The Fires

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Abstract

Qualitative and semi-quantitative analyses presented in this article suggest that the massive fires caused by the crash of the planes into the World Trade Center Towers and the spillage of large amounts of jet fuel inside the buildings played a major role in their quick collapse on September 11, 2001. It is argued that the WTC fires, while unprecedented in form, magnitude and extent, resembled massive compartments fires in which the primary fuel —the jet fuel— spilled over a large area, ignited almost immediately, supported the formation of huge fireballs that extended outside the crash zones, and triggered very large-scale secondary fires that engulfed all available combustibles contained within the floors surrounding the impact area. These *post-flashover* fires, which sent thick smoke plumes a long distance downwind over lower Manhattan's previously cloudless skies, continued to burn long after the catastrophic collapse of the buildings. The analysis presented in this article relies on models of compartment fires to estimate the burn rate and the resulting fire and structure temperatures, incorporating rational assessment of the crash damage on the exterior and the interior of the Towers that were created by the plane impact. Using these models, scenarios for the fires during their different stages are developed, and approximate rates of overall heat release and the prevailing temperature history within the buildings are obtained. It is shown that the fire power, measured in terms of total heat release rate, was of the order of gigawatts, the fire temperatures may have exceeded 1000° C, and the structural steel elements attained dangerously high temperatures for an extended period of time. While these estimates are approximate and preliminary, they remain relatively unchanged when varying some of the assumptions and numbers used to define the burning conditions over ranges supported by available data, and confirm the assertion that the fired played a major detrimental role in the quick collapse of the Towers on that tragic day.

1. Introduction and preliminaries

On September 11, 2001, two Boeing 767-200 planes were deliberately crashed by terrorist onto the World Trade Center towers. The planes pierced through the exterior walls, immediately disintegrated, spilling huge quantities of jet fuel, and igniting massive fires that

engulfed various floors and set the combustible office materials ablaze. These unprecedented fires, and the associated dense smoke plumes that results almost immediately after the crash, were visible many miles away from the disaster site, and are well documented in video footages. The role these fires played in the quick collapse of the two Towers has been the subject of much debate and some preliminary studies[1]. Much of the confusion in the early assessments regarding the importance of the fires in the WTC collapse stemmed from the enormous complexity of this event, the lack of studies of fires of similar scale, and the scarcity of data from the accident itself. Most importantly, the difficulty in applying existing standards to classify the fires, and the absence of partial, let alone full-scale models that can be used to quantify its impact on the structures, had opened the door for arbitrary interpretation and speculation. This is likely to continue until careful scientific studies are conducted.

Indeed, when attempting to elucidate the causal relationship between the fires and the collapse of the buildings, it is very important to first develop as complete a fire scenario as possible. Such a scenario should describe the different stages of the event, quantify the corresponding fire phenomena in each of these stages, and utilize both to estimate the burn rate and local temperatures and their dependence on the conditions that prevailed during the fires. These conditions include the amount of flammable materials available —both the jet fuel as well as other combustibles, such as furniture— the ventilation, the volume and surface area of the compartment where the fire raged, the outside wind conditions, etc. The conditions are strongly dependent on crash analysis and structure failure studies, and on careful examination of the video images that have been collected during the accident. Since the fire must have contributed to the structure failure, there is also tight coupling between fire progression and the building collapse, and a detailed model studying the interaction between the two should be incorporated. In the interim, one must rely on approximate estimates of the conditions to assess the fire impact.

Many fire models are available, including pool fires, fire plumes, compartment fire models, etc. [2,3], which could be used to describe some elements and stages of the fires in question. For instance, fire plume transport models could be used to back out the heat release rates near and around the crash site, given the smoke plume trajectory that have been recoded in video images [4,5]. Moreover, other fire dynamic models could be used to confirm these data by carefully observing the fire dynamics in the immediate proximity to the fuel zone [6,7]. Such studies could be very useful and insightful, and should be conducted. However, given the overall conditions of the WTC fires, the interest in assessing its impact on the structure of the Towers and their role in the tragic and quick collapse of the buildings, *compartment fire models* are chosen here. In compartment fires, fuel is spilled inside an enclosure, which initiates a fire that may or may not remain contained inside the compartment. These models have been used before, and will be applied here to obtain approximate estimates of the fire intensity, the burning rate, the fire temperature, and the temperature history of the structural elements in the WTC fires. To apply these models, the following preliminary data on the size of the WTC buildings, the crash location and the planes shall be used.

The dimensions of the South Tower were 63.5×63.5 meters on the sides, and 411.5 m in height. The North Tower was virtually identical to the South Tower, except that it was slightly taller. Both towers had 110 stories, and hence their inter-story height was about 3.75 m. The exterior of each tower was made of a dense lattice of prefabricated steel columns, while the $24m \times 42m$ interior core consisted of 48 steel columns fireproofed in concrete.

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[1] Some careful studies are also being conducted, however their results were not available at the time of writing this paper [1].

The external dimensions of a Boeing 767-200 plane are 15.8 × 47.5 × 48.5 meters in height, width and length, respectively, the first two of which are measured at the tail and the wingspan. These data provide approximate numbers for estimating the size of the initial hole in the exterior steel shell of the building that was created by the crash, and the initial volume of the cavity within the tower, which resulted from the crash and very early local collapses inside each tower, where the fire started.

The takeoff weight of a fully loaded Boeing 767-200 plane is approximately 178,000 kg, and is able to carry a maximum fuel volume of some 90 m^3. The approximate density of jet fuel is 800 kg/m^3. Thus, the total maximum fuel weight is about 72,000 kg—almost half of the plane weight at take-off— and the plane's takeoff weight without fuel is 106,000 kg. It is known, however, that the two planes were only partly loaded with passengers. In addition, government sources indicate that the typical fuel loads for these types of aircraft when flying coast to coast is some 45 m^3 (12,000 gallons). When this information is considered, along with the estimations on the amount of fuel burned between the planes' departure from Boston to their arrival in New York (about 8 m^3), one concludes that the fuel tanks at the moment of impact may have been no more than 42% full (37 m^3), and that the planes must have weighed some 136,000 kg each. A substantial portion of the fuel got burned in the initial fireball on the exterior, which suggests that the fuel volume that was ignited in the interior of the towers may have been on the order of 25 m^3, or about 20,000 kg. It should be remembered, however, that the initial fireball contributed to the heating of the building and the ignition of some of its flammable material.

The enthalpy of reaction of the fuel, that is the heat generated as the fuel is burned under stoichiometric conditions in air, is almost 45 MJ/kg of fuel. Thus, for a plane fueled to capacity (72,000 kg), the total heat load —the heat generated if all the fuel is burned— is a staggering 3,240 GJ (giga-Joules). Burning this fuel continuously over a period of almost an hour, this energy generates a power of almost one gigawatt, equivalent to the power of a large conventional or nuclear power plant. A small fraction of this power is indeed capable of causing enormous damage if unleashed close to a building.

The rest of this article defines a compartment fire in its different stages, proposes the use of models of compartment fires to estimate qualitatively and at times quantitatively the conditions of the WTC infernos, and discusses the impact of a fire on the enclosing structure and the mechanisms by which the damage is incurred. The numbers required for that purpose are estimated using publicly available data on the planes, the buildings and the dependence of compartment fires on the fuel and the enclosure. Some detailed review of the dependence of burn rate of compartment fires on the conditions is included, and more detail regarding how to estimate the fire and the structure temperatures are then presented. The article relies heavily on material in Refs [2,3], and references therein.

2. Effects of a fire on a structure, and its contribution to failure

It is well known that fires affect the structural integrity of buildings in several ways, including:

i. Direct engulfment and rapid consumption of flammable building materials of relatively low ignition temperatures, including furniture, etc. If some of these materials are used as load bearing elements, a rapid collapse ensues.

ii. Intense heating of structural elements with high ignition or break down temperatures, through heat flux generated by both the flaming materials and the hot combustion

products. In the case of structural steel members, this progressive heating leads to significant losses of stiffness and strength, and ultimately to failure. In concrete elements, such as floors, the intense heat induces surface spalling caused by the uneven heat expansion, vaporization of the interstitial water, dehydration and degradation of the cement paste, and chemical changes affecting the strength of the concrete.

It is reasonable to assume that both factors played important roles in the WTC collapse. The exterior steel lattice was exposed to direct contact with the initial and massive fireball that must have consumed a substantial fraction of the available jet fuel, as was clearly observed in the video footage. This initial fireball must have resulted form the burning of some of the fuel spilled following the impact, close to the collision area at the exterior walls. During the burning of the fireball, a large heat flux generated by the hot, jet-fuel-combustion products was directed toward the exterior and interior load bearing steel elements.

Direct contact between the fire and the structures produces the worst damage, because it leads to a fast rate of temperature rise and rapid softening of the steel. This is a likely scenario for the fate of the exterior lattice of the WTC, which was exposed to the initial fireball and to the subsequent interior fires (evidence of some melting of steel has been reported from careful analysis of the video footage). Direct contact also damages the insulation material used to protect the metal-based structural elements, making them more vulnerable to the intense heat. In this case, the temperature in the structural elements continues to rise even without direct flame contact, albeit at a somewhat slower rate. This is the case, because under the high temperatures prevailing in fires, both the heat fluxes due to radiation and convection cause the temperatures of the structural elements to rise continuously. Loss of insulation leads to rapid breakdown of the heat transfer resistance in the structural material and thus causes these insulation-deprived elements to experience a dangerous rise in temperature. Slender elements with high surface to volume ratios, like trusses, are more vulnerable to this effect than more massive elements, such as wide flange (or box) beams and columns.

Persistent flames can also damage structural elements normally utilized to contain the fire within one compartment, such as doors, windows, floors and ceilings. When this occurs, the fire invades neighboring compartments and expands its overall size. Thus, the collapse of the containing elements allows the fire to extend its reach far beyond its original location, and causes radiative heat fluxes to travel further within the structure. Moreover, in terms of the damage caused by a fire, not only is the maximum fire temperature important, but also the length of time that the temperature remains at or close to this value, because the prolonged heating increases the exposure of the structure. As will be seen later, the combination of a high fuel load (fuel mass per unit area) and good ventilation through holes in the exterior walls or broken windows (either natural or caused by fire damage) allow fires to burn for tens of minutes at temperatures close to, or even above 1000°C. In the case of the WTC fires, the initial massive crash created large ventilation openings on the sides of the towers that fed the fuel inside the building with sufficient air to burn fast and steadily for tens of minutes. Meanwhile, the collapse of several floors caused by the aircraft impact together with the domino effect of falling rubble accumulating on the lower floors, allowed an initial compartment to be formed that supported the early stages of the fires. As more floors became weakened and failed, the size and reach of the compartment extended, and as both got heated by the surrounding fireball, the fuel density within that compartment increased.

The total heat flux generated by a fire depends strongly on its temperature, and to some extent, on the gas motion it induces. Strong rising plumes carrying hot combustion products and some unburned fuels can be seen in all large fires. These plumes induce strong drafts towards the fire source that further enhance its ventilation. To determine the gas temperature, one must know the heat release rate, which is the rate of burning times the heat

release per unit mass. Hydrocarbon fuels, such as jet fuels, and other combustibles such as building materials and furniture, have different burning rates and heat release rates, and hence produce different intensity fires. In a strong fire, it is very likely that all available material is readily turned into fuel, that is heat producing element, upon combustion, as the temperature exceeds their ignition temperature, no matter how high it is.

It is useful to distinguish between a primary fuel, which starts the fire, and a secondary fuel, which participates in the fire at a latter stage. In the WTC case, the jet fuel acted as the primary fuel, while the furniture and building material was the secondary fuel. Some of the plane material also contributed to the available combustibles. The crash must also have "snowplowed" some of this material within a relative small volume, which increased the fuel load within that volume.

3. Compartment fires: a detailed account

A *compartment fire* is defined as the fire resulting from the ignition of a fuel contained within an enclosure, normally as a result of a liquid fuel spill or solid fuel spread on the floor of the compartment, which is ventilated through wall openings [2,3]. The growth of these fires occurs in two phases, namely *pre-flashover* during which only the original fuel is burning and the fire is localized close to the primary fuel source, and *post-flashover*, during which all combustible items within the enclosure are engulfed in flames, and the fire is thought to be fully developed. Failure to escape during the first phase often leads to death as the temperature increases substantially near the ground during the post-flashover phase. Flames spilling outside lateral openings are often observed during the latter phase as some of the combustible volatiles can not find enough air inside the compartment to burn completely, and get carried out by the hot buoyant products into the cooler environment outside. With enough primary fuel in the enclosure, transition between the two phases occurs faster than the time it takes for the fully developed fire to decay. One can argue that the initial fireball seen following the plane crash into the WTC resulted form the jet fuel sloshing outside through the crash hole and broken windows, and supported latter by evaporation of fuel spilled inside.

Severe building and structural damage occurs during the latter period of a fire when the flames literally engulf the entire structure. At this stage, the heat release rate, the gas temperature and the heat flux to the structural components reach their maximum. Direct contact with the flames may cause failure of the structural barriers designed to limit the spread of the fire and hence expand the enflamed area. Direct contact also damages the insulation of the structural elements, such as steel, and hence exposes these elements to higher temperatures. At the beginning of a fire, higher temperatures occur close to the ceilings due to the strong buoyancy of the combustion products—this is why fire detectors are installed at the ceilings— and there is a chance for the occupants to escape. However, as flashover is approached, these high temperatures penetrate downwards and reach the floors as a result of the strong radiation fluxes from the ceiling and the accumulation of the hot combustion products. Factors affecting the time to transition and the burn rate during post-flashover will be discussed later.

To model the WTC fire as a compartment fire, it is necessary to estimate the area and height of the compartment within which most of the early burning took place, the area and height of the lateral openings that exposed the compartment to the outside, the fuel load within the compartment and how far it spread upon impact, the floor area of the compartment, and its total wall area. Moreover, the time history of all these quantities, following the initial impact and the onset of the series of events leading to the collapse, need to be estimated and introduced into the analysis. Clearly, it is very difficult to come up with accurate estimates for

these quantities, not only because they are hard to quantify, but also because in all likelihood they evolved with time in ways that would require careful consideration of the coupling between the fire and structural analysis[2]. However, as will be shown in later sections, to arrive at a qualitative picture, one needs only rough estimates. Moreover, most of the models available for analysis are empirical and apply only approximately to the case in hand since they were derived for smaller scale compartment fires. Such initial estimates can then be used as the starting point to more comprehensive analyses in the future.

Based on the wing span as well as the height and width of the fuselage of a Boeing 767-200 plane, we estimate that as the plane hit the tower, it must have created an hole of approximate dimensions of 50m × 20m, given that the planes hit while banking at an angle with respect to the horizontal plane. Furthermore, the size of the initial compartment inside the tower, created by the severe collision, is estimated to have been 20m high, and covering almost two thirds of the available floor area of the tower, from the outer lattice to the inner core. This is based on the assumption that several floors were damaged by the collision, and the observation that debris were seen flying out of the side opposite to where the plane pierced through the tower. Thus, the initial area of damage is estimated to be about 2000 m^2, or about half of the floor space of the building between the external lattice and the concrete core, and fuel spillage must have occurred over a fraction of this area. We will use these numbers to estimate the temperature inside the tower during the fully developed stage of the fire, based on available models for the dependence of the burn rate in compartment fire on the fuel area, the opening areas, the surface area of the compartment, and other factors described next.

4. Fire stages in compartments

4.1. Initiation

Compartment fires begin at the ignition source, which is located near the primary fuel source, and consume the nearby fuel, initially at a relatively low rate. That defines the pre-flashover stage. Transition from pre- to post- flashover or fully-developed fire occurs as the heat generated by the primary fuel raises the temperature of the rest of the available combustibles to their ignition temperatures, causing them to ignite and participate in the burning. As heat is radiated and convected to the elements walls, structural elements and furniture, depending on their properties, may either ignite directly or pyrolyze first, in which case they give out volatile combustible materials able to burn at a fast rate. Confinement may cause the transition to fully developed conditions, or speed it up substantially because heat is not allowed to escape, and instead both the heat and the combustible material are trapped within the compartment.

When the primary or original fuel is available in large quantities, such as in the WTC case, the first flames inside the compartment are long enough to touch the ceilings and directly heat other combustibles, thus accelerating the transition to flashover. Indeed, much higher burn rates, up to almost an order of magnitude higher in case of hydrocarbon fuels, have been observed in the presence of ceilings. Flames touching the ceiling lead to structural failure, which in turn expands the burn area by increasing the fire intensity. During the pre-flashover stage, fires are mostly ventilation-limited since there is normally plenty of fuel but air is in short supply through the ventilation opening. This, however, mostly reverses as the fire transitions to post-flashover.

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[2] A time-dependent computational crash analysis, followed by a computational fluid dynamics analysis of the fires, which is carefully interfaced with a structural analysis code that accounts for the change in the material properties as it gets heated and/or inflamed, could offer insight and possibly a predictive tool to analyze this and similar problems. This, however is an extremely demanding computational effort.

The observation of a massive fireball outside the WTC Towers soon after the crash may be used to determine that the fires never really existed in a pre-flashover state, as the high momentum jet fuel spilling and sloshing around, following the impact, ignited both inside and outside the building, and continued to burn as long as more fuel evaporated, escaped and supported the fire ball. The contribution of this fireball to the heating of the steel elements on the outside lattice structure can not be ignored, as evidence of some steel melting was suggested by the photographs.

4.2. Transition and post-flashover
Studies suggest that the time needed for transition from localized fires, to post-flashover, fully engulfed fires is shorter for:

   i.   Enclosures that are well insulated where heat is trapped within small volumes.
  ii.   In the presence of large fuel loads, defined as total mass of fuel per unit area.
 iii.   When fuel is spread out uniformly over large areas, increasing the access of air.

These studies also suggest that the growth of the burn rate during this phase is proportional to $(t - t_0)^2$, where t is the current time and t_0 is an incubation period or pre-ignition delay, which must be considered in the absence of an ignition source. The conditions or criteria for transition suggested are either one of the following:

   i.   Heat flux of 20 KW/m^2 reaching the floor, or
  ii.   500-600 °C ceiling temperature.

Given the burning intensity of jet fuel, the high fuel load resulting from the spill of the aircraft fuel in the WTC Towers, and the likelihood that this fuel did spread out widely as a result of the strong impact following the crash, the pre-flashover stage must have lasted a very short period, perhaps no more than few minutes. In the very early moments following the crash, no external flames were visible, instead very large thick smoke plumes followed by the ignition of the fireball. This could have happened because the opening created by the plane crash into the tower exterior was large, the amount of jet fuel and its density were such that the fires were indeed under-ventilated. It should also be mentioned that the massive impact must have acted as a distributed ignition source that set the jet fuel on fire almost immediately, let alone the heat generated as some of the kinetic energy of the plane was dissipated as heat (part of the plane's momentum was transferred to the building as vibrational energy). The hot engines themselves could have acted as powerful ignition sources, placed as they were very close to the jet fuel tanks. It can conservatively be estimated that in the early stages, the burning jet fuel generated at fire power of the order of megawatts, which must have made the transition to fully developed fire very fast indeed. These estimates are based on using 1% of the original fuel, deposited within the initial compartment whose dimensions were estimated as above, and burning at 20% efficiency (that is only 20 % of the available heat in the fuel is released during combustion) due to the lack of sufficient air [2].

5. Severity of fully-developed fires

5.1 Burning Rate
Conditions following the plane crash into the WTC Towers must have lead to fast transition to a post-flashover fire in the interior of the building, supported by or accompanied with a

sustained fireball on the exterior of the building that contributed to the fast rise in the temperature of the material inside. It is important to attempt to estimate the burn rate inside the building and the concomitant temperatures, including that of the fire and the building material. For this purpose, we review some models for compartment fires, and use them in the quantitative analysis.

Experimental evidence suggests that the rate of burning in ventilation-controlled fires, both during the pre- and post-flashover, is proportional to the ventilation parameter $A_w \sqrt{H}$, where A_w is the *window* or opening area that exposes the fuel to a continuous supply of external air, and H is the height of this window above the floor where the original fuel pool existed. Flashover, during which full engulfment is observed, occurs only when this parameter exceeds a critical value. Following flashover, all combustibles participate in the burning and heat release process, and a much faster growth of the fire and a heat release rate are observed. This is due to two factors:

i. More material burns within the original compartment, including both the primary fuel and other combustibles available in the same area, e.g., furniture, supplies, structural material, etc.

ii. The failure of fire-confining elements, such as walls, doors and floors/ceilings, and the spread of the fire from the original compartment to neighboring space creating additional exposure to the outside and thus a bigger supply of air.

Fig. 1: Dependence of burn rate of ethanol pool fire in a small compartment on the opening parameter $A_w \sqrt{H} / A_f$ (values shown on individual curves) and the fuel surface area. Reproduced with permission from [2]

Figure 1 shows some experimental correlations for the dependence of the burn rate on the fuel surface area and the opening parameters (the ventilation parameter normalized by the fuel surface area) [2,8]. These data show how increasing the opening parameter, in the case of a large opening, positioned high with respect to the fuel pool, can impact the burning rate. The

data are shown only for illustration, and will next be extrapolated to estimate the burn rate in the WTC fires (note that the burning rate itself is normalized by the opening parameter).

In the WTC fires, the direct damage done by the plane must have created an interior compartment of several floors in height where the fire started. The size of this compartment depends on the momentum of the aircraft, the vertical and horizontal angles of impact, the elevation where the plane hit, the resistance of the columns and floors to the collision, and the progressive failure of structural elements caused by the fire. It is estimated that the initial height of the compartment could have been about five stories high, based on the size of the plane and its momentum. Damage to the ceilings and floors caused by the early fires must have expanded that volume quickly, both above and below the collision area. Jet fuel must also have flowed downward through building openings, which then contributed to the propagation of the fire to lower elevations. The expansion of the burning area must have continued downward as collapsing floors applied heavier loads onto the floors underneath. Thus, it is estimated that the height of the post-crash compartment could have been 20m.

The opening in the exterior wall, through which the plane sliced into the building, can conservatively be estimated to have been 20m high and 50m wide. The external steel lattice was probably strong enough at the moment of impact that it minimized the size of this external hole. It is more difficult to estimate the extent of the interior compartment, but it may well have been comparable to the floor area facing the crash opening, which is approximately 2000 m^2. The jet fuel must have spilled over a major part of this floor area, perhaps 25-50% of it. The opening parameter defined in Fig. 1, namely $A_w\sqrt{H}/A_f$, is thus in the range of $2 - 5$, where A_f is the fuel surface area. From these numbers, the total surface area of the compartment would have been approximately 10,000m^2. This is only valid immediately after the crash, as subsequent collapse must have resulted in a continuing growth of the compartment area. In the light of this very large fuel surface area, it is clear that the WTC fire parameters far exceed the ranges of prior experimental data. Thus, extrapolation of available burn rates vs. compartment size are necessary.

Performing the requisite extrapolations (in consistent units) on the curves depicted in Fig. 1, we obtain $\dot{m}/A_w\sqrt{H}$. Note that the burning rate is estimated by extrapolation of the available correlations for a different fuel, namely ethanol. The lower estimate for the fuel-mass burning rate in the WTC is thus about 50 kg/s, which leads to a heat power release rate of almost 1 - 2 gigawatts. This number is close to that estimated crudely at the beginning of this article, one the basis of the total amount of available fuel, its heat of combustion, and the overall burn time. These model based predictions are less dependent on the amount of fuel, and do not use the observed burn time.

Attempts to sharpen these fuel burn rate estimates on the basis of other experimental data are shown next, using data that were obtained from alternate experiments and physical modeling assumptions. These data cover a wider range of physical parameters than what was shown before, and hence may be somewhat more reliable. Nevertheless, they still show strong dependence of the burning rate on the opening or ventilation parameters, the fuel surface area, and the total surface area of the compartment. The model shows that the burning rate depends strongly on:

i. The fuel load, defined as the mass of combustibles, especially the primary fuel, per unit area of the total floor. In the case of the WTC fire, the mass of combustibles must also include the combustible plane materials and the building materials in the immediate vicinity of the plane crash.

ii.   The fuel type, with hydrocarbons burning more intensely due to their higher volatility (see Fig. 2, and Refs [2,9]). Jet fuels are hydrocarbons capable of intense burning with high heating values.

iii. The fuel surface area, and how far it is spread horizontally following the initiation of the fires. The spillage of the fuel inside the Towers following the crash must have created an opportunity for a widespread distribution of the jet fuel.

Fig. 2: Compartment fire burn rate for different fuels. While a wide scatter is exhibited, reasonable correlations are observed above the horizontal line close to the classical scaling). Reproduced with permission from [2].

Data obtained from experimental measurements and analytical models have been assembled in the fire science and engineering literature. A sample of accepted data collected from many sources is shown in Fig. 2 [2]. The impact of fuel type, characterized by the heat of combustion and heat of evaporation, on the burning rate has also been delineated in various studies, showing less than an order of magnitude variation in the burn rate as the evaporation rate of the liquid fuel varies by a factor of almost five. Perhaps not as important, but nevertheless strongly present in these empirical correlations, is the dependence on the shape of the compartment and its overall internal dimensions. The strong dependence of the burn rate on

the ventilation factor ceases as $A_w\sqrt{H}$ reaches a critical value, at which point sufficient air is available to burn the available fuel and the fire becomes fuel-controlled. In the WTC, this was probably the case during most of the burning time, because: (i) more destruction to the external steel shell resulted from the post-crash damage and the early fires thus by increasing the fuel available, and (ii) larger values for the opening parameter were achieved.

Because of the complexity of the problem posed by the WTC fires together with the scarcity of data available at the moment of this writing, it is difficult to estimate with much accuracy the parameters needed for the empirical models of compartment fires referred to previously. Moreover, these numbers change with time between the moment of the crash of the aircraft into the building and the beginning of their collapse. However, one may roughly assume that the compartment created by the initial impact is several times the volume of a 767-200 plane, and that the compartment's horizontal footprint spreads over a substantial fraction of the building cross section. The plane pierced through the building at an angle, and hence it is conceivable that the initial cavity created within the tower may have been about five plane heights, while the opening created on the external lattice in all likelihood was comparable to the plane height. Using these estimates, the more elaborate definition of the opening parameters in Fig. 2 has a value in the range of 6 - 15. The numbers obtained from this figure indicate that the burning rate may have been in the range 10-100 kg/s (please note the logarithmic scale). By contrast, in our earlier analysis we obtained nearly 50 kg/s, which falls almost half way between the two new limits on the burning rate. Given the different sources for the two empirical correlations, the agreement between the different estimates is reassuring.

5.2. Fire temperature history: how hot did it get?
The temperature history of a compartment fire, including its spatial variation as well as duration, plays a very important role in determining the structural damage caused by fire. Ultimately, when assessing the impact of a fire, we are interested in how hot the structural elements, including walls, windows, beams, etc., get as a result of the burning of the surroundings, even when the elements themselves are not combustible. A sense of these values can be obtained from Fig. 3, where a compilation of the steady-state temperature of the environment due to a fire inside the compartment, is shown as a function of the previously defined opening factor [2,10]. While the data in this figure were compiled for the burning of wood, they are applicable to other fuels with similar burning characteristics, such as hydrocarbons.

The fire temperature, measured in close proximity to the flames depends on factors similar to those controlling the burn rate, namely:

i. The ventilation or opening parameter, which controls the supply of air to the fuel inside the compartment and the local stoichiometry of the fire.
ii. The primary fuel area, which defines the extent of the fires, at least in its early stages, and total exposed area in the compartment, as defined by the walls, which determines the maximum volumes of the flame before walls are damaged.
iii. The fuel type, as characterized by the heat of evaporation/volatilization, the heat of reaction or the amount of heat released as a unit fuel mass is burned, both of which determine the intensity of the fire and contribute substantially to the burn rate.
iv. The fuel load, or the distribution of combustible material per unit area, including the primary and secondary fuels.

Figure 3 shows measurements of the steady-state fire temperature for some representative fires, collected from many sources [2]. As in most controlled fire studies, wood was used as a fuel and its mass and spread was varied to change the fuel load. The ventilation factor was also varied as it was found to have an important effect on the gas temperature. These data are shown only as representative data for compartment fires, estimate for the WTC fires will be made separately.

Fig. 3: Average gas temperature in a compartment fire (burning wood) and its variation with ventilation. Note that A_T is the total wall area and A is the window opening. Reproduced with permission form [2].

While the minimum observed temperature is 500° C for a poorly ventilated fire with little air supply, temperatures exceeding 1000° C are found at the transition between ventilation-controlled and fuel-controlled burning. The demarcation between the two regimes, as seen in Fig. 3, is defined by the normalized ventilation parameter $A_w\sqrt{H}/A_T$, with A_T being the total wall area without the openings, and the other parameters as defined previously. At this transition condition, the fuel-air stoichiometry is nearly ideal and the fire burns fast. Maximum temperatures are observed for values of the ventilation parameter in the neighborhood of 10, expressed in the units of Fig. 3. It is interesting to observe that the fire temperature falls slowly as more air becomes available, and that the range of maximum temperatures of 800-1100° C prevails for a very wide variation of the opening or ventilation parameters.

Most compartment fires exhibit external flaming following a brief period of post-flashover burning, if sufficient fuel is available. During external flaming, bright intense flames are seen to burn steadily from the windows, extending the reach of the fire to the outside walls of the compartment. External flaming is a sign of high fuel loads in the compartment, and fire plumes carrying high temperature products to the exterior of a building is an ominous sign. Temperatures observed during events of external flaming show strong dependence on both the fire area A_F and the ventilation parameter. In the WTC fires, the intense fireballs observed at

the early stages, as well as later, may be thought of as a form of external flaming that exposed the outside walls of the Towers to direct flaming. The early fireball in the WTC fires most likely resulted from the early violent sloshing of the jet fuel following the strong impact and the residual momentum in the spilled fuel. The early disintegration of the fuel tank, not far from the area of collision, would have distributed the jet fuel throughout the crash zone, and left plenty of it near the area where the planes pierced into the Towers. Immediately afterward, a fireball would ensued, consuming this fuel. Later, as the interior fires expanded to include all combustible material, flames again extended through the exterior openings.

In light of the early estimates made for the WTC parameters, $A_w \sim 1000$ m^2, $H \sim 20m$ and $A_T \sim 10,000\text{-}50,000$ m^2, we obtain a total-area-based ventilation parameter $A_w\sqrt{H}\,/A_T$ in the range of 0.4 - 2.0, implying that temperatures in the vicinity of 1000° C are not unlikely to have been reached during the massive fires in the WTC Towers.

Fires do not burn steadily since the available fuel is progressively and rapidly consumed once flashover starts, including both the primary and the secondary fuels. In addition, the dimensions of the openings providing ventilation air continuously increase as fire damage exacerbates the building structure and challenges its integrity. At the same time, the original compartment grows in size as protective walls, ceilings and floors fail to withstand the assault of the fire, in a multi room and multi story building. Eventually, as more of the building material becomes flammable, the fire becomes fuel controlled, and the fuel load starts to decrease, leading to a concomitant decrease in temperature. This is shown in Fig. 4 for a sample fire [2,11], which also illustrates the expected and close correlation between the burn rate of the fuel and the prevailing fire temperature.

Fig. 4: Measured and modeled temperature history for a compartment fire burning wood, 96 MJ/m2 load and opening factor or 0.068 m1/2. The insert shows the burning rate for the same fire. Reproduced with permission from [2].

The history of the fire temperature demonstrates strong time-dependent trends and depends on: the opening factor, the fuel load, the thermal properties of the compartment walls, and the fuel type. The temperature estimates obtained via correlations derived from experiments and modeling studies of compartment fires, are based on spatial averages for the temperature in the compartment, in the neighborhood of the flaming zone. In general, the temperature is not uniform but may vary strongly between the location where the flames burn and the location where the combustion products mix with cool ventilation air. This average values of the fire temperature has been used to estimate the convective and radiative heat fluxes to the structure as well as the conductive heat loss through the walls. etc. In a post-flashover fire, with external flaming visible from nearly every available opening —as in the case for the WTC during the stage an external fireball was seen— flames totally engulf the outside of the building and a steep, substantial rise in the external temperature takes place. Figure 4 shows the sharp temporal variation of temperature in a typical compartment fire, measured within the compartment [2,11].

Fig. 5: Impact of fuel loading in MJ/m2 and opening factor on gas temperature history in compartment fire. Reproduced with permission from [2]

Depending on several parameters, e.g., the fuel load and the fuel type, fuel spread within the compartment, the opening parameters and ventilation factors, the gas temperature inside the compartment may rise quickly to values in the range of 600°-1100° C, then fall slowly as the primary and secondary fuels are consumed within the fire. The fuel load exerts the strongest influence on the maximum temperature reached and the duration of burning at, or

close to that temperature. The higher the fuel load, the higher the maximum temperature, which exceeds 1000° C for well ventilated fires (i.e. $A_w \sqrt{H} / A_T \sim 0.1$) and with fuel loads, measured as total heat per unit area, exceeding 1000 MJ/m^2, or 20-50 kg/m^2. For these conditions, the fire temperature remains above 1000° C for more than one hour. Table 10.2 in Ref [2] and the set of comprehensive curves in Fig. 5 can be used to estimate the temperature history for a given opening factor and fuel load [2,11]. It should be emphasized that the total load is measured during post-flashover when every available combustible inside the room is inflamed and is actively participating in the fire. Please note that the rise time of the temperature is weakly dependent on the conditions! In well-ventilated fires, the temperature reaches its maximum value within 15-30 minutes of the start of the fires. Moreover, high-powered fires sustain the highest temperatures for a longer period of time, after which the temperature drops more slowly than in the case of weaker fires, creating more dangerous conditions for the buildings, inhabitants and fire fighters.

The preliminary estimates of fuel load for the WTC fire given earlier imply heat loads of the order of giga-Joules/m^2. Furthermore, the estimates of total area-based ventilation parameter is in the range 0.4-2.0, again confirming that the highest possible interior fire temperatures could have been reached, possibly exceeding 1000° C, as seen in Fig. 5. Such temperature could cause glowing, softening and melting.

Fig. 6: Temperature history for compartment fires (burning hydrocarbons) for different fuel load, given in Kg/m^2, and ventilation expressed as % of one particular value of wall opening. Reproduced with permission from [2]

Figure 6 shows temperature histories for burning hydrocarbon fuels —which are similar to jet fuels— for different fuel loads, given in terms of fuel mass per unit area, and ventilation openings, expressed as a fraction of a standard opening [2,12]. Higher fuel load dramatically increases the fire temperature, and less ventilation slows down the temperature rise but achieves higher values. Given the estimates for the amount of fuel in the plane, and

the surface area of the initial damage zone, a fuel density of 30-60 kg/m^2 is not unlikely for the initial stages of the WTC fires. The figure also includes the standard temperature curve used to estimate the impact of a hypothetical fire on a structure. Note the significance of the fuel load in determining the duration of a severe fire, or the length of time during which the temperature remains dangerously high. This duration may even be a more important consideration than the exact value of the fire temperature in determining the fire damage to the structure. Moreover, both factors grow hand in hand; hotter fires seem to last longer, although the rise time is almost the same whatever the intensity of the fire is. In all cases shown, reducing the opening by 50% increases the temperature and duration. It is likely that a large opening introduces more air and results in a fuel-lean burn (that is, less fuel than required for stochiometric burn). Reducing the air supply also reduces the burn rate and increases the fire duration.

Fig. 7: Temperature history of the fire, measured at the ceiling steel bean. The fire load is 100 MJ/m^2, and the opening factor is 0.08 m$^{1/2}$, subscripts f and S correspond to fire, and steel Reproduced with permission from [2].

When calculating the history of the fire temperature, it is important to remember that what matters for the structural integrity of buildings, in this case the WTC Towers, is the time history of temperature of the steel columns and floor trusses, which were initially protected by fireproofing materials, but in time lost this protection. Input to these structural elements is the total heat flux, composed of radiative and convective fluxes, which they receive from the radiation and convective fluxes that may be very significant if the fire is raging in the immediate vicinity of the structural elements. Calculations show that steel may reach temperature close to 550° C in 15-17 minutes following the start of a fire, when exposed to a standard fire source. More significantly, a steel girder exposed to a fire of 100 MJ/m^2 and an opening factor of 0.08 reaches 650° C during the first 15 minutes, and remains at temperatures higher than the fire from then on, because steel loses heat slowly by convection while the fire runs out of fuel and its temperature decays fast. Given the current lack of data describing in sufficient detail the conditions inside the Towers, it is not possible to apply similar analysis to them, e.g., the interior steel columns that constituted the core structure of the Towers, or the structural elements of the upper floors. Figure 7 shows an example of the temperature history in a fire occurring in a compartment whose ceiling is made of steel girder carrying precast concrete floor units on the bottom flange [2]. The figure shows the relative rise time of the fire and steel column temperatures, and that while the steel temperature is below that of the fire at the early stages, it stays higher at the later stages.

6. Conclusions

The analysis presented here was based on simplifying assumptions that reduced the problem to that of a compartment fire, albeit of a much larger scale than anything that has been analyzed before. Further simplifications have been applied to estimate the values of the various parameters that appear in compartment fire models, and allowed estimates for the burn rate and the temperatures to be obtained. Preliminary results, based on approximate estimates of the fire conditions following the crash of the planes into the WTC Towers and the initial damage caused by the impact, shows that the fires generated very significant heat release rates and the fire temperatures were likely to have exceeded 1000° C. Given the amount of fuel available at the moment of the crash, such temperatures are likely to have lasted long enough to raise the temperature of the building material to dangerously high levels, and hence for the fires to have contributed significantly to the weakening of the towers structures and their collapse, contrary to some early speculations.

The next step in assessing the contribution of the fire to the collapse of the Towers is to define the fire conditions more precisely, e.g., the initial size of the exterior wall opening created by the crash, the volume and surface area of the initial impact zone, the initial distribution of the jet fuel and other combustible material, and the fraction that participated in the initial fireball, etc. Conditions must have changed rapidly due to the further weakening of the structure, the caving-in of the floors and the seepage of the jet fuel downward, which must have also changed the fire conditions and have strengthened the fire as more air was fed through the damaged exterior walls. Results of a study of the crash and the dynamics of the structural failure that followed can provide the necessary input to update the fire conditions and will lead to better estimates of the temperature history of the fire and the surrounding structures. The strong coupling between the progress of the fire and the further damage to the structure should be considered next, in a modeling analysis in which a two-way interaction is maintained. Such complex analysis must rely on powerful computational models, running on state of the art computational facilities of very high sustained speeds.

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