amounts of aluminum and plastics; the deck was aluminum covered in teak to allow for operation of vertical takeoff and landing aircraft. There was no shortage of water or pumps or traditional firefighting expertise, but it still burned vigorously for a week after which it was towed out into the Pacific Ocean and sunk. The point that needs to be emphasized here is that when an Al or plastic-Al fire is fueled with an excess supply of the catalyst water, in the mistaken belief that it will act as an extinguishant, it has exactly the opposite effect. It will burn ferociously, possibly explosively, until all the accessible aluminium within the fire bounds has burned away to alumina seen in **Figure 6** as white smoke.

Figure 6. The USS Bonhomme Richard burns in San Diego harbor in a fire that started on July 12th 2020, with massive plumes of alumina white smoke and steam as water is continually pumped on to the vessel for several days.

When ships are attacked it is often the case that fire does major damage. Similarly, in aerial bombardment, it is the fire storm that has proven most devastating from Dresden to Hiroshima. Fire has been used continuously as a weapon of war from ancient trebuchets to the napalm flame throwers of WW2, bombs in Vietnam, and Molotov cocktails in Belfast. It is not surprising that much effort has been expended to attempt to understand fire and more particularly to find ways to extinguish it rapidly. To do this most effectively, it is necessary to appreciate what fire is at the molecular level, how it propagates on various distance scales and, more importantly, how it might be best extinguished in particular circumstances.

The conclusion that we draw from this section is that from every one of these fires, there was a scientific lesson to be learned by those in positions of responsibility for fire emergencies. A plastic-aluminium fire cannot be extinguished with water; it just fuels the flames. The combination rapidly accelerates the fire out of control and can be explosive.

3. Combustion Reaction Thermodynamics

Water as a Catalyst

Catalysis, by definition, is the process of enabling, or increasing the rate of, chemical reactions. Catalysts are not consumed in the reaction and remain unchanged after it. Small amounts of catalyst can often suffice to trigger the spontaneous reaction; mixing, surface area, and temperature are important factors in reaction rates. Catalysts generally react with one or more reactants to form intermediates that subsequently give the final reaction product, in the process regenerating the catalyst. In the oxidation combustion of aluminium to alumina in burning polymer cladding, there are two possible mechanisms, both of which require water as a catalyst [7].

As with the oxidation of almost all metals, chemical reaction for the redox reaction of aluminium with oxygen is driven by the huge Gibbs energy difference between reactants and product of the combustion reaction. We will see below from the Ellingham diagram in **Figure 6** that the propensity of Al to react with oxygen is at its greatest when the aluminium is solid at low temperatures, partly because the entropy change is negative. Thermodynamics tells us what the equilibrium state of reactants and products are, but it tells us nothing about the reaction kinetics mechanism of the chemical reactions involved, or under what conditions the reaction will proceed. We will address the science of reaction rates, insofar as relevant to GI-Final Report in next section.

Neither solid aluminium ($T < 660˚\text{C}$) nor molten aluminium ($T > 660˚\text{C}$) will burn with oxygen or air below the melting temperature of alumina (2250˚C) because of inhibition of the reaction by alumina at the surfaces. We have known for decades [8] [9] that solid aluminium will not react with water or steam to give hydrogen. A thermodynamic analysis of Gibbs energies, however, shows that (i) the combustion reaction is highly exothermic and (ii) aluminium will displace hydrogen from water, also highly exothermic, thus providing a mechanism with water as the catalyst.

There are no "suppositions" in these statements based upon a knowledge of the thermodynamic state functions of reactants and products of combustion. They are based upon established fundamental principles that 1st Law: enthalpy (H) is a state function, and 2nd law entropy (S), (hence also Gibbs energy ($G = H - TS$), is a state function. To facilitate the combustion of aluminium and liberate the vast heat of combustion as flames, all that is required is a mechanism. The thermodynamic description of combustion looping mechanisms is well known to industrial chemical engineers [10] [11].

There are two possible mechanisms in the case of Al-cladding combustion since the Al is in contact with a H-unsaturated polymer that burns to carbon in a confined space with restricted oxygen. The thermochemistry of oxidation can be summarised in Ellingham diagrams [12].

The first mechanism, via hydrogen, requires the molten aluminium to be in contact with water. The second mechanism via methane requires the molten aluminium to be in contact with dispersed carbon from burning polymers and also water.

$$4/3Al + 2H_2O \rightarrow 2/3Al_2O_3 + 2H_2$$

$$2H_2 + O_2 \rightarrow 2H_2O$$

Cancelling 2 (H_2 +H_2O)

$$4/3Al + O_2 \rightarrow 2/3Al_2O_3$$

H_2O is the catalyst and H_2 is the intermediate. The thermodynamic properties used to construct this Ellingham (Fig. 6a) are taken from references [8] [13].

It is well known that when carbon is dispersed within an aluminium matrix, a range of surface reactions can take place on the hot solid Al surface, corrosion of the Al is advanced with the evolution of methane. The microstructural characterisation reported recently by Liu et al. [14], even with powdered diamond, shows that when water enters the composite, it can react with an interfacial aluninium carbide (Al_4C_3) phase to generate $Al(OH)_3$ and methane gas (CH_4). The *in situ* production of carbon [C] from combustion of H-unsaturated polymers such as polyethylene reaction is: $X(C_2H_4)_n$ (polymer)+ $nXO_2 \rightarrow 2nX\ C + 2nX\ H_2O$. Unsaturated polymers burn to carbon black in oxygen limited reaction conditions. H_2O is the catalyst and both Al_4C_3 and CH_4 are intermediates: the thermodynamic properties in **Figure 7** are taken from reference [15].

$$4/3Al + C \rightarrow Al_4C_3$$

$$Al_4C_3 + 2H_2O \rightarrow 2/3Al_2O_3 + CH_4$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

cancelling the catalyst (H_2O) and intermediate (CH_4)

and since $C + O_2 = CO_2$

$$4/3Al + O_2 \rightarrow 2/3Al_2O_3$$

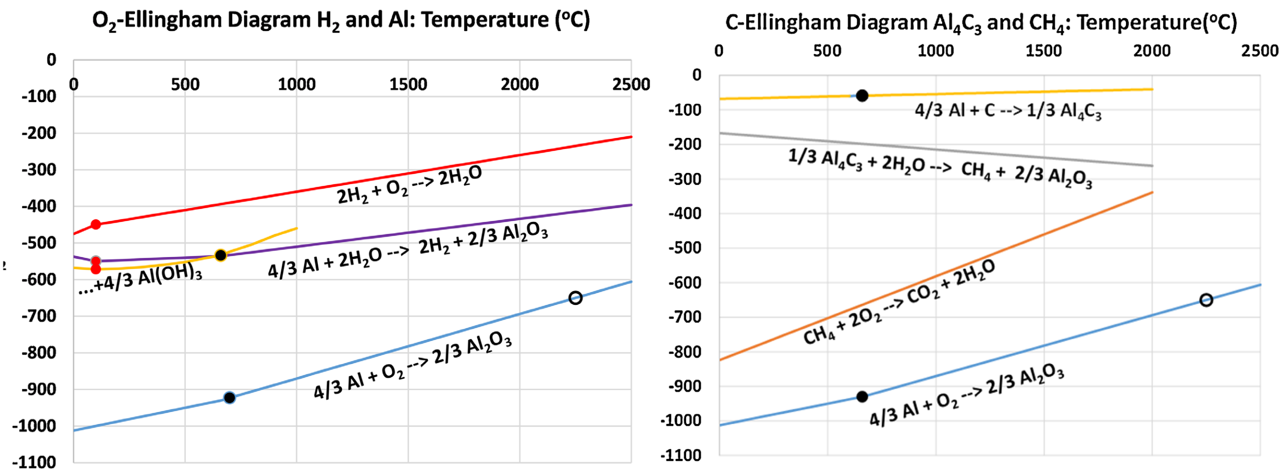

Figure 7. Ellingham plots of standard reaction free energy (ΔG°: kJ/mol) as a function of T for the catalytic oxidation of aluminium to alumina by "chemical combustion looping" mechanisms [10] [11]: the red circle is boiling point of water, black solid and open circles are the melting points of Al and Al_2O_3, respectively: the orange lines are the hydrolysis of aluminium to $Al(OH)_3$, the hydroxide bayerite via the formation and hydrolysis of aluminium carbide (Al_4C_3): the black solid and open circles are the melting points of Al and Al_2O_3, respectively.

Conditions prevail for both these mechanisms in the combustion of polythene/aluminium in Rainscreen Façade ACMs of the type used on the Grenfell Tower. The formation of the intermediates, and subsequent reactions show how the explosive gases methane and hydrogen are transient and obey Dalton's law of mole balance within the overall chemical reaction. Water remains unchanged but liberated as steam as both a reactant and product of the intermediate stage of the H_2 oxidation process. In both H_2 and CH_4 mechanisms, we see from the chemical equations that water is the catalyst, and that the highly inflammable gases both hydrogen and methane are the intermediates that react directly, and under certain conditions, explosively, with oxygen in air to deliver the reaction heat of combustion of aluminium to alumina to propagate the inferno.

4. Combustion Reaction Kinetics

4.1. Acceleration of Grenfell Inferno

"What caused the fire to spread so quickly?" was the remit of the Grenfell Inquiry. The most significant part of the renovation of Grenfell Tower was the addition of external cladding. This consisted of aluminium sheets bonded to a central plastic (polyethylene) core. In his report to the public inquiry [5], expert witness Professor Luke Bisby is quoted "evidence strongly supports the theory that the polyethylene material in the cladding was the primary cause of the fire's spread". This theory is easily discredited as is does not agree with the experimental facts.

GI-Final Report salient finding, based upon Bisby's evidence, contradicts the known science of plastic-Al fires. Quote: [5] "The ACM (aluminium composite material) product on Grenfell Tower incorporates a highly combustible polyethylene polymer filler which melts, drips, and flows at elevated temperature. The polyethylene filler material is expected to release large amounts of energy during combustion". Both statements are incorrect and misleading. The Bisby hypothesis tells us nothing about the reason for the rapidity of conflagration. We shall discuss below, in some detail how fire propagates. We must first point out the obvious counter fact, *i.e.* that while the polymer "melts, drips, and flows down", the fire-front that advances vertically upwards, with a rapid gravitational acceleration given water supply as the combustion reaction catalyst.

Simplified models of any complex multi-stage thermodynamic reaction mechanism can be described by a set of coupled differential equations that capture the chemical reaction order mechanism and transport processes. Boundary conditions require integration over some spatially macroscopic region with well-defined limits. Besides reactant and product components, there can be a multitude chemical species or components, if free radicals and transient entities are taken into account. For full understanding it would be necessary to elucidate the atomistic and molecular rearrangements of each reaction pathway (mechanisms) and determine the activation energies etc. This will be at best an exceedingly challenging long-term project and could be technically intractable. Notice that it would also require great attention to specifying the actual thermodynamic path taken and boundary condition in addition to the usual chemical stoichiometry and thermodynamic state functions.

For example, a polymeric fiber may burn in the form of a cloth covering on a couch and/or on the surface of a foam cushion. Carbon products will form as a distribution of both aerosol particulates that cause "flash over" at the ceiling and as charred material on the surface of the burned or scorched couch; this surface material may then act a thermal barrier coating that suppresses further oxidation on the couch while fine particulate carbon will burn at a greatly accelerated rate near the ceiling. The overall fire becomes both autocatalytic and self-limiting at the same time. This requires careful attention as to how a fire field propagates within a volume element and between volume elements.. It also illustrates why it is necessary to make simplifying assumptions when attempting to describe fire in a computer simulation.

4.2. Computer Models

The general approach, illustrated in **Figure 8**, and applied to Grenfell by Guillaume *et al.* [16] is to discretize the problem into small but statistically macroscopic volume elements *i.e.* individual flats in the case of the Grenfell Tower. Each flat is assigned a "fire load" and a much-simplified reaction pathway. The techniques of reactive fluid flow are then used to describe how energy, mass, momentum, are transported between elements at discrete times. Mathematically they usually reduce to using the second difference of a discrete Taylor expansion in the spatial coordinate and a single difference in time.

Notwithstanding these challenges it is now abundantly clear that computer simulation is an exceedingly valuable tool in the quest to understand and predict the evolution of a fire; how it spreads in buildings, forests, and cities. While it is true that the sets describing the spatial transfer coefficients {Ti} and kinetic rate constants $\{k_i\}$ are only poorly known such models when combined with a well-defined set of reaction pathways and boundary conditions allow us to gain critical insights into the way real buildings and other structures burn. More importantly, they might also be used at the architectural design stage to place resources so as minimize risk and enable a fire to be extinguished safely and rapidly or in detailed forensic analysis.

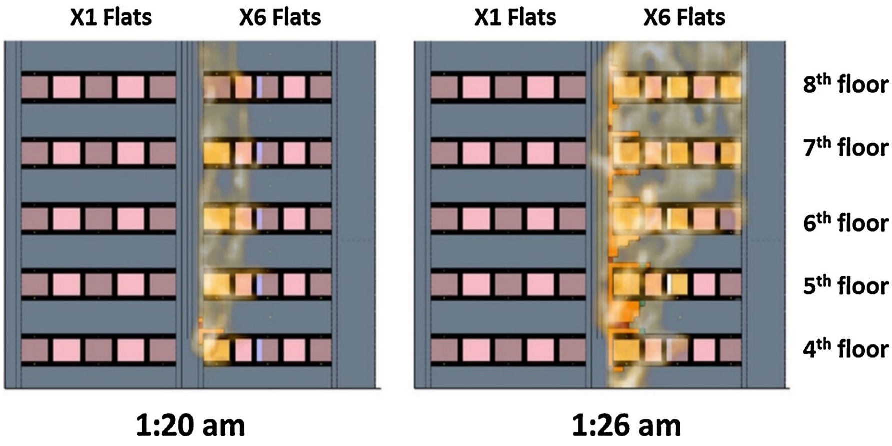

Figure 8. Computer graphics representation of the temporal and spatial development of the Grenfell Tower Fire. Notice that the depiction of flames has been generated as an artist's impression.

The level of detail seen in **Figure 8** is presently extremely limited. While this kind of coarse model is at a relatively early stage of development, some of the initial findings [16] are already intriguing. For example, it has been noted that the fire load of the polymer in the cladding is very small compared with that in any particular flat. Also, the model gave the same result when the insulation was changed from flammable organic material to inorganic material. Clearly, much remains to be done here to further define, research, and develop the technique. This will enable the various contributing factors to be more clearly separated in the model, particularly the impact of the carbide-water reaction and aluminium-water reaction pathways.

4.3. Extent-of-Reaction

In order to elucidate the detailed chemical kinetics, we need methodology [17] [18] to measure how each product was formed and consumed in time and devise a scheme to sensibly average the results. A quantitative description of fire requires four *a priori* assumptions. The first is the so-called quasi-thermodynamic approximation. The idea is that as the set of reactions proceeds, the total heat evolved will be proportional to the degree of burn. This is intuitively appealing, but two points need to be made. First, enthalpy is a function of state and taking its time derivative, even if a pathway were specified, may be a questionable procedure. Second, with many reactions running in parallel what defines the extent of the overall combustion reaction?

The "burn temperature" is a useful practical indicator of the ferocity of a fire; the amount of energy released per unit time is the wattage; this may be expressed in terms analogous to those used in the lighting industry and everyone knows that a 250-Watt bulb "burns" a lot brighter than a 30-Watt bulb. We shall simply adopt the quasi-thermodynamic approximation for the degree of burn (or reaction extent) and write,

$$\xi(t)=\frac{1}{q_0}\int_0^t \lim_{\delta t\to 0}\left\{q(t+\delta t)-q(t)\right\}\mathrm{d}t \tag{1}$$

where $\xi(t)$ is extent of reaction to time t, q_0 is the total thermal load for the flat *i.e.* the total heat output when the contents are burned to time, t.

With this definition, ξ has the character of a normalized local degree of burn with $0 < \xi < 1$ *i.e.* 0 for no burn, or 1 when burnt to maximum extent possible for the local thermal load. This index could be easily related to the maximum flame temperature if the usual assumptions are made about adiabatic boundary conditions and heat capacity of gases etc. It is useful to cast the intensity of burn parameter as a reduced unit that allows us to illustrate more clearly how the phenomenon of fire initiation and growth may be discussed in terms of the physics of non-linear systems and to indicate how various parameters can be measured experimentally.

The second assumption is that it is possible to characterize the rate of the chemical reactions by a rate "constant" which will, according to transition-state theory, depend on temperature and an activation energy,

$$k = A\mathrm{e}^{-\frac{\Delta G^{\mp}}{k_b T}} \tag{2}$$

Here A is the well-known pre-exponential factor, k_b is Boltzmann's constant, T is the absolute temperature and $\Delta G^{\mp}$ is the activation energy. This equation is an established result in transition state theory. It may be used with some accuracy to estimate how the rate of a chemical reaction varies with temperature. While we do not have all detailed rate constants and, transport coefficients of the reactants and products, it is still possible to formulate an approximate general analytic model of fire that is educational. At the start of a fire, the local temperature will rise, and the rate will increase exponentially. This provides a positive feedback effect so that fire grows autocatalytically.

The third assumption is self-evident in that natural fires are self-limiting. When you attempt to burn something the first stage is to trigger a start. The fire then grows to a quasi-steady state, holds more or less constant for a while and then starts to decay. In the absence of added fuel it will start to decay and will naturally burn out. At a very general level the burn rate in these circumstances may be written by an equation of the form,

$$\dot{\xi} = k\xi^m\left(1-\xi\right)^n \tag{3}$$

This equation, while intuitively applicable, is hypothetical and will need to be tested experimentally; it may not be obvious that the rate of burn, essentially (normalized) wattage might be related to the degree of burn. But as a fire starts to burn the temperature increases *i.e.* T in Equation (2) increases thereby accelerating the rate of reaction. This in turn further raises the temperature; this positive feedback acts to accelerate the reaction autocatalytically. The heat generated further raises the temperature. The thermal energy is dissipated into the various degrees of freedom giving rise to conduction, convection, and radiation. The precise molecular mechanisms of chemical energy dissipation is complex but may be represented phenomenologically by an index, m, defined below, without specifying detail.

Similarly, as the fire proceeds the fuel, household contents etc., is used up and this is reflected in the exponent n. A plot of $\dot{\xi}$ versus ξ will produce a complex curve that may be used to characterize the fire mathematically with just three numbers. As indicated above, the prediction of the exponents would require much detailed work in chemical physics, but the gross phenomenology is clear enough and any fire may be represented parametrically by Equation (3).

The numerical values of m and n provide a measure of the physical character of the fire and are analogous to the "order" of reaction in chemical kinetics. Here we have a clear intuitive engineering interpretation. If $n = 0$ and $m \geq 1$ we have an unphysical fire that has an unlimited fuel supply and could burn indefinitely. This is the type of fire whence a highly flammable fuel is added with unlimited supply, perhaps as an accelerant. Similarly, n determines how rapidly the fire dies out. Real typical fires start small, grow, burn steadily for some time and then die out. Equation (3) captures this with appropriate values of k, n, and m.

Equation (3) also provides a general framework for characterizing a fire in terms of three parameters that can be determined by experiment. If a movie of the fire is recorded and the intensity of the frames are normalized relative to the most intense frame then a curve fitting procedure could be used to extract k, m, and n. This could be done for various burn conditions and the degree to which fire may be described by universal equations and critical exponents could be explored experimentally. This procedure is the basic physics for the investigation and characterization of any fire. At the same time these simple models could be tested against large-scale computer simulations. These in turn may prove invaluable in prediction of how fire may grow and propagate and serve as a solid basis for disaster planning.

For instance, as we have seen when $n > 0$, $m = 0$ we have the unphysical exponents associated with uninhibited growth, *i.e.* burning out of control. Natural fires, however, are inhibited as $m \geq 1$ and die out eventually for lack of fuel. Solving (3) for some orders may be possible analytically and always numerically before the onset of chaos. Also, the k's, n's, and m's can be measured experimentally in suitable cases. Indeed, all that is needed is a movie of the evolution of the fire--repetitive. While we simply do not yet have experimental data we may still infer the overall form of the general result from related work. For example, note that when $m = n = 1$ Equation (3) reduces to the very well-studied case of the logistics equation [19]. Equations of this sort may be integrated yielding some sigmoid or

"S"-shaped or sigmoid curves that represent the degree of burn as a function of time. Here we are not so interested in the degree of burn, *per se*, but rather in the stability of the equation that describes how a fire might approach a quasi-equilibrium burn that might be extinguishable or possibly escalate completely out of control. The fourth assumption is that Equation (3) can be iterated in time

$$\xi(t+\delta t)=\xi(t)+\dot{\xi}\delta t \tag{4}$$

Equation (4) allows us to gain insight into how a fire might grow. The important thing to note is that if we know the current state we can iterate to the next state and examine how quasi-steady progression might be achieved. Starting with an initial burn $\xi(t)$ and knowing $\dot{\xi}$ it is possible to map the path to steady state as a function of k. In fire applications we typically have not yet found values for m and n. However, when $m = n = 1$ Equation (3) reduces to the logistics equation which has been studied in great detail over the last 50 years. The so-called bifurcation mapping is shown in **Figure 9**.

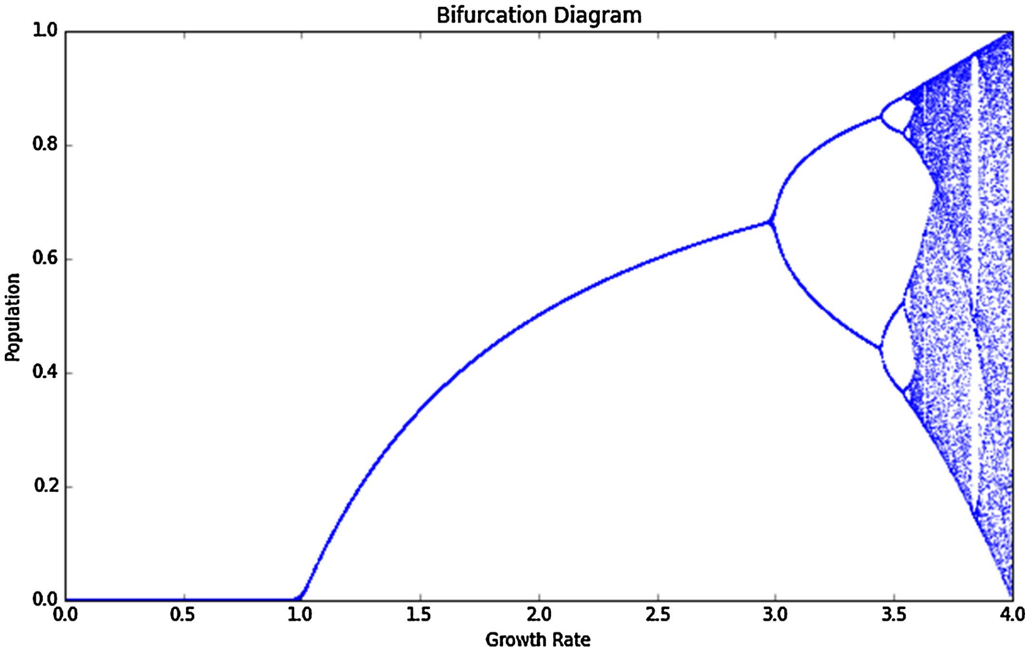

Figure 9. Schematic representation of the bifurcation mapping [19] applied to fire propagation logistics equation ($m = n = 1$): in the present combustion-physics context, the abscissa "growth rate" is analogous to our rate constant (k) and the ordinate "population" is analogous to our final extent of burn ξ_{inf}.

When k is between 0 and 1 a fire is not supported and will "fizzle out"; from 1 to 3 a standard quasi-equilibrium fire is possible; above 3 the fire enters a chaotic regime and will be extremely difficult to extinguish. In the region $0 < k < 1$ fire is not possible; region $1 < k < 3$ a steady burn rate is possible with the fire "flickering" and eventually reaching a quasi-equilibrium burn rate with constant flame temperature. In region $k > 3$ a transition to a raging inferno takes place. In this region the temperature will fluctuate wildly, gas plasma kinetics will operate, and the usual (negative) linear relationship between gradients and fluxes will not hold.

If growth rate (k) is increased, however, the rate curve will extend above the diagonal such that the iteration will reach a fixed point whereupon we shall have a fire that is burning in quasi-equilibrium. At this point, if fuel is added the fire intensity increases, the temperature increases, and the rate constants rise exponentially. In the presence of sufficient fuel this process will continue until a critical acceleration is reached. As the rate constants increase, the height of the "rate curve" increases until a point is reached where a fire is viable and a fixed point is reached. Such a fire will burn in quasi-stable state until it simply burns out. However, if an additional forcing fuel is added the rate of burn may be increased sufficiently to reach a critical point where the locus of quasi-stability splits. This splitting has been the object of intense study with fitting polynomial expressions and much discussion on the numerical value of the leading power. It has been found that such equations are somewhat sensitive to the exponent but very insensitive to the precise algebraic form *i.e.* non-linear equations have very similar mappings with the precise fashion in which they transition to chaos defining their so-called "universality class".

We have hitherto focused on how fire will develop within a single flat. But we know that if fire is burning vigorously in one flat there is a probability that it will spread. The precise mechanism involved is again complex and may involve a plethora of unquantifiable factors including construction permeability, and environmental effects such as variables wind speed and direction.

4.4. Overall Combustion Rate

In addition to the extent of reaction, ξ, that refers to the local fire, the parameter we define Ξ, representing the total burn of the building. While is important to extinguish a fire in a particular flat it is clearly essential to save the building *i.e.* Ξ must be kept equal zero. Thermal energy will be transferred by the usual physical processes of diffusion, conduction, and radiation but in addition factors like embers or wind speed may play an important part. In a building made of stone or concrete it is easy to assure that thermal transfer for these mechanisms is very small or zero. In a formal sense we assume that some transport coefficients are appropriate and write,

$$\dot{\Xi} = T\nabla^2\xi + k\xi^m\left(1-\xi\right)^n \tag{5}$$

The transfer coefficients T capture the spatial transport between flats while the k refers to the temporal evolution within flats. The T in equation (5) is a matrix quantity that may have very different values in different direction; for example, a burning gas applied to the external of a building at a given flat will transfer heat in the vertical z-direction but much less in the x-y direction on a given floor. In general, the order of a chemical reaction may have higher and non-integer powers or negative powers. Any attempt at solving such a complex expression analytically is very challenging indeed. But with careful attention to numerical stability such a model can be simulated on the computer. But notice that we can make some headway in terms of fire classification. The first point to note is that when the building burn rate is very low ($\dot{\Xi}$ approximately zero *i.e.* a flat is on fire but the building is not), we can apply dominant balance and write,

$$\lim_{T\sim T_b}\left\{\left[T\nabla^2\xi\right]\Big/\left[k\xi^m\left(1-\xi\right)^n\right]\right\}=\beta \tag{6}$$

where T_b is the quasi-steady state burn temperature of the flat. When $\beta < 1$, T is small and even a well-established flat fire will have difficulty spreading between flats. It is the primary objective of firefighters to achieve this state and prevent spread if they wish to save the building. When $\beta = 1$ the fire is just capable of spreading and when $\beta > 1$ a low-grade fire can be just be started through transmission; note that this ratio could be used to check on the values of the T_s and k_s in computer simulation. This sort of fire will initially have the minimum burn rate possible insofar as a fire can only burn at a rate compatible with the *slowest* rate at which reactants become available.

4.5. Aluminium Carbide

In the case of the Grenfell Tower façade, the aluminum cladding initially acts as a barrier for oxygen transport so that combustion of the polymeric filler materials can occur only along the seams. Aluminum cladding will act initially as a fire barrier; oxidation of the core polymer can only occur through reaction with the relatively small amount of entrained air which, in the presence of excess polymer, will lead to charring and reaction to the carbide on the inner surface of the aluminum panel. The thermal degradation of the polymer filler will involve scission of C-H bonds to form reactive free radicals that will form H_2 as well as soot which is a plethora of highly noxious polyaromatic compounds. Thus, the initial blaze will be a relatively low-grade fire with black smokey aerosol and low, red-yellow, flame temperature as was observed initially (**Figure 1**). As the blaze continues and the temperature rises the rate of combustion increases steadily with the formation of in-situ side-reaction products especially on the inner aluminum/soot surfaces of the external facade. An estimate from transition state theory (Equation (2)) shows that the rate of formation of carbide will be massively greater ($\sim e^{300}$!) at the melting point of aluminum than at room temperature (300K).

Aluminium carbide is not unstable in air at this temperature. The amount of carbide formed will rise as a function of the temperature-time history of the blaze, but this poses no particular or immediate danger in that the carbide is thermally stable. The danger arises when a new reaction pathway is opened by supplying just enough (but not enough to extinguish the fire by deluge) water to hot aluminum carbide. This liberates large amounts of flammable methane gas; the longer the fire has been allowed to burn, the greater the amount of carbide and the more violent the eventual explosive eruption will be when water is added. The fire transitions rapidly from the stable burn regime into the chaotic regime. As argued above, when the external source is physically located on the outside wall of the flat by the window it greatly enhances transfer of energy between flats. At this stage the fire will spread rapidly (vertically) and look like a raging inferno. Flames will erupt spontaneously in some flats and seem to die out in others only to re-erupt sometime later in the same or different location. Explosions will be heard and flame temperatures will approach the maximum theoretical value· The kinetics will be dominated by exceedingly non-linear effects with the signs of gradients reversed and all sorts of patterns (flames) forming and decaying.

In summary, the major regions are: In region I, [0] [1], $\beta < 1$ and a single flat fire will not be supported. In region II, $1 < \beta < {\sim}3$, and a steady state burn is possible within a flat with the possibility of transfer between flats. In region II, $\beta > 3$ we have a burning explosive inferno with little or no hope of extinguishing a fire within a flat nor saving the building before it is completely burnt out.

5. Root Cause Analysis

Root cause analysis (RCA) when combined with multi-scale modeling is very useful when analyzing disasters. It is a well-established engineering technique that has proved valuable in uncovering the underlying cause of the World Trade Center Tragedy in New York, the massive fire following the Great Kanto earthquake near Tokyo (Richter scale 8 with about 138,000) burned to death. It is used routinely in manufacturing failures and accident investigations [20]. Many aspects of RCA are apparent in the Grenfell Inquiry Final Report [5] especially as it relates to the role of government regulations, building materials testing and qualification, management oversight, communications, legal ramifications, commercial fraud as well as an atmosphere of ubiquitous lackadaisical indifference and a prevailing general incompetence. One noteworthy flaw of the final report is that it largely ignores any meaningful technical analysis of the root cause. This is puzzling when the hazard of aluminum in contact with carbon and the potential for aluminum carbide fires are well-documented for 100 years [1].

Although the basic physics and physical chemistry of fire is well known [3] [4], complexity arises when the particular local circumstances must be taken into account. Factors such as the geographical topography, wind direction, building design etc. Here the use of large-scale computer simulation will be invaluable. It is clearly absurd to consider physical small-scale modelling of large buildings to see how they might burn. Realistic models may be constructed using supercomputers or even personal workstations and various "what if" scenarios can be modelled with high fidelity to gain insights and understanding. Such simulations can be carried out for buildings, forests, or even cities, and accurately for nuclear bombs. They hold great promise but there are also several caveats. As the model complexity increases there is a rise in the number of parameters such as the thermal conductivity, reaction rates etc.. Some or most of these variables are not known with great accuracy and few, if any, will have been measured as a function of temperature. If these numbers are allowed to vary then the model may easily be manipulated to yield any "acceptable" result.

For this reason, the results of large-scale computer models need to be treated with some circumspection unless the investigators have paid very careful attention to the quality of the input data and mathematical methodology. On the other hand, simulations can be used as an "experiment" upon a model to conduct a sensitivity analysis of the various interactions. In numerical work it is essential that the results are compared with both real experiment and prevailing theory or hypotheses. The problem with fire is that it is far too complex for analytic theory (mathematical physics) to be of much value. This is not true of explosions: approximate analytic solutions have proved an important part of fire and explosives research.

This gas mixture of air with either hydrogen or methane gas will react essentially instantaneously, possibly explosively, so that the initial rate of burn will be proportional to the flux of fuel. If this mechanism is important we might simplify an exceedingly complex coupled reaction, detonation, and growth phenomenon (equation 5) and write, using dimensional analysis,

$$h(t) = C\left(\frac{\dot{\Xi}}{\rho}\right)^{\frac{1}{5}} t^{\frac{3}{5}} \tag{7}$$

where C is a constant, ρ is density, t is time and $h(t)$ is the height the flames have risen to in time t after the fire has established a steady growth rate. Equation [A1] will certainly not hold throughout the combustion process but might hold during that initial period when the fire has just started but has not taken full hold; in particular the 3/5 exponent might be expected to hold in the limit of $t \sim 0$.

Unfortunately, we do not have anything resembling experimental data for Grenfell fire. The best we can do is to extract frontline heights and times from scientific timelines and journalist witness submissions [3] [4], These rough estimates are collected in **Table 1**.

Figure 10 shows a plot of the data in **Table 1** for the Grenfell fire. If the assumptions underlying equation A1 would hold we would expect a straight line with slope 3/5. This is clearly not the case. But notice that the initial early slope converges to 0.6 which is in good agreement with the scaling prediction which holds during the very early stage of the fire. The fire dynamics is totally consistent with the presence of an accelerant.

Table 1. Flame height as a function of time of the Grenfell Tower fire. These estimates are crude and nothing is available for the early stages of the fire *i.e.* before the journalists and film crews arrived. The heights have been estimates using the height of the tower (67.3m) with 24 floors.

t/min	h/m	log (t)	log (h)
1.0	1.0	0.0	0.0
8.0	4.6	0.90	0.66
9.0	5.6	0.95	0.75
16.0	17.4	1.20	1.24
18.0	56.0	1.26	1.75

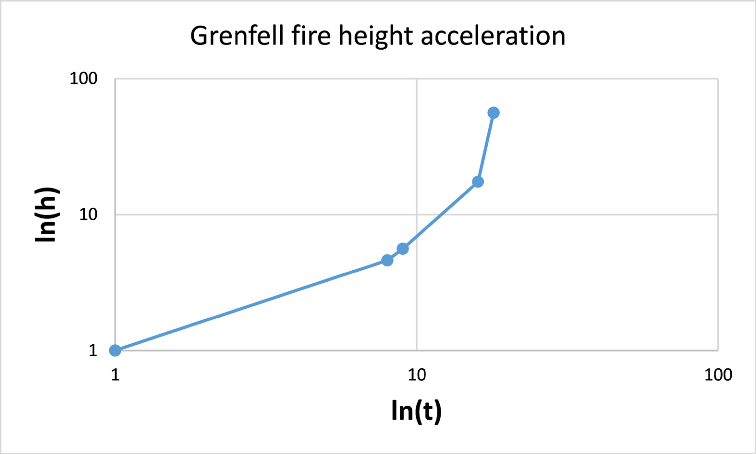

Figure 10. Log-log plot of the flame height as a function of time with uncertainties of the order of dot size(*i.e.* ±1 minute and ± 1/2 metre): a line through the origin (1, 1) and the point $t = 8$, $h = 4.6$ is the prediction of Equation (7): the slope approaches 3/5 at short time: there is some indication of a rapid change in slope around $\ln(t) = 10$. After 10 minutes it accelerates when water hoses begin to encircle the building (see scientific timeline [4]).

Note that the plot does not show a linear flame height as might be expected if this was a low-grade fire creeping up the side of a building. There is a rapid increase with height over time implying that a strong accelerant is being applied. For about the first five minutes the slope is near linear with a limiting value of about 3/5. During the first ten minutes the temperature and reaction rate continues to rise very rapidly so that the assumptions underlying the term in parentheses become increasingly untenable. The reaction rates are increasing exponentially with temperature and the density of air falls rapidly with increasing temperature. These factors can be taken into account numerically in computer models but the analytic theory proves useful in keeping numerical calculation bounded. Notice that after about ten minutes the slope rises very rapidly suggesting a possible transition into a chaotic regime. At this stage the fire is not really burning but rather exploding. At this point the gases within the composite panels are exploding, melting and burning the aluminum cladding and raining molten burning polyethylene down the side of the building. This burning falling polymer is a symptom but not the root cause of the fire acceleration.

The sudden change in slope is consistent with the transition to chaos as shown in **Figure 9**, or it could be operational to coincide with the point in time when the number of fire engines pumping water were increased to encircle the building. Computer simulation could be used to determine the coefficients m and n in equation 5. It is a relatively straightforward though tedious matter to explore how the burn curve intersects the identity line and if the possible kink in **Figure 9** at ~1.2 can be captured in a simulation. In this way the themodynamics, kinetics, and transport properties and overall fire dynamics could be modelled and assessed using a rigorous physics-based analysis.

Another qualitative observation is that the windows of many flats indicate fire in flats that are well removed from the main wall of flame. We might wonder what is causing these flats to burn so quickly? Here again the underlying thermodynamics offers a plausible explanation. If a mixture of methane and hydrogen has been mixed with air and carbon aerosol (smoke), then that lethal gas mixture might well diffuse very rapidly throughout the building with devastating consequences, including "flash over" effects.

While questions of detail may only be answered by large-scale computer simulation supported by physico-chemical analysis, a word of caution is in order. It will be obvious that a large number of physical constants are required, some or many of which will only be known approximately. Every effort should be made to determine these numbers accurately by experiment and not let them float as adjustable parameters or to "calibrate the calculation" as is sometimes said in engineering. It is always possible to let such parameters float, even between broadly "acceptable" limits, and get whatever answer you are looking for. This produces computer printout that has nothing to do with science or physics but may be useful to inquiry pseudoscientists or marketing. On the other hand, if parameters are controlled carefully then a sensitivity analysis provides really useful information. The work of Guillaume *et al.* [16] is a step in this direction.

The speed at which the fire spreads horizontally between flats, $w(t)$, will be governed by the thermal diffusion so we might expect a much slower horizontal spread going like,

$$w(t) \sim T^{1/2} t^{1/2} \tag{8}$$

where T is the thermal diffusion constant. The predictions are certainly in qualitative agreement with what was seen on the night. The fire spreads rapidly up the building along an initial trajectory consistent with an accelerant being used trajectory. As more water is added the rate continues to accelerate until the top of the building is reached at which point it spirals more slowly around the building.

The level and quality of scientific information could easily be extended by making *in-situ* measurements. It is straightforward to insert the stainless-steel capillary of a small quadruple mass spectrometer into a panel and record where and when the various reaction products form. This experiment could include a number of thermocouples placed both inside and outside the composite panel. Including fiber optics for remote spectroscopic in-situ sensing In advanced composite manufacturing has been possible for some time and could be extended to real-time fire testing. The Grenfell enquiry final report essentially discounted the science "so far as it is known" as largely irrelevant and focused on legal and regulatory aspects.

6. Conclusions

The above scenario accurately describes essentially what was seen and widely reported at the Grenfell Tower incident, and since. While a mathematical description of how fire propagates will require experimental verification and validation, it should be stressed that our theoretical discussion of the reaction kinetics does not detract from the simple observation that applying a "blow torch" of burning natural gas in regions between the flats sealed the fate of the building. As the Grenfell Final Report states [5], there were many factors that contributed to the tragedy ranging from the 1980's relaxation of regulations to the omnipresent incompetence, fraud, waste and abuse of all the authorities and contractors involved. In situations where many adverse circumstantial factors like this interact, it is difficult to identify a single or root cause. However, if instead of asking "what caused the fire" we reverse the question and ask instead: "what action, had it not been taken, would have avoided the catastrophic disaster and consequent incalculable fallout effects?"

Applying the scientific logic of *reductio ad absurdum* and the principle of minimum hypothesis (Occam's razor) then we arrive at three clear conclusions, that complement the findings of both the Grenfell Inquiry Interim [3] and Final [5] Reports for future safety of Al-clad tower block residents.

1) *The fire in the kitchen fridge may not have exploded and spread within the kitchen if the occupant had access to non-aqueous 5 kg kitchen* CO_2*-foam extinguisher. The implication is that all apartments in tower blocks should be equipped with a standard household 5 kg* CO_2*-foam extinguisher at the ready.*

2) *If residents had not been told to "stay put", and an immediate evacuation drill had been in place and implemented at the outset, irrespective of the water-extinguishant debacle, there would doubtless have been no loss of life. This implies that all apartment blocks should have a fire alarm evacuation facility with regular rehearsal of evacuation fire drill.*

3) *The kitchen fire could not have flared up so suddenly and spread so rapidly, from window of flat 16, if the LFB had not sprayed water on it. The implication for all future Al-clad tower blocks susceptible to plastic-Al fire emergency services must be prepared beforehand with a non-aqueous* CO_2*-foam or similar to extinguish by suffocation.*

In this root cause assessment, we have re-examined and described the scientific nature of the acceleration of Grenfell fire from the perspective of chemical physics with special reference to the final report of the Grenfell Inquiry [5]. More specifically, we question the extent to which the Grenfell Inquiry report has delivered any scientific truth at all that is relevant to its very clear original objective. The goal of independent, *bone fid*e, scientists, as distinct from subjective pseudo-scientists, is wholly objective. We must coexist with ignorance unless, or until, there is scientific evidence to support the explanation of purely objective observations. Then, the hypothetical explanation must withstand scrutiny against further experimental observations. We have found that the UK Government reports [3] [5] failed to deliver its original objective of the truthful scientific root cause. The final report [5] further exacerbates the plight of the millions of Grenfell Interim Inquiry fallout victims, both in UK and worldwide, who still live in Al-clad tower blocks [21].

Distinguished research physicist, John Ziman, commenting in Nature [22], 30 years ago, forewarned the science community about an insidious ascendancy of pseudoscientists whose subjective circumstances are such that they cannot be objective in the pursuit of scientific truths. Ziman was not the first. 100 years earlier, the Editor of Nature [23] criticised the foundation of an Institute of Chemistry with Royal Charter. He argued that a "trades union for scientists" would compromise objectivity when its members were called upon to be advisors to government officials, or courts of law, or commercial sponsors, at the expense of scientific truth. We also find in this commentary the original renowned quotation: "There are three types of witness, simple liars, damn liars, and experts…whose cultivated faculty of evasion effect is worse than lies." ([23], p74, col. 2, lines b16-9). This 1885 Nature Editorial is a prophecy fulfilled.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix: List of Symbols

k is the usual chemical rate constant defined in transition state theory for a single reaction pathway. The overall k will depend on the interaction of many individual pathways in a very complex way; but a single "average" k may be used to illustrate the very sensitive dependence of rate on the activation energy—$\Delta G\pm$.

∇^2 the del squared operator: $\mathrm{d}^2/\mathrm{d}x^2$ in one dimension; the second spatial derivative of the thermal field with respect to distance.

ξ lower case Greek xi used to represent the overall degree of burn. It is 0 when no fire (burn) has occurred and 1 when the flat is burned out. Note that this is the total heat evolved up until time t. The time derivative is the rate at which energy is being emitted at time t(wattage) by a fire which is allowed to burn freely in air at NTP. It is NOT the thermodynamic heat of combustion in a bomb calorimeter.

$\dot{\Xi}$ upper case xi with dot representing differentiation with respect to time is used to represent the rate at which the building Wattage is increasing.

q_0 is the average thermal load of a flat. This is the heat that would be evolved if a fire was to catch in an individual flat and burn to completion; the fire will burn out when a fuel is exhausted. This will happen before the thermodynamics enthalpy of total combustion. Note that the bedding, couches, TVs etc. have a q far greater than the plastic insulation in the panels (by orders of magnitude).

$\mathrm{d}\xi/\mathrm{d}t$ or ξ (with a dot over it) is the rate of energy release at time t within a given flat. This is normalized by dividing by q_0 so as to keep everything dimensionless (*i.e.* reduced units) to emphasize the generality of how a fire may be initiated, grow to a quasi-steady-state and ultimately become a chaotic raging inferno. Note that the "oscillations" that appear do not represent an "unburning" of the fire but rather the "flickering" of the flame as different pathways may fleetingly dominate the oxidation kinetics. The flickering represents the level of instability as the fire approaches a steady state.

T is a thermal transfer coefficient. It is analogous to the thermal diffusion coefficient in Fourier's law but is much more general. Note the ks will govern the rate at which an individual flat will burn but the T_s will determine the rate at which the building burns. It was spraying water that enabled the release of highly flammable gases right at the interfaces between flats; this essentially increased the local T values and ensured that the whole building would burn.

The capital X_i is identified as the rate at which the whole building burns.