

Fire Safety in High-rise Buildings, Lessons Learned from the WTC

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Abstract

This paper addresses the tragic events of September 11th, 2001. Provides a brief background on the philosophy of fire protection for high-rise buildings and the behavior of a fire within a compartment. It further describes the events and the particular scenario corresponding to the World Trade Center. No attempt is made of providing a description of what caused the collapse but the objective is more to illustrate the characteristics of the fire and highlight the possible uncertainties. The paper concludes with a list of lessons learned and questions yet to be answer but fundamentally, with a plea for a detailed analysis of this event and a subsequent plan for fire research. Understanding the mechanisms that led to the collapse of the World Trade Center will enable engineers to provide a safer environment for the users of similar and other types of buildings but also for the firemen that sacrifice their lives trying to save the lives of other people.

1. Introduction

From the perspective of a Fire protection Engineer, the design of a building can be approached in two different ways. The first is for the building to comply with existing regulations, and the second one is to achieve certain safety goals. Regulations have not been developed to fully specify the design of unique and complex buildings such as the World Trade Center and even, in the event that they existed, they are of questionable effectiveness. Furthermore, if a scenario such as the one of September 11th, 2001 needs to be considered as a possible event during the life of the building, design on the basis of safety goals is the only path that can be followed.

Fire, % Evacuated, % of Total Structural Integrity, etc.

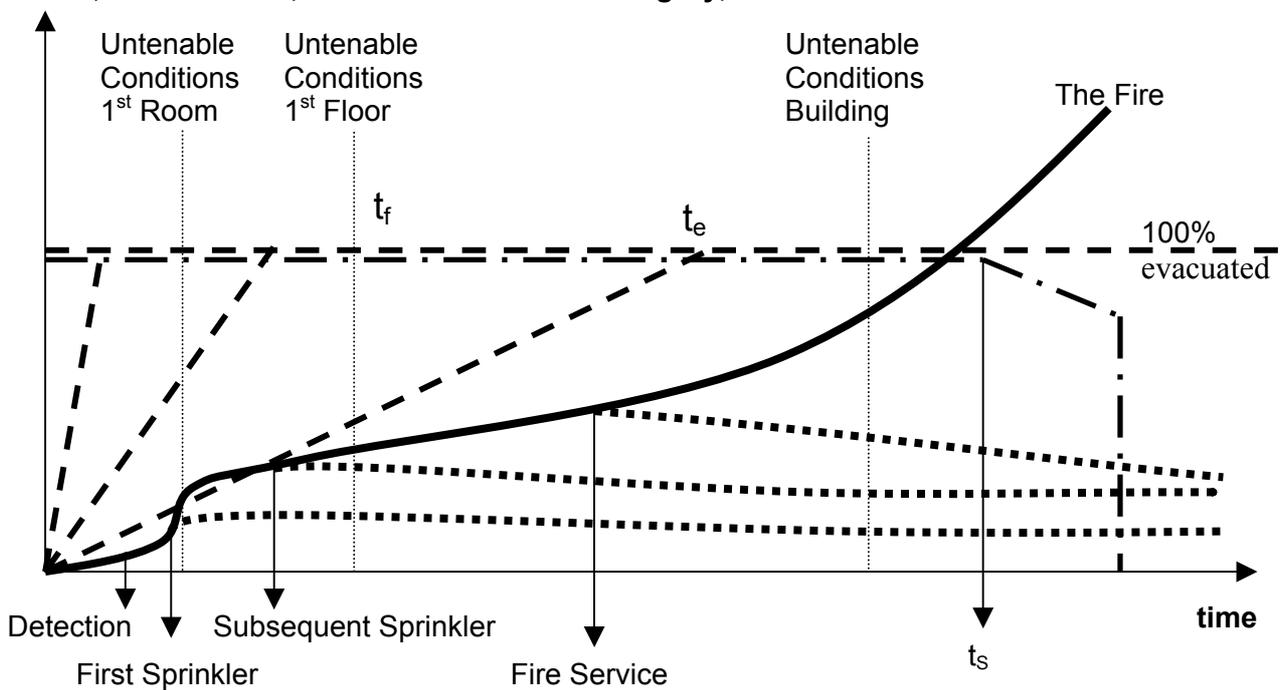


Figure 1 Schematic of the sequence of events following the onset of a fire in a multiple story building. The thick line corresponds to the “fire size,” the dotted lines to the possible outcome of the different forms of intervention (sprinkler activation, fire service). The dashed lines are the percentage of people evacuated, with the ultimate goal of 100% represented by a horizontal dashed line. The dashed & dotted line corresponds to the percentage of the full structural integrity of the building.

The schematic presented in Figure 1 could represent the behavior of a building in the event of a fire. It could be argued that the safety objective should be that the time to evacuation (t_e) at each compartment (i.e. room of origin, floor, building) be much smaller than time necessary to reach untenable conditions in the particular compartment (t_f). Characteristic values of t_e and t_f can be established for different levels of containment, room of origin, floor,

building. Furthermore, it is necessary for the evacuation time to be much smaller than the time when structural integrity starts to be compromised (t_s).

In summary:

$$t_e \ll t_f$$

$$t_e \ll t_s$$

It could be added to these goals that full structural collapse is an undesirable event, therefore:

$$t_s \rightarrow \infty$$

Although these criteria for safety times can be considered as a simplified statement, it is clear that it describes well the main goals of fire protection.

With the objective of achieving these goals a number of safety strategies are put in place. These include those strategies that are meant to increase t_f which include active systems, such as sprinklers, or the intervention of the fire service. As shown by Figure 1 (dotted lines), success of these strategies can result in control or suppression of the fire. Passive protection such as thermal insulation of structural elements becomes part of the design with the purpose of increasing t_s . Finally, but most important, evacuation protocols and routes are design to minimize t_e at all stages of the building. It is important to note that within the estimation of t_e the safe operations of the firemen need to be included.

The events following the attack on the World Trade Center showed that these safety goals were not attained. It is therefore important to seek the best possible understanding of why this happened. For this purpose an adequate understanding of the nature of the event and the characteristic of the structure and its safety systems is necessary. This paper will attempt to highlight the different elements that have to be studied to reach appropriate conclusions, the need for an exhaustive investigation of this event and to put in perspective how this information can be used for the safety evaluation and design of similar buildings.

Up to now there has been a preliminary investigation conducted by the American Society of Civil Engineers (ASCE) and sponsored by the Federal Emergency Management Agency (FEMA). It has been dubbed a “building performance evaluation”. Their report is scheduled for official release at the end of April. The Congress has held one hearing on the status of the investigation and is advocating for the National Institute of Standards and Technology (NIST) to conduct a deeper technical investigation, but no funds have been allocated yet. Some have advocated for a US national commission (e.g. the Skyscraper Safety Campaign, link at www.HeroWTC.org). Agencies with investigative mandates such as the National Transportation Safety Board (NTSB) and the Bureau of Alcohol Tobacco and Firearms (federal arson) were not involved. Hence, the preservation of data and information has not occurred. The recycling

sale of the steel from the WTC has upset many (NY Daily News, Jan 17, 2002). By the time this paper is presented, we may see the official FEMA report and NIST may then be involved. But the sensitivity for urgency in an investigation of the cause of the WTC buildings collapses has not been evident.

2. Data gathering

2.1. Buildings

2.1.1. Background on Compartment Fires

A fire has a significant effect on a structure but the characteristics of the compartment that encloses the flames also have an impact on the nature of the fire. Temperatures within the compartment and duration of the fire are defined by the supply of fuel and oxidizer as well as being affected by heat transfer through the compartment boundaries. Fuel generation, in turn is the result of energy feedback from the flames. Both thermal and oxygen-limiting feedback processes can affect the fire in a compartment. In the course of fire safety design or fire investigation in buildings, all of these effects, along with fire growth characteristics of the fuel, must be understood. The ability to express the relevant physics in approximate mathematics is essential to be able to focus on the key elements in a particular situation. The accuracy of such approximate analyses are usually sufficient, especially when their consistency is confirmed by other information, e.g. witnesses, alarm records, video, etc.

A fire undergoes a series of processes from its inception, through spread and growth to its fully developed stage. A singularity in the growth process is the event of “flashover.” Here, “flashover” is defined as a transition, usually rapid, in which the fire distinctly grows bigger in the compartment. The “fully-developed” state is where all of the fuel available is involved to its maximum extent according to oxygen or fuel limitations. The growth of a fire is generally described through a two-zone model (Figure 2(a)) where the fire through a cold lower zone entrains air and products of combustion migrate to an upper layer. Pressure in a compartment fire is considered to be atmospheric and flows occur at vents due to hydrostatic pressure differences [1,2]. For the scenario of this paper, the fully developed fire is of more relevance and is presented in Figure 2(b). In this case the flow can be modeled via a single zone and the use of the ideal gas law in conjunction with conservation of energy and mass.

The onset of flashover is considered to be induced by thermal effects associated with the fuel and its configuration, the ignition source, and the thermal feedback of the compartment. A “thermal-runaway” will occur at a critical temperature and the result of this critical event will lead to a fully-developed fire. For the present scenario it seems relevant to assume that the onset of the fire is that of flashover the fully developed fire is the one in need of evaluation.

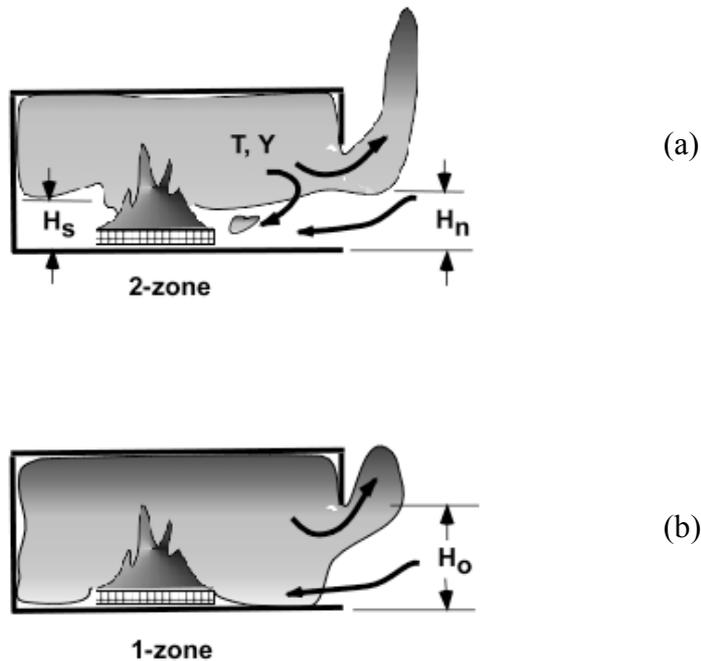


Figure 2 Stages of fire growth (a) growth period represented by a two zone model (b) fully developed fire represented by a single zone model

The fully developed compartment fire is defined as the ultimate (not always maximum) state of burning and either the fuel available or the ventilation determines its characteristics. The fuel available is determined by the burning rate and the ventilation is generally defined by a ventilation factor that is associated to the size of the openings of the compartment. Although significant research has been done to establish the characteristics of fully developed compartment fires [3] many questions of relevance to the scenario of the World Trade Center still remain with no answer.

The C.I.B. (International Counsel for Buildings) undertook one of the most comprehensive studies on the subject [4]. Wood cribs were used as fuel and although this arrangement has particular burning characteristics the observations serve to illustrate the main factors controlling a fully developed fire. This study used scales of $H=0.5$ to 1.5 m, and the cribs nearly covered the entire floor. The burning rate results are presented in [5]. For wooden cribs in a compartment, the area of the vertical shafts of the crib, $(HA_o/A)_{\text{crib}}$, and the ventilation factor of the compartment, $A/A_o\sqrt{H_o}$, control the oxygen flow through the crib. For limited oxygen the ventilation factor controls the burning rate ($A_oH_o^{1/2}/A=0.02$ m^{1/2}) and a constant burning rate is observed for different vertical shaft areas. With sufficient oxygen ($A_oH_o^{1/2}/A=0.114$ m^{1/2}), the exposed surface area of the sticks controls the burning rate and therefore the burning rate increases with $(HA_o/A)_{\text{crib}}$.

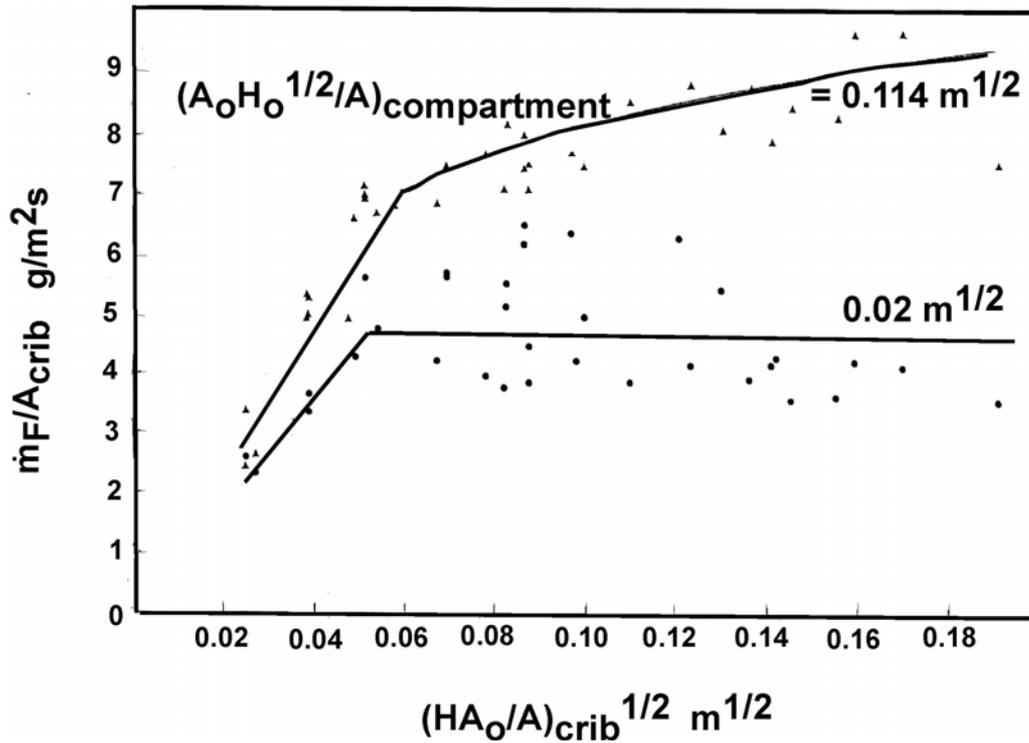


Figure 3 Wood crib burning behavior in a compartment based on the total crib surface area, from Thomas and Nilsson [5].

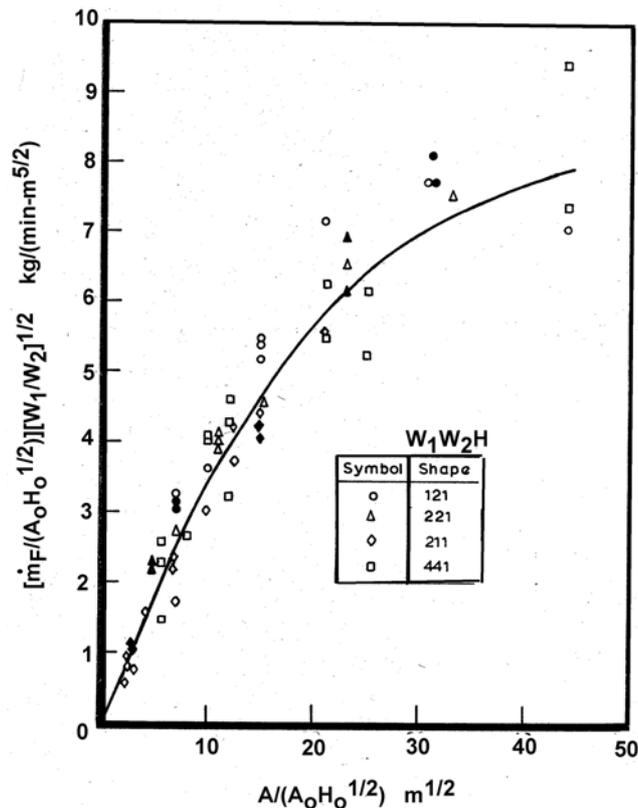


Figure 4 Wood crib burning rate in the CIB study.

The aspect ratios of the floors in the World Trade Center would have lead rapidly to a ventilation-limited state. In this particular condition the burning rate of fuel could have been expected to attain an asymptotic steady-state value rapidly. Figure 3 shows a plot of the asymptotic burning rates for ventilation

limited wood crib fires. As can be noted, the burning rate is strictly dependent on the incoming air or ventilation factor. It is important to note that these empirical relationships between the burning rate and the ventilation can be supported by simple analytical expressions allowing for the calculation of the conditions within the compartment.

If the burning rate can be established then, knowing the heat of combustion, the energy release rate can be calculated and thus the temperature of the compartment. An element that still remains un-addressed is the fraction of the energy that remains within the compartment.

It is important to consider the conditions that promote the maximum possible compartment temperature from a structural fire protection interest. Standard structural fire testing exposes elements to about 900 °C in 1 hour and up to 1100 °C by 4 hours. The expectation of these standard tests could well be defined as providing a worst-case fire scenario. Comparison between a realistic scenario and the design constraints can give some insight to the possible behavior of the structure.

The maximum gas temperature will occur under adiabatic and stoichiometric conditions, nevertheless, these temperatures, which are available in any combustion textbook, might be unrealistically high. Recorded gas temperatures near the ceiling are reported as high as 1350 °C [6], and mean temperatures over the peak burning period of 1000 to 1200 °C for polyethylene fires [6] and about 900 °C to 1200 °C for wood cribs [7]. Figure 5, from Thomas and Heselden [7], gives estimates of the temperatures that could be expected for wood cribs in small scale (1 m high) compartments. Expressed in terms of the ventilation-factor and surface area, the results are hoped to be scale independent. However, theory suggests that fuels with higher heats of combustion will give higher temperatures, and that scale can affect adiabaticity with a maximum possible adiabatic turbulent flame temperature of 1500 °C [8].

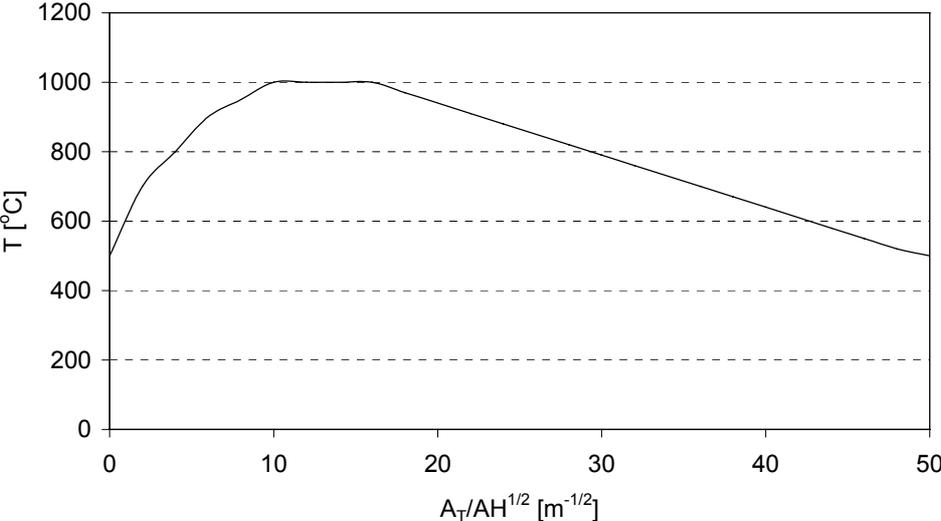


Figure 5 Time mean temperature near the ceiling. Where A_T is the total area excluding floor an opening, a the window area and H the height of the window. The fuel loads for these tests are in the range 20-40 kg/m² that is smaller but nevertheless comparable to what would be expected in a modern office.

Different temperature correlations are available for fire plumes [9,10,11] which can be established analytically by using an appropriate radiative fraction, X_r . From the best available data as the fire diameter increases, the radiative fraction falls due to soot blockage [12]. Flame temperature data for turbulent plumes as a function of X_r shows an increase in temperature as X_r decreases. The extrapolated adiabatic temperature is about 1500 °C ($X_r \approx 0$) as proposed by Thomas [8]. For a large fire in a compartment with large vents, the core maximum flame temperature could approach this value.

The theoretical arguments leading to temperatures of 1500°C remain to be validated by appropriate experiments. In a similar way, the experimental values presented above are for a limited number of fuels, i.e. wood cribs, and discrepancies can be expected with variations in the fuel. Data on other fuels is limited for fully developed compartment fires, especially data relevant to a combination of liquid fuels and office fuel loads. The absence of this empirical information poses a significant limitation to the evaluation of the uncertainty involved in any attempted calculation for the World Trade Center scenario.

2.1.2. Fuel Load

Based on the above discussion it is important to establish the fuel load within the building. There are two sources of fuel, one is the aircraft fuel, and the other is the fuel inherent to the building.

- Aircraft fuel once ignited resulted in a “fire ball” mostly outside of the building. The question to be addressed is how much of this fuel burn outside, what fraction burned inside and what was its impact on the growth of the fire.
- The fuel within the building could be considered a typical office space building. Numbers quoted for this type of office are approximately 40-60 kg/m².

Except for scale effects, there is no reason to believe that the temperatures inside the floor of the WTC fires would be bigger than those given by Figure 5. The only area where temperatures could be expected to be slightly higher is the area close to the windows where flames projected through openings have been found to reach up to 1200 °C [13]. But limited flaming is seen from the WTC windows from available videos. To date there has been no systematic archiving or review of the video records of this event. Indeed some footage may have been suppressed.

Here it is of importance to add that the outcome of this event should serve to encourage us to question the completeness of Figure 5. The analysis of the previous section raises the question of how applicable this data could be to a scenario such as the World Trade Center, the outcome validates this question and pushes us to insist that further research should be conducted.

NIST is employing their CFD fire code, Fire Dynamics Simulator [14], to calculate aspects of the fire. The accuracy of these calculations is questionable

since the code has not been validated for such fires, but can and will be an indispensable tool if NIST obtains support for the investigation.

2.1.3. Construction

The plan area of the two main towers of the building complex formerly known as the World Trade Center in New York was quadratic (Figure 6) with each side measuring 63.5 meters in length. Each of these towers was 411 meters high and contained 110 stories.

Their uniqueness within the skyline of New York was not only an optical but also a technological one. The applied tube construction (Figure 7) is a structural form of construction that is optimal for very tall buildings. It provides the required strength and stiffness by utilizing:

- A rigid perimeter frame (framed tube) to carry all wind loads and resist all overturning forces, and
- A coaxial running central core that took solely the gravity loads of the building.



Figure 6 Isometric View of WTC [15]

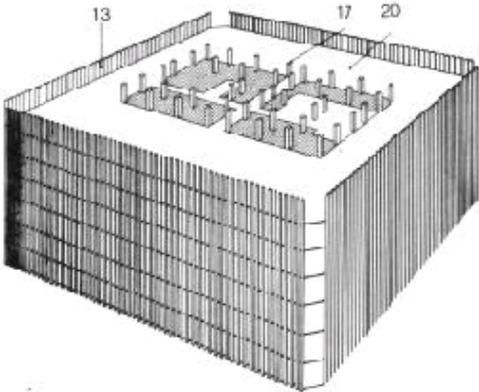


Figure 7 Isometric View of Building [16]

- 13 – Perimeter frame
- 17 – Core box columns
- 20 – Floor

This principle resulted in a very light and economical structure. It kept the wind bracing in the most efficient place (the outside surface of the building) and did not transferring the forces, as in most curtain-wall structures, through the floor membrane to the core.

Each of the four 63.5 meters long sides of the plan area quadrate, that formed the perimeter frame, consisted of 59 Exterior Box Columns (Figure 8) that were spaced on approx. 1 meter center and interconnected. Window glazing 0.56 m was between each exterior column, and framed by aluminum alloy-sheathed piers each 0.48 m wide (“Sometime Lofty Towers”). Each of the four sides of the perimeter frame were interconnected with their perpendicular standing counters sides forming, together with the floors, a momentum rigid framed tube that was fixed to the foundation.

The central core (Figure 9) ran coaxial within the frame tube and spanned over a rectangular area of 24 by 42 meters. The core contained 44 Core Box

Columns that were designed to carry the vertical loads only, and hosted the access and services.

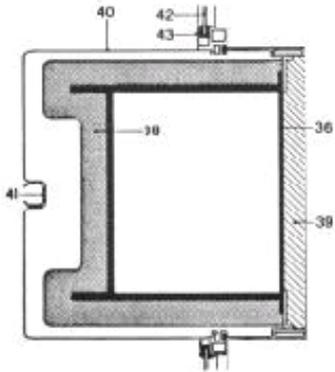


Figure 8 Exterior Box Column [16]

36 – Steel column
38, 39 – Fire resistant plaster

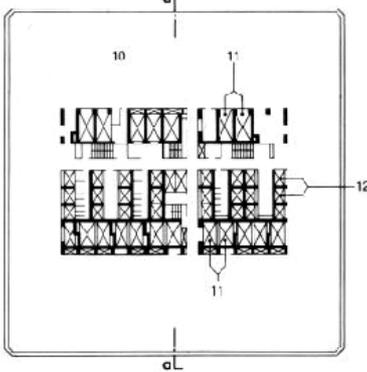


Figure 9 Plan View of Typical Floor [16]

11, 12 – Lifts
10 – Open plan offices

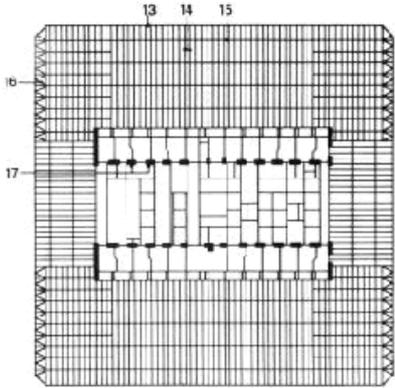


Figure 10 Structural System for Typical Floor [16]

13 – Perimeter frame
14 – Bar joists
15 – Secondary joists
16 – Horizontal floor bracing
17 – Core box columns

In between the perimeter frame and the central core the floor, constructed of prefabricated trussed steel (900 mm deep bar joists), spanned over the full 18.3 meters, braced by secondary joists (Figure 10). These joists acted as a diaphragm to stiffen the outside wall against lateral buckling forces. The secondary joists supported a profiled deck on which a 100 mm thick light-weight concrete was poured.

Figure 11 and Figure 12 give an additional insight in respect to how the structure of the two main towers of the World Trade Center was constructed. The floor-truss system was not supported by the columns directly, but was connected by bolts and welded flange connectors to the columns. These connections would only be able to support the combined load of several floors. They may have been the weakest link in the progressive collapse that occurred.

Passive fire protection was provided to the structure:

- Possibly by applying vermiculite plaster to the columns, and
- There is some unconfirmed report of a fire rated suspended ceiling to the underside of the floor systems.
- The steel floor truss system was sprayed with mineral fiber.

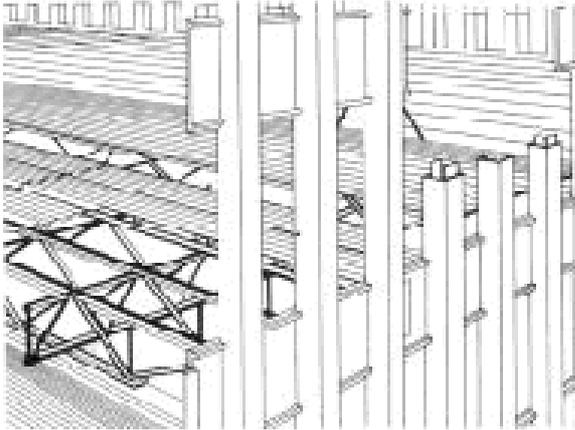


Figure 11 Isometric View of Floor and Exterior Wall System [17]



Figure 12 View of Floor and Exterior Wall System from within the building [15]

2.2. Airplanes

The two airplanes that were part of the World Trade Center event on September 11th, 2001 belonged to the Boeing 767 family. The Boeing 767 family is a family of airplanes designed to providing maximum market versatility in the 200- to 300-seat market range in which the Boeing 767-200 is the smallest of it's kind.

Table 1 contains the basic technical characteristics of a typical Boeing 767-200 applicable for the entire range of aircrafts.

Seats	181 – 255	
Cargo	2875 ft ³	81.4 m ³
Engines		
• Pratt & Whitney	63300 lb	28713 kg
• General Electric	62100 lb	28169 kg
Maximum Fuel Capacity	23980 U.S. gal	90770 l
Maximum Takeoff Weight	395000 lb	179170 kg
Maximum Range	6600 nautical miles	12220 km
Typical Cruise Speed at 35,000 feet	530 mph	850 km/h
Basic Dimensions (Figure 13)		
• Wing Span	156 ft 1 in	47.6 m
• Overall Length	159 ft 2 in	48.5 m
• Tail height	52 ft	15.8 m
• Interior Cabin Width	15 ft 6 in	4.7 m

Table 1 Characteristics of the Boeing 767-200 [18]

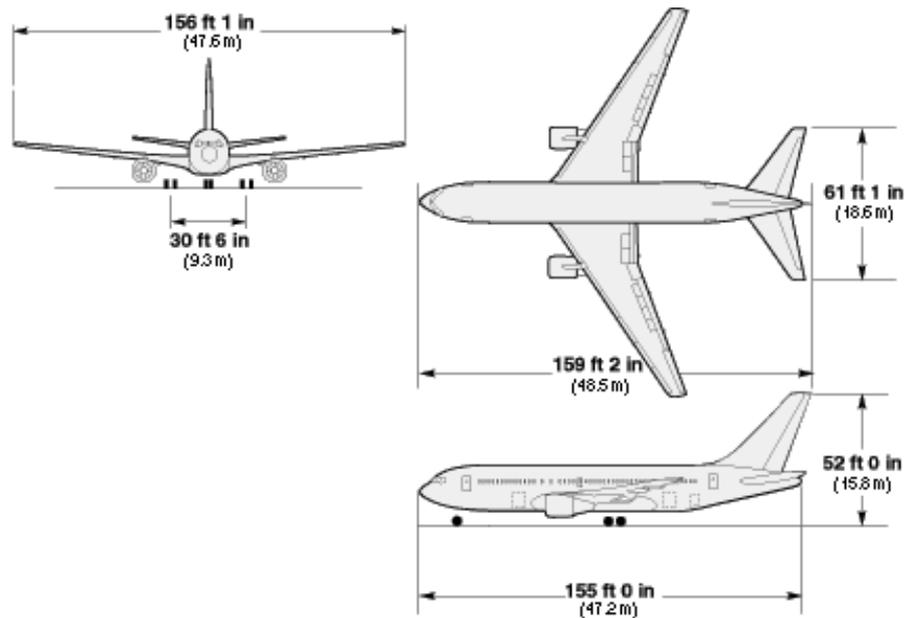


Figure 13 Basic dimensions of a Boeing 767-200 [18]

The specific characteristics of the two disaster planes can be found in Table 2.

Airline	United Airlines	American Airlines
Flight Number	175	11
Aircraft Boeing	767-222	767-223ER
Registration	N612UA	N334AA
People on board at time of accident	65	92
Fatalities	65	92
Manufacturer Serial Number	21873	22332
Line Number	41	169
Engine Manufacturer	Pratt & Whitney	General Electric
Engine Model	JT9D-7R4D	CF6-80A2
Year of Delivery	1983	1987

Table 2 Specific airplane information [19]

2.3. Incidents Facts

2.3.1. Initiation

2.3.1.1. North Tower Crash

On the morning of the 11th September, American Airline's flight 11, operated by a Boeing 767-223ER, departed at 7:59 from Logan International Airport in Boston, Massachusetts for a more than 5 hour flight to Los Angeles, California. On board the aircraft were 81 passengers (including five hijackers), nine flight attendants, and the two pilots. Shortly after its departure, flight AA11 disappeared from the radar screens of the Federal Aircraft Administration

(FAA), and ceased responding to radio calls from air traffic controllers. At 8:45 the aircraft was flown into the side of the north tower of the World Trade Center between the 80th and 90th floor. The speed of the aircraft at impact has been estimated at 650 km/h⁻¹. This impact led to a severe structural damage within the tower, and collapse occurred 104 minutes later at 10:29.

2.3.1.2. South Tower Crash

On the morning of the 11th September, United Airline's flight 175, operated by a Boeing 767-222 departed at 8:14 from Logan International Airport in Boston, Massachusetts for a more than 5 hour flight to Los Angeles, California. On board the aircraft were 56 passengers (including five hijackers), seven flight attendants, and the two pilots. Shortly after its departure, moments after its crew had reported suspicious radio transmissions from another flight to Boston, Flight 175 disappeared from the Federal Aircraft Administration (FAA) radar screens, and ceased responding to radio calls from air traffic controllers. At 9:03 the aircraft was flown into the south tower of the World Trade Center, between the 65th and 75th floor. The speed of the aircraft at impact has been estimated at 650 km/h⁻¹. This impact led to a severe structural damage within the tower, and collapse occurred 47 minutes later at 9:50am.

In terms of mass, each aircraft was estimated as 170 tons, and hit a tower weighing about 750,000 tons. This impact is analogous to a 1-ounce sparrow hitting a 275-pound person. Indeed, in an article in the NY Times (March 29, 2002) reporting on a leaked version of the forthcoming FEMA report stated that the building had a "remarkable ability to redistribute the load to those [columns] that remained intact. This rearrangement was so efficient, the calculation show, that stresses on columns no more than 20 feet from the hole punched in the tower's face were barely higher than what they were before the impact."

A sequence of images that describe the South Tower impact and the fire that followed the North Tower crash is presented in Figure 14. These images were extracted from reference [19].

2.3.2. Response

We will not elaborated in detail on the fire fighter response since Firehouse magazine does a very good job at relating the facts and issues (April, 2002) [20]. Following the impact of the second aircraft, the first recall of the entire NY City fire department in more than 50 years was made. This was more that 11,000 uniformed personnel involving 203 engine companies and 143 ladder companies. In the collapses, 343 fire fighters were lost and 25 engines and 15 ladder companies were destroyed. The situation quickly became one of rescue, since the water system had likely been destroyed and suppression was not viable. Additional issues were the cross flow paths on the stairways between the fire fighters and the occupants, height limited radio communications and other factors. It is indicated that firefighters were being told to evacuate about 25 minutes before the North Tower collapsed ([20], p.94). Before the collapse,

firefighters experienced warnings: “Suddenly the building started to shake.” (Ibid, p 86), “the building shook violently, damn near knocked you off your feet. You could hear a faint sound of a rumble. ... It lasted maybe about four seconds and then it go quiet and lighting went out and the emergency lighting came on.” (Ibid, p.81). A coordinated timeline of these indications could be invaluable in determining the nature and cause of the collapses.

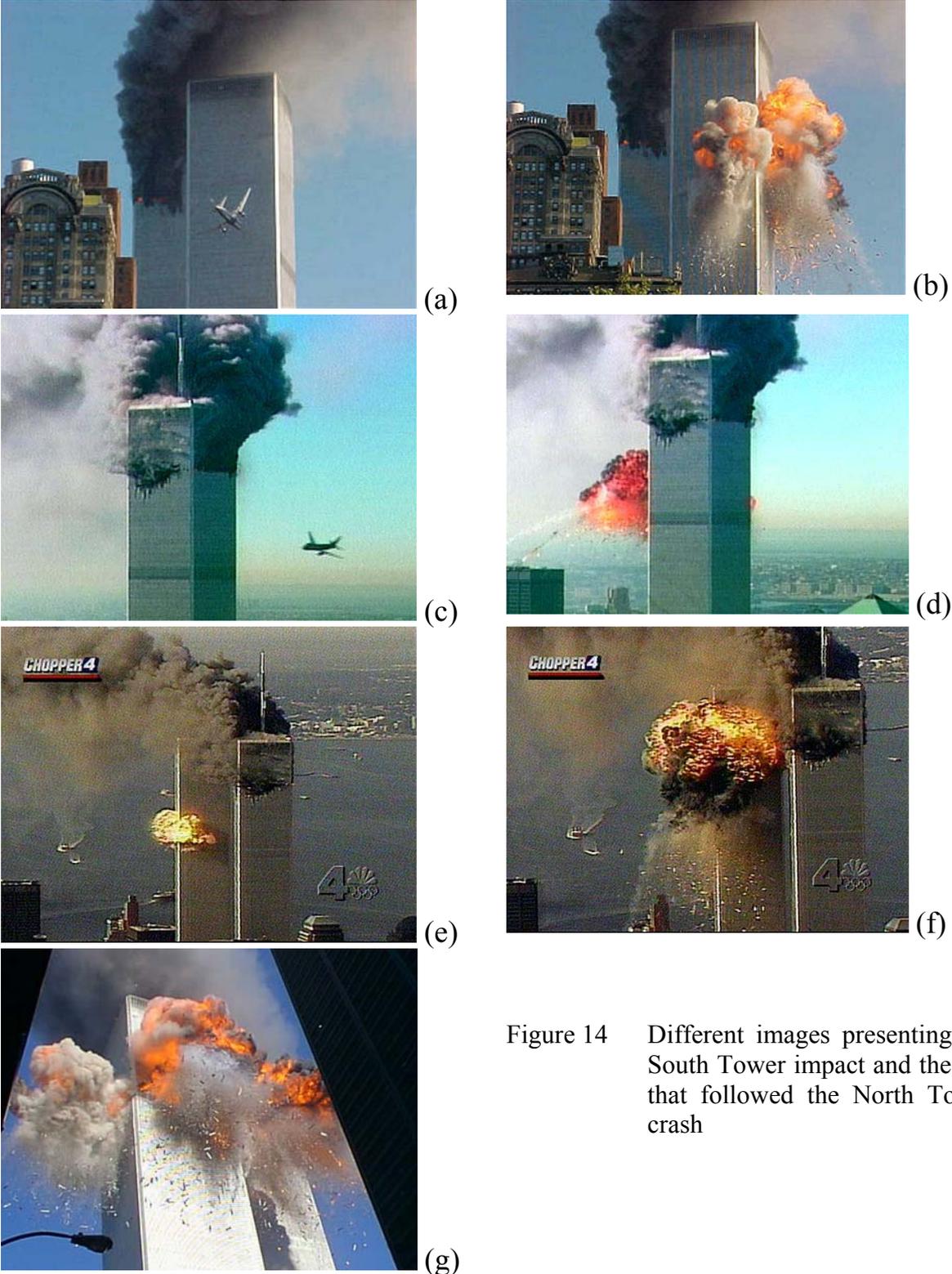


Figure 14 Different images presenting the South Tower impact and the fire that followed the North Tower crash

3. Fire characteristics

3.1. Burning Behavior

Much can be speculated on the way burning occurred throughout this event, nevertheless it seems clear that the intensity of this fire was not much different than that of other high rise fires (First Interstate Bank Building (Los Angeles) or Meridian Plaza Building (Philadelphia)). These others did not lead to collapse, yet the Meridian Plaza had severe damage and had to be demolished. It is clear that in the evaluation of the WTC fire it is important to consider the contribution that the different fuel sources might have had.

The aircraft fuel has been singled out as being the origin of an “unusually hot” fire, but these statements can be challenged on the basis of plume fire temperatures that are weakly affected by fuel type, and on the overall role of the jet fuel. What is clear is that the presence of aircraft fuel resulted in a generalized fire on the floors of impact. The subsequent burning was entertained by the aircraft remnants and by the fuel inherent to the building. In this particular case, the fuel load consisted mostly of furniture and partitions. Data on these type of fuels is available (www.bfr.nist.gov) and indicates no unusual energy release rates. However, the exact nature of the fuel load on the floors has not been determined so far.

It has been pointed out [17] that comparison between the images of the WTC and those of the First Interstate Bank fire (Los Angeles), show for the latter case, greater heating effects over larger regions. Furthermore, the author points out that complete window breakage did not seem evident in WTC as occurred in 1st Interstate. In an important point, the author of this report, uses the Cardington Tests as an example of such fire conditions that appeared more severe and did not lead to measured temperatures above 700 °C. The Cardington Tests are the most recent and best-documented study that attempts to better understand the behavior of steel frame structures under generalized fire conditions. The information from these tests, the subsequent modeling and the lessons learned should be used when trying to understand the behavior of the fire and structure in the WTC.

3.2. The High Rise

Before analyzing the specific building it is important to establish what are the constraints imposed by high-rise buildings. In this section it will be accepted that the building has to include, as part of the design constraints, a scenario equal or similar to that of September 11th, 2002.

It is clear that as the height of the building increases the time to evacuate the occupants will increase. Several methodologies can be used to estimate the evacuation time and they will all point out to the conclusion that evacuation of a floor (or a limited number of floors) to an adjacent area is feasible within the characteristic times corresponding to the fire reaching non-tenable conditions.

Further evacuation can then proceed under the assumption that the time for loss of structural integrity is much larger than the total evacuation time. Different fire conditions produce different results. This is graphic from the 1993-bombing incident at the WTC that produced non-lethal smoke that obscured vision and retarded egress considerably. But in the September 11th incident, evacuation below the floors of impact was very successful. There are currently about 4 uncoordinated studies on the evacuation of the towers in the September 11th case.

For a scenario of the nature of the one being analyzed here, the loss of a specific region of the building and of its occupants will have to be accepted and design will have to concentrate in minimizing live loss and damage beyond the area of impact. For this scenario it will have to be assumed that the time interval to reach untenable conditions within the region of impact cannot be managed by any form of escape protocol.

The present scenario implies the loss of active and passive fire protection systems within the area of origin, therefore structural behavior needs to be addressed in the absence of these features. Furthermore, as the elevation of the area of impact increases the efficacy of firemen intervention decreases significantly. This leads to a worse case scenario where firemen intervention could be eliminated from the design specifications. The limitations on firemen intervention in high-rise buildings have been known for years and are discussed by Chief Vincent Dunn [21]. In the April 2002 issue of Firehouse, he calls for many improvements in the fire service. These include a new radio, a tracking system for fire fighters, robots and helicopters for suppression, and improved breathing equipment.

In summary, as a building increases in height and the conditions approach those of the World Trade Center event, its design will tend to a worst case scenario where the building needs to be designed on the basis of:

- Structural integrity of the area of origin needs to be achieved in the absence of any form of fire control and passive protection for a time that tends to infinity ($t_s \rightarrow \infty$).
- Structural integrity of the rest of the building needs to be achieved under the same principles as above ($t_s \rightarrow \infty$), although passive protection systems can be assumed to remain in place. The reliability of active suppression systems under the present conditions would have to be assessed in great detail. In a similar manner, firemen intervention within areas beyond the origin can be considered nevertheless, it needs to be weighted on the basis of the elevation.
- Smoke management and escape need to be designed on the basis that only local evacuation is possible within the time duration of the fire.

3.3 The Issues Presented by the WTC Incident

The questions raised above were never stated within the constraints of the World Trade Center design and subsequent improvements and the ultimate fate of the WTC buildings was collapse. Three high-rise buildings collapsed including the 42 story WTC 7 that was ignited and damaged by the falling towers. This turn of events leads to the unavoidable question of what induced the collapse and furthermore, what modifications in building design philosophy are necessary to achieve the goals stated in the previous section. This issue has raised great speculation and this paper will not attempt to add to it. Instead it is the intention of the authors to point what questions need to be raised to achieve better understanding of what determined the final fate of these buildings and their occupants. It is appearing that the fire was the principal reason for the collapse after the impact. But the circumstances of that cause are unknown.

Over-simplified initial analysis of the impact and subsequent fire seemed to point out that that collapse could have been a foreseeable event. More detailed evaluations seem to point in the opposite direction. It is apparent that at this point no one can establish in detail the sequence of events that could lead to the collapse of such buildings.

It is well recognized that no one single event or design feature is responsible for the generalized destruction of the building nevertheless, the different issues involved can be raised. The structural elements are questioned on two different bases, their capability of withstanding the impact and their resistance to a long duration fire. Separation of the particular implications of each of these two sources of damage at this point is impossible. Attempts to isolate the different elements that are being questioned will be made, and in some cases tentative answers will be presented, at least to indicate possible approaches.

1. The airplanes inflicted severe damage on the façade columns. The fraction of these columns that was damaged should be precisely determined and compared to an analysis of the resulting strength of the building as a function of a reduction of the structural elements of the outer core.

Based on the leaked FEMA report to the NY Times, it appears that the outside columns did not experience an increase in load. The internal damage needs to be evaluated. The same NY Times article states that building would have stood indefinitely had there been no fire.

2. The aircraft would have damaged the inner core of the building. An estimation of the magnitude of this damage should be made and, again, compared to an analysis of the resulting strength of the building as a function of a reduction of the strength of the inner core.

No information on the inner core has been reported. It appears that computer modeling will be eventually used. However, impact-scale modeling might be an alternative.

3. It is clear that if all the structural elements of a floor are eliminated, the floors above will collapse over it. It is essential to establish if a single floor failure will lead to progressive collapse of the entire building. Progressive collapse is a well-known process [22,23].

Connections of the floors to the outer columns has been a focal point of speculation.

4. A realistic description of the fire needs to be made and should include a detailed evaluation of the impact of the aircraft fuel on the ultimate size of the fire. Isolating the aircraft fuel from the subsequent fire is essential since it will allow separating this particular event from other more probable scenarios that could lead to a generalized fire within the building.

Our preliminary assessment attempts to sort out the fuel and fire effects will be presented in the final section of this paper simply as an example of a possible analysis.

5. A detailed evaluation of the ventilation patterns, flames projected from the windows, external plume is essential in establishing the amount of oxygen that can reach the fire. As shown in previous sections, a simple calculation of the available ventilation areas will show that the size of this fire is most likely limited by ventilation.

The inability to completely model this fire makes it essential to examine available video and photographic records to create a demographic timeline.

6. Within the fire service community there is a generalized lack of confidence on the behavior of lightweight trusses. Furthermore, a number of preliminary reports have suggested that the joints between these trusses and the external core are the initial point of failure. The impact of the fire on these elements seems to be a recurrent point of discussion that needs to be investigated in detail [21].

7. “Fireproofing” as a mechanism of fire protection for structural elements has been long required. It has been pointed out that faulty fireproofing might have accelerated the collapse process (NY Times, December 13th, 2001). Fireproofing is advocated on the basis of standards such as ASTM-E-119 (ISO-834) that rely on a pre-specified environment temperature to quantify the evolution of the temperatures within structural elements. Criticism to this methodology is common within the fire community. Some researchers even advocate that the absence of fireproofing might be beneficial to a structure in the event of generalized fire. The temperatures expected in a post flashover fire will lead to deformation of a structure, albeit not to failure. The deformation leads to redistribution of loads that

could be of benefit to the overall resistance of the structure [26]. In any event the role of the insulation for fire protection needs to be critically studied in this incident.

3.4 Sample Calculations for the WTC Scenario

The Effect of the Aircraft Fuel

Each plane is estimated to have had 10,000 gallons of jet fuel on board at impact. Based on the asymptotic burning rate for JP-4 [24, p.3-201] of 60 g/m²-s, we obtain a total burning rate of 242 g/s if it burns homogeneously over the entire floor. For 10,000 gal., this is approximately 28,500 kg. About four fireballs of roughly 60 m in diameter resulted from a jet impact. The mass (M) burned by these fireballs can be estimated from [24, p. 3-230] to be:

$$M=(D/5.25)^{(1/0.314)},$$

Or about 9,400 kg per impact. The burning duration of the remaining fuel over one floor is

$$t = (28,500-9,400)/242 = 79 \text{ s.}$$

Hence, the jet fuel fire was short lived. Indeed, all did not burn above since accounts have pointed that fuel spilled down the elevator shafts, burning people in the lobby.

The Impact of The building contents

We do not know, at this time, exactly what the demographics of the office spaces involved in fire. The Japanese building code designs to 560 MJ/m², but office space can vary considerably, especially in storage areas. Let us use the CIB correlations for wood-based fuel established in Thomas and Heselden [5]. Furthermore, at this time, the state of the openings on a floor has not fully been determined. Nevertheless, it is roughly estimated that 50 % of the building side at impact was opened with about 30 more additional windows broken. This gives AoHo^{1/2} is 252 m^{5/2}. The surface area (per CIB: walls and ceiling) might be about 5000 m², neglecting partitions and the core utility space. This gives A/AoHo^{1/2} = 20 m^{-1/2}.

Using a 50 % variance, this gives a range on the CIB correlations in Figure 16 and Figure 17. Note that Figure 16 and Figure 17 were previously presented as part of the background. The results indicate temperatures of 800 to 1000 °C, and a burning rate of about 15 to 30 kg/s. As mentioned before, it is quite possible that the temperature could have exceeded those values estimated here.

For wood (15 MJ/kg) at 560 MJ/m², the burning duration of the office furniture can then be estimated at about 86 to 171 minutes. The towers collapsed in 56 and 104 minutes.

Figure 17 shows the estimated maximum temperature in the WTC office floors in comparison with the ISO 834 temperature curve. From the collapse times, the temperatures corresponding to the test are within the error of those estimated. It can be therefore argued that protection on the steel members was not adequate. The uncertainty, nevertheless, can go both ways, since the temperature could have been well in excess of ISO 834 or the values predicted here, or the uncertainty can be related to lack (or poor) of insulation due to the impact or original state of the protection. The actual state of the fire proofing at the time of impact is not known.

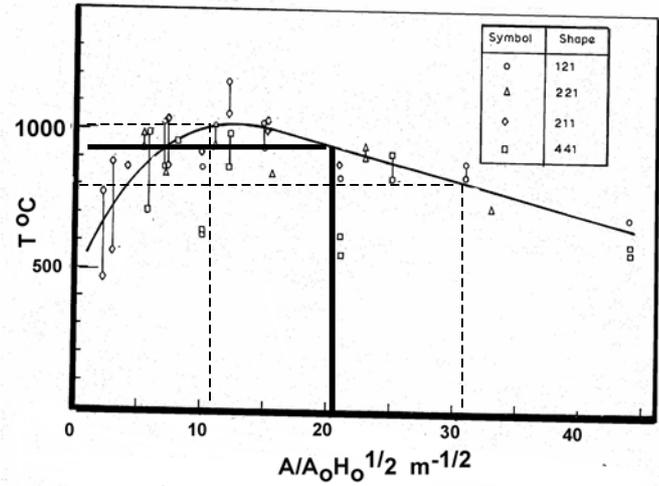


Figure 15 Temperature from CIB [5].

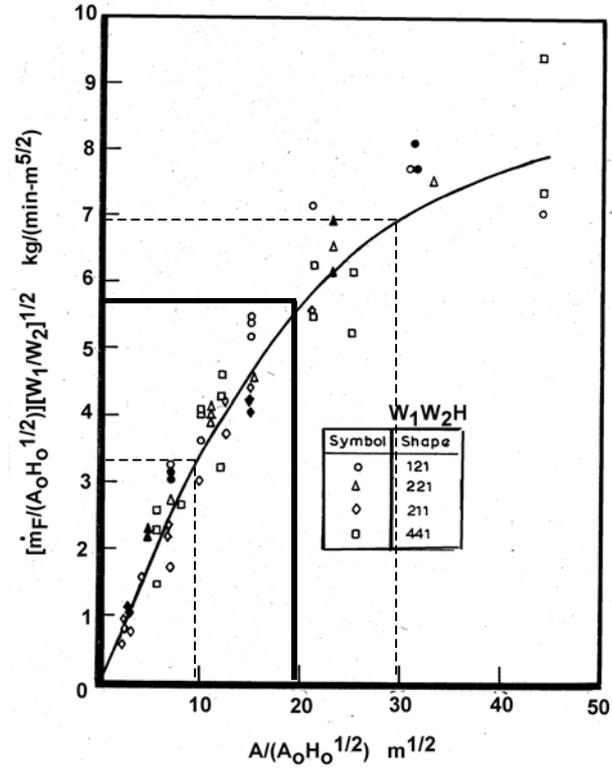


Figure 16 Burning Rate form CIB [5]

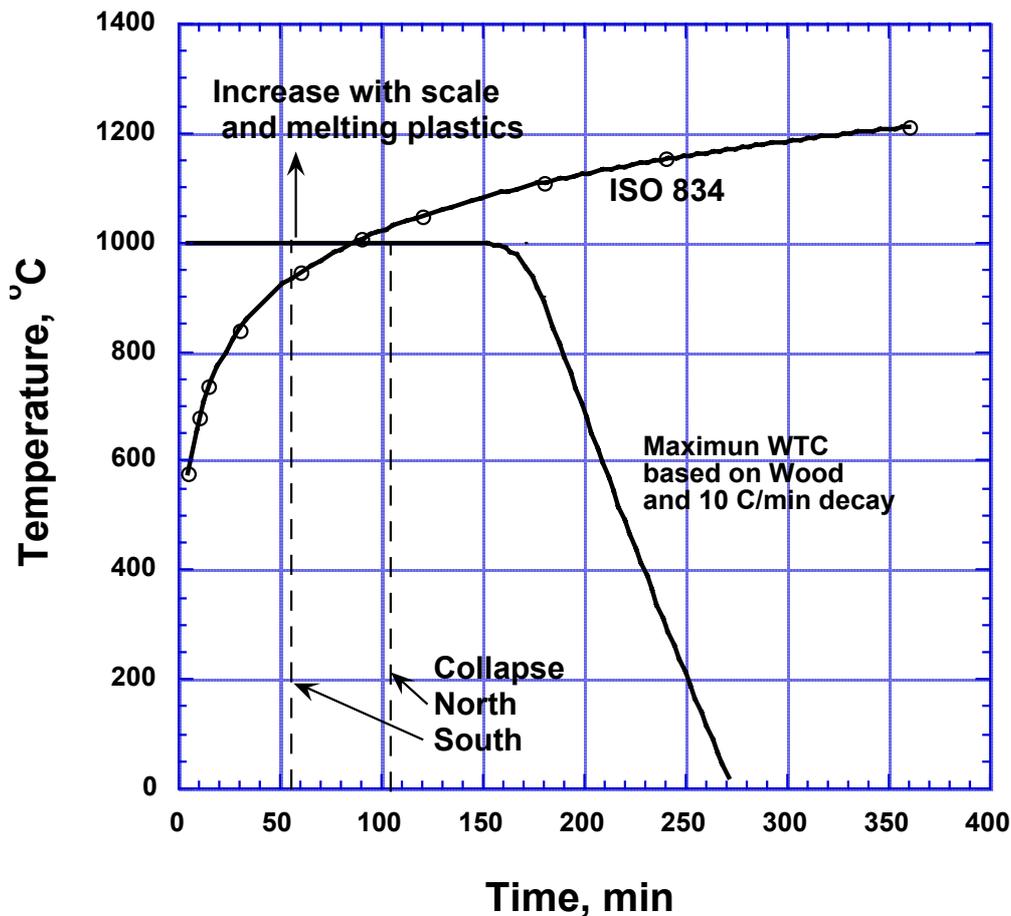


Figure 17 Estimation of WTC floor temperatures and ISO 834.

4. What Should Have Been Done – Final Comments

When this terrorist attack occurred, its shock and magnitude brought out many emotions and actions. The call for an investigation of the collapse of the WTC buildings (2·110 story towers and WTC 7, 48 stories) was not one of them. Investigative agencies, such as the BATF or the NTSB, were not in the forefront. The responsibility for action went to the City of NY and the FBI. The ASCE stepped forward with a voluntary team that took about a month to get access to the site, and FEMA funded the ASCE to continue their investigation—called a building performance study. NIST stepped forward to propose action but has yet to be funded. The steel members were recycled and valuable evidence may have been lost. The NY Times (April 8, 2002) presented a story on questioning the standard furnace test for structural members. Underwriters Laboratories (UL) responded in a Letter-to-the-NY-Times-Editor (April 15, 2002): “The World Trade Center stood for almost an hour after withstanding conditions well beyond those experience in any typical fire. ...UL’s testing procedures helped make that possible.” Whether this fire was atypical and how does it relate to the test method needs to be fully answered. Three high-rise buildings received structural damage leading to collapse at the WTC; two were hit by aircraft and they seems to have not damaged the buildings sufficient for collapse. The Meridan Plaza high-rise fire also led to a structure being damaged

in an office building fire. Fire events are rare, and our standards are absolute, and in these cases not based on science. It seems obvious to us that we cannot afford to rely on an empirical basis for fire safety. Hopefully, this tragic event will catalyze those in fire safety to take a deep look at what they are doing, and seek to obtain assured fire safety levels through engineering analysis and data.

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