Smoke Control and Occupant Evacuation at the World Trade Center

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ABSTRACT

This paper examines smoke control and occupant evacuation in WTC 1 and WTC 2 on September 11, 2001, focusing on the impact region and above for each tower. Approximately 2,000 individuals were at or above the area of impact in WTC 1 and WTC 2 who did not successfully evacuate. NIST found that the smoke management (smoke purge) systems in WTC 1 and WTC 2 were not initiated on September 11, 2001. Had the smoke purge sequence (required by the BCNYC for post-fire smoke venting) been initiated in WTC 1 or WTC 2, it is unlikely the system would have been capable of operation, due to damage caused by aircraft impacts. Even if fully operational, none of the hypothetical potential smoke management approaches evaluated would have prevented smoke spread given the damage caused by aircraft impact. During the events occurring on September 11, 2001, stair pressurization would have been ineffective in improving conditions for occupants trying to exit the building due to the extensive damage to the stair shafts. Installation of combination fire/smoke dampers in HVAC ductwork, which was not required in WTC 1 or WTC 2 at the time the WTC was constructed, may have acted to slow the development of hazardous conditions on the uppermost floors of the building, but would likely not have had a significant effect on the ability of occupants to egress the building due to the impassibility of the exit stairways.

INTRODUCTION

On the morning of September 11, 2001, the World Trade Center (WTC) in New York City was attacked by hijacked commercial airplanes. The collision with each tower (WTC 1 at 8:46:30 a.m. and WTC 2 at 9:02:59 a.m.) produced significant structural damage. The impact generated a large, luminous external fireball that consumed a portion of the jet fuel, with the remaining fuel acting as an ignition source for the combustible material within each tower. At 9:58:59 a.m., 56 minutes after it was struck, WTC 2 collapsed due to a combination of the aircraft impact damage and subsequent fire. WTC 1 stood until 10:28:22 a.m, when it also collapsed. This paper summarizes the findings from several projects included in the National Institute of Standards and Technology (NIST) Investigation into the collapse of the WTC towers with respect to the occupant evacuation and the smoke control system. Additional information and detail can be found in NIST NCSTAR 1, NIST NCSTAR 4, NIST NCSTAR 4d, and NIST NCSTAR 7.

The NIST investigation of active fire protection systems in World Trade Center 1 and 2 included the design, installation, capabilities, and performance of the automatic fire sprinkler, standpipe, standpipe preconnected hoses, fire alarm, and smoke management systems on September 11, 2001,. The purpose and normally expected performance of each active fire protection system in the buildings are described, as well as details about the systems installed in WTC 1 and 2. Using fire protection engineering methods, the capabilities of the installed systems to respond to various fire threats, from normal office fires up to and including the extraordinary challenge of the fires ignited by the aircraft impacts on September 11, 2001, were assessed. Findings of the investigation are presented with regard to the smoke management systems installed on the day the buildings collapsed.

WORLD TRADE CENTER 1 AND 2

Building construction details and building systems in WTC 1and 2 were evaluated to develop an understanding of

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building features that may have impacted smoke movement within the buildings or the design/function of smoke management systems. Building heating, ventilation, and air conditioning (HVAC) systems are described in somewhat greater detail in order to understand the capabilities of the HVAC systems to perform smoke management functions.

WTC 1 and WTC 2 were comprised of 110 stories above grade and seven levels below grade and had an approximate footprint area of 42,900 ft^2. The interior of each floor differed due to the particular tenant build-out on that floor. In addition, the service core for the north tower (WTC 1) was oriented east/west while the service core for the south tower (WTC 2) was oriented north/south. The service cores contained the elevators, exit stairs, bathrooms, and miscellaneous equipment rooms. The service core gradually decreased in size on the upper floors of the building as the numbers of elevators contained on the floors decreased.

The core spaces were separated from the perimeter spaces in the building by a 2 h fire resistance rated barrier extending slab-to-slab (i.e., between the floor and ceiling slabs). The perimeter office spaces were generally open-plan office spaces containing office cubicles. Individual office spaces on the perimeter were generally separated by non-fire resistance rated partitions extending only to the drop ceiling (i.e., not all the way up to the ceiling slab). The ventilation air plenum above the drop ceiling was generally open around the perimeter of the floor.

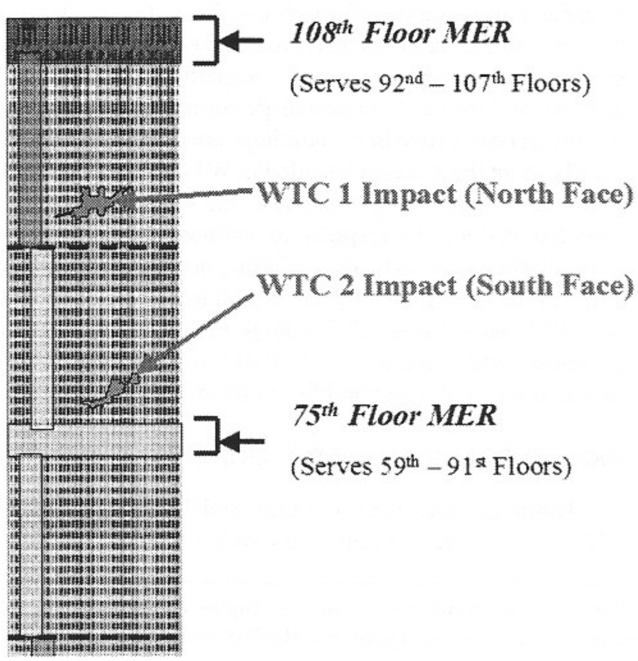

Figure 1 *Location of MERs for WTC 1 and WTC impact zones.*

Assembly spaces were located near the top of each building (Windows on the World in WTC 1 and Top of the World Observation Deck in WTC 2), presumably to capitalize on the scenic views available from the location in the building. Each assembly space permitted occupant loads in excess of 1,000 people per floor, resulting in the potential for a high concentration of people near the top of the building, which is the most remote component of the egress system.

Building ventilation (heating and cooling) was provided in WTC 1 and WTC 2 by HVAC systems located in four mechanical equipment rooms (MERs) located on the 7th, 41st, 75th, and 108th floors of each building. Each MER was approximately two stories tall and had an upper and lower level. With the exception of the 108th floor MER, which was located at the top of the building, above the floors that it served, the MERs served the floors immediately above and below the floors on which they were located. The aircraft impact into WTC 1 occurred in the uppermost portion of the building (92nd–98th floors), served from above by the 108th floor MER. The aircraft impact into WTC 2 occurred lower in the building (77th–84th floors), served from below by the 75th floor MER.

HVAC supply fans were located on the lower level of each MER. Supply air was provided to the building via core, interior, and peripheral HVAC units. There were two core supply ventilation zones (north/south in WTC 2, east/west in WTC 1, due to the orientation of the core), four interior space HVAC zones (corresponding to the four quadrants of the building), and four perimeter zones (north/south/east/west). Each supply fan delivered air to a supply duct network serving the respective HVAC zone associated with the supply fan.

Return fans were located on the upper level of each MER. These fans drew air from four sets of vertical return air shafts located at the perimeter of the core. The gypsum wallboard shafts were connected to return air plenums located above the drop ceiling in the four interior quadrants of each floor via openings between the shaft and plenum. Air was drawn from the occupied space, through return grilles located in the ceiling tiles into the ceiling plenum. Return air was then drawn vertically to the MER exhaust fans via the gypsum wallboard shafts. In this manner, the exhaust fan acted to "return" air from the occupied space back to the MER where it could be recirculated back to the supply fans or exhausted out of the building depending on positioning of the main supply, return, and exhaust air dampers.

The smoke management system (smoke purge) for WTC 1 and WTC 2 utilized only the interior air systems and core systems, which were not modified substantially as a result of tenant retrofits. Perimeter air (supply air only) was not used for smoke management. Further, the return air plenum arrangement and total air quantities remained unchanged, despite individual tenant retrofit configurations. While smoke movement may have been impacted on a given floor due to changes to the ventilation system on individual floors, overall air quantities were be expected to remain the same.

Stairwells

WTC 1 and WTC 2 each had three primary stairwells designed for emergency egress, designated as A, B, and C, and each was enclosed in 2 h construction. There were additional stairwells located in the basement levels (B1 – B5), convenience stairs for tenants leasing multiple floors, and mechanical room stairs. These secondary stairs are not considered part of the emergency egress system and are not described here. Stairwells A and C were 44 in. (1.1 m) wide and extended from floor 2 (plaza or Mezzanine Level) to floor 110 (lower mechanical space). The stairwell landings by the exit door were 92 in. (2.3 m) wide by 78 in. (2.0 m) deep. Stairwell B was 56 in. (1.4 m) wide and ran from the subgroup 6 levels below ground to floor 107 including the Concourse (main lobby); there was no exit from Stairwell B onto the 2nd floor (plaza / Mezzanine Level). The stairwell landings by the exit door for Stairwell B were 116 in. (2.9 m) wide by 78 in. (2.0 m) deep.

The WTC 1 and WTC 2 stairwells were occasionally routed horizontally through transfer corridors in order to avoid equipment on mechanical floors and to reduce the occurrence of continuous vertical shafts that extended the entire height of the building, to reduce the impact of stack effect. Stairwell B included a horizontal transfer at floor 76. For all other floors, Stairwell B maintained vertical alignment through the building. Stairwells A and C included horizontal transfers (some longer than others) at floors 42, 48, 66, 68, 76, and 82. Horizontal transfer distances ranged from several feet (floors 66 and 68) to over 100 ft (33 m), including smoke doors (which were closed but not locked) and multiple right angle turns in the transfer corridors on floors 42, 48, 76, and 82 for Stairwells A and C. Note that the mechanical floors were located on floors 41-42, 75-76, and 108-109. One problem with the horizontal transfers was that they extended the total evacuation time, when compared to a similar design without horizontal transfers.

SMOKE CONTROL SYSTEM

In the event of fire in World Trade Center (WTC) 1 and 2, there were two primary means to control smoke movement throughout the building. The first means was passive smoke control via the construction of smoke barriers, which were typically integrated into the architecture of the building. Smoke barriers included fire dampers at penetrations due to HVAC system ductwork. The use of smoke barriers is also commonly referred to as compartmentation, and walls and smoke dampers are used to form the "compartments". The second means was active smoke control via the use of air movement equipment to contain smoke. This approach uses either dedicated equipment, used only for smoke management, or non-dedicated equipment that is also used to provide HVAC air to the building.

WTC 1 and WTC 2 were equipped with a non-dedicated smoke management system (a smoke purge system required by the BCNYC for the purposes of post-fire venting) that utilized the base building HVAC systems that provided normal ventilation to the buildings. No dedicated smoke management systems were installed in the buildings.

The normal base building HVAC systems could be manually aligned in a smoke purge mode that allowed smoke to be removed from the building. Smoke purge could only be accomplished for an entire ventilation zone served by a particular MER; thus, in the smoke purge mode the entire ventilation zone represented a single smoke zone. Because no remotely controllable fire/smoke dampers were present within the ventilation ductwork, it was not possible to provide the smoke purge, or any other smoke management sequence, on a floor-by-floor basis.

Smoke detectors were located at the exhaust duct inlets on each floor and within the HVAC system ductwork in the MER to provide automatic shutdown of individual fans in the presence of smoke. Automatic shutdown of the ventilation systems could be overridden in the smoke purge mode.

The fire safety plan for WTC 1 and WTC 2 (PANYNJ 1995) defines smoke purge as the removal of smoke and other gaseous combustion products from the (fire) area "after a fire has been extinguished." As documented in the fire safety plan, mechanical systems could be manually adjusted to perform the smoke purge function by the Port Authority mechanical section staff when requested by the chief officer of the responding Fire Department of the City of New York (FDNY) units. The FDNY would ask the WTC fire safety director to provide a smoke purge for a given zone. The WTC fire safety director would then instruct the mechanical section staff to perform the requested action.

The smoke purge sequence is documented in WTC Instruction Manual No. 23, Operation and Maintenance of Fire Protection System, dated February 1986 (PANYNJ 1986). The documented sequence involves using the interior exhaust fans to exhaust an entire multi-floor ventilation zone. Based on the information contained in the fire safety plan for WTC 1 and WTC 2 and WTC Instruction Manual No. 23, it could be concluded that the buildings were equipped with a manual purge system that utilized the interior zone exhaust fans serving the four quadrants of the building to remove smoke after a fire was extinguished. Core supply/exhaust fans and peripheral supply fans would be shut down. Smoke purge could be accomplished within each HVAC zone, the largest of which consisted of 32 floors.

During the course of the NIST investigation, a number of sources were found containing conflicting information regarding how the smoke purge system functioned and how it was intended to be used. Accounts of a major fire occurring in 1975 on the 11th floor of WTC 1 (Powers 1975; Lathrop 1975) state that the smoke purge sequence pressurized the core with 100 percent outside air and exhausted 100 percent from the office spaces. These accounts also state that during the 1975 fire, the smoke purge sequence for the fire floor and adjacent floors was manually initiated from the appropriate MER shortly after discovery of the fire, once police had examined the fire floor and identified the presence of a significant fire.

This documented sequence of events is important, as it signifies that the system was used at that time as an active fire protection system, to control smoke during the fire event and that the mode of operation differed from the that contained in the 1986 Instruction Manual No. 23.

As part of the NIST investigation, the Port Authority was asked to clarify the operation of the smoke purge sequence, since the available information regarding its intended operation provided conflicting accounts of smoke purge operation. According to the Port Authority, smoke purge would occur by starting the supply and exhaust fans serving one of the four interior quadrants within a ventilation zone. Core supply/exhaust fans and peripheral supply fans would be shut down. HVAC systems serving the other ventilation zones in the building would be left operating unless they were shut down at the direction of FDNY. The Port Authority further recognized that WTC Instruction Manual No. 23 had not been updated since the base building fire alarm system was upgraded after the 1993 bombing. Therefore, this manual did not always reflect the most current fire protection system configuration.

Operation of the smoke management system for WTC 1 and WTC 2 could be achieved by controlling the equipment within the individual MERs or at a central control panel located in the Operations Control Center (OCC) located on the B1 level of WTC 2. At either location, building personnel had to perform two distinct operations: configuring the HVAC systems in smoke purge mode and starting the appropriate HVAC fans.

Operation of the purge switch aligned all dampers that served as part of that quadrant's HVAC systems in a 100 percent outside air configuration. This would mean that supply and spill dampers would be fully open and that recirculation dampers would be closed.

To achieve the smoke purge, it was up to the operator of the systems to turn on those fans necessary to achieve system operation. It would have been equally possible to initiate an exhaust only type sequence as outlined in the fire safety plan, the core pressurization sequence (supply and exhaust operating) reportedly initiated during the 1975 fire, or the sequence stated by the Port Authority as the smoke purge sequence in effect on September 11, 2001. Alignment of the system would be up to the understanding of the operator as to the proper function of the smoke purge sequence, when called upon to initiate this sequence.

With regard to the use of the smoke purge function to aid in active smoke management system during a fire event versus during post-fire cleanup operations, it would be up to the responding fire department personnel to initiate system operation. Depending on the type of fire event, it was possible that the system could have been used either during the fire or after it was extinguished.

At the time the buildings were constructed, the ability to provide a smoke purge from each HVAC zone was the only smoke management system provided in the buildings. Local Law 5 (New York City 1973) retroactively imposed the requirements for smoke shafts for existing high-rise buildings, when it was enacted in 1973. In lieu of such smoke shaft(s), stair pressurization systems could be provided.

In order to respond to the requirements of Local Law 5, the Port Authority initiated a pilot study into the requirements for pressurizing the exit stairs in WTC 1 and WTC 2. Stair pressurization was examined as a means of meeting the requirements of Local Law 5 since the smoke shaft requirements would have been prohibitive for a building the size of WTC 1 and WTC 2. Existing buildings that were sprinklered throughout were exempt from the smoke shaft and optional stair pressurization requirement by the requirements of Local Law 86 (New York City 1979). A decision was made at some subsequent time to fully sprinkler the WTC buildings. Therefore, the Port Authority did not move forward with the stair pressurization option. Because WTC 1 and WTC 2 were fully retrofitted with automatic sprinklers, smoke and heat venting and/or stair pressurization was not required in WTC 1 and WTC 2 on September 11, 2001.

WTC 1 and WTC 2 were equipped throughout with fire dampers at duct penetrations into vertical shafts, consistent with the Building Code of New York City (BCNYC) (New York City 1968). Combination fire/smoke dampers were not required by the code to be provided in existing buildings. Since tenant retrofit projects generally connected to the existing base building systems, fire/smoke dampers at HVAC shafts were not generally provided during tenant retrofits.

Emergency power was not retroactively required by the BCNYC, but was provided subsequent to the 1993 bombing for WTC 1 and WTC 2, serving all emergency systems (lighting, fire alarm system, etc.) and the building elevators. While one account summarizing the building restoration activities following the 1993 bombing suggested that emergency power was provided for smoke purge fans, the Port Authority stated that emergency power was not provided to WTC 1 and WTC 2 base building smoke purge fans. However, the MERs were equipped with redundant power sources from different substations. No other redundant features were identified with respect to the HVAC systems used to accomplish the smoke purge functions. No backup system or emergency power was provided.

EVALUATION OF SYSTEM PERFORMANCE ON SEPTEMBER 11, 2001

The following discussion documents the normal operation of the fully functional smoke management systems and their impact on smoke conditions in WTC 1 and WTC 2 on September 11, 2001. Elements of this task involved the evaluation of expected system performance for postulated design fires in business occupancies, as well as documentation of the expected performance of fully functional smoke management systems in the towers.

The smoke management systems in WTC 1 and WTC 2 were designed to provide a manually-initiated smoke purge function. Given the design and intended operation of the smoke management systems, two key questions were sought to be answered to ascertain the performance of the system on September 11, 2001:

- Was the smoke purge system in either WTC 1 or WTC 2 manually initiated by emergency response personnel?
- Were the systems capable of operating given the damage caused by the aircraft impacts on each building?

In order to answer the second question, damage to both the building electrical and mechanical systems needed to be evaluated. It was first necessary to determine whether electrical power was available to the building mechanical systems subsequent to impact so that they were capable of operating. Then, potential damage to HVAC system components was evaluated to determine if the systems were capable of performing as designed.

Actions of Emergency Response Personnel

The events of September 11, 2001, clearly represented an extreme challenge, both to emergency response personnel and to the installed building systems. The damage caused by an aircraft impact into a building is outside the range of typical design considerations for the design of most building systems, including fire protection systems.

The WTC fire safety director on duty stated that no recommendation was given on his part to initiate a smoke purge sequence, nor was smoke purge performed on September 11, 2001, to his knowledge. NIST found no record of FDNY personnel having initiated a smoke purge sequence in WTC 1 or WTC 2.

Damage to System Components

The exact extent of damage within individual floors of WTC 1 and WTC 2 may never be known, since the collapse of the buildings prohibited a detailed inspection of the impact area. However, the potential extent of damage was estimated based on the results of engineering analysis and based on observations recorded by people located within WTC 1 and WTC 2 at the time of the events.

Potential damage estimates were overlaid onto representative floor plans for the impact areas in WTC 1 and WTC 2 in order to determine the potential damage to key electrical/mechanical system components located in the core spaces. The damage estimates were corroborated to a certain extent using observations made by people located in various locations in the buildings after aircraft impact. The observations primarily have to do with stair shaft damage, damage to freight elevator #50, and in some cases elevator shafts. HVAC shaft data could be corroborated using visual evidence of smoke spread seen from the exterior of the building. An attempt was also made to corroborate the extent of core damage using observations as to the presence of power in the building.

In WTC 1, it is likely that the impact eliminated or significantly impaired electrical power on floors above the impact zone. Therefore, because power would not have been available at the 108th floor MER (which served the zone of impact) HVAC systems likely would not have been operational. In addition, the ventilation shafts for at least the north half of the building were likely damaged, thus reducing the possibility for the smoke purge to function properly even if the HVAC systems had been operable.

In WTC 2, it is possible that electrical power may have been available to the fans located in the 75th floor MER, which was located below the impact zone in this building. Survivor accounts indicate that power may have been available up to the 75th floor and visual evidence suggests power was available even above the floors of impact (Beyler 2002). Initially, all fans would have shut down due to detection of substantial quantities of smoke by the duct smoke detectors. The HVAC shafts utilized to accomplish smoke purging would likely have been damaged on the east side of the building, eliminating half of the smoke venting capacity for the floor. Even if the ventilation shafts on the west side of the building remained intact, the performance of the smoke venting system would have been reduced.

Summary of System Performance on September 11, 2001

Examination of the available evidence provided strong indications that the smoke management systems in WTC 1 and WTC 2 played no role in the events that occurred on September 11, 2001. There was no evidence to support the fact that an attempt was made to activate the smoke purge sequence. If a decision had been made to attempt to align the building ventilation systems into the smoke purge mode, it is doubtful that this would have had any impact on overall smoke conditions within the building. Since the WTC 1 impact occurred near the boundary between ventilation zones at the 91st/92nd floors, smoke purge may have been inadvertently initiated for the 59th–91st floor HVAC zone in WTC 1, rather than the HVAC zone for the upper floors. The aircraft impacts caused significant damage to the core spaces in both WTC 1 and WTC 2, making it unlikely that the smoke purge could have been accomplished in either building.

EVALUATION OF POTENTIAL SMOKE MANAGEMENT SYSTEM EFFECTIVENESS

In order to fully understand the potential impact of smoke management systems for events like those occurring on September 11, 2001, it is important to analyze how various smoke management system configurations might have performed in WTC 1 and WTC 2 had they been available on September 11, 2001 (NIST NCSTAR 1-4D). To develop an understanding of the capabilities of the various smoke management system configurations that were evaluated, it is also important to analyze their performance for other hypothetical fire scenarios in high-rise buildings, including both typical/expected design scenarios and worst case scenarios. All of the smoke management approaches analyzed utilized some variation of the pressurization method of smoke management.

The performance of each of the smoke management approaches, given the postulated design fire scenarios, was evaluated using the CONTAM building airflow and contaminant dispersal model (Dols and Walton 2002). CONTAM is a recognized tool for the evaluation of smoke management systems that are based on the pressurization method of smoke management.

The various codes and standards that reference the use of pressurization smoke control require the provision of 0.05 in. H_2O (12.5 Pa) pressure differentials in sprinklered buildings and 0.1 in. H_2O (25 Pa) in non-sprinklered buildings to contain smoke. It is important to note, however, that these pressures are measured with a building's HVAC systems placed in smoke management mode, without the presence of a fire. The required pressure differentials are high enough to contain heated smoke were a fire to be present in sprinklered and non-sprinklered occupancies, and are used for design purposes.

Smoke Management System Approaches

Five distinct smoke management approaches were examined for the WTC towers. These approaches are as follows:

- Smoke Purge
- Core Pressurization
- Building Pressurization
- Sandwich Pressurization
- Zoned Smoke Control with Stair Pressurization

The smoke purge approach is based on the documented smoke purge sequence for WTC 1 and WTC 2 as it appears in WTC Instruction Manual No. 23, Operation and Maintenance of Fire Protection System, dated February 1986. The sequence involved placing the interior HVAC zone exhaust fans and core exhaust fans (toilet exhausts, elevator machine room (EMR) exhausts) in the multi-floor ventilation zone containing the fire in 100 percent exhaust mode. HVAC systems in all other ventilation zones in the buildings were aligned in a summer normal mode. Peripheral supply fans were shut down.

The core pressurization approach is a slight variation of the documented smoke purge sequence for WTC 1 and WTC 2, in that the supply fans, rather than the exhaust fans, in the core were activated to pressurize the core, in an effort to prohibit smoke spread into the core from the surrounding office spaces. Accounts of the 1975 fire and other sources cite this variation as being the "smoke purge" sequence provided for the building.

The building pressurization approach was recommended to be used in the event of a severe fire involving a substantial portion of one floor of the building, where windows were observed to be broken out (HAI/DCE 1996). The approach involves turning on the supply fans in the entire building and turning on the exhaust fans only in the ventilation zone of fire origin. The intent of this approach was to exhaust smoke, where possible, from the floor containing the fire and to induce a substantial airflow toward the floor of fire origin to force smoke out of the broken windows.

The sandwich pressurization approach typically involves exhausting the floor of fire origin and pressurizing the floors above and below. The HVAC systems in WTC 1 and WTC 2 were not equipped with operable fire/smoke dampers; thus, it was not possible to configure the system to exhaust and supply to only single floors within a ventilation zone. Instead, an approach was examined where the "sandwich" was achieved by ventilation zones. In the event of a fire, the ventilation zone of origin would have all of its exhaust fans turned on, and supply fans turned off. The ventilation zones above and below would have all supply fans activated and exhaust fans turned off. These actions would create a multi-floor sandwich effect in the building, with the net effect being the creation of a pressure differential between the core and perimeter spaces within the HVAC zone of fire origin.

The final approach, zoned smoke control with stair pressurization, was a hypothetical approach based on best practices in smoke management system design enforced in many jurisdictions in the United States as of September 11, 2001. It was assumed that the building was retrofitted with stair pressurization systems, as required for all new high-rise construction by the model building codes in the United States, and was capable of exhausting on a floor by floor basis within the ventilation zone containing the fire to create the desired pressure differential with respect to the floors above and below. Other ventilation zones were assumed to operate in the summer normal mode. It was assumed that operable fire/smoke dampers were also installed in all supply/exhaust ducts at the appropriate shaft connections and that these dampers were closed within the zone of fire origin.

Design Fire Scenarios

Several different design fire scenarios were evaluated for WTC 1 and WTC 2, encompassing the range of expected fires that could be envisioned within the office spaces of the building. The fire scenarios were limited to those that could occur on the above-grade office floors of the building. Other fire scenarios are possible that could result in smoke migration through the towers, due to a fire in the sub-grade areas or adjacent spaces within the WTC complex (i.e., truck dock fire, car fire in the garage, fire in the concourse). Because the focus of this report is on examining the fires that occurred on September 11, 2001, (which occurred on the uppermost floors of the building) and bounding these events with other comparable fires, it was desirable to examine only those fire scenarios on the office floors of the building. The design fire scenarios that were evaluated are as follows:

- Sprinklered Fire
- Full-Floor Burnout
- Two-Floor Fire
- WTC 1 and WTC 2, September 11, 2001 Fire Scenarios (No Shaft Damage)
- WTC 1 and WTC 2, September 11, 2001 Fire Scenarios (Shaft Damage Assumed)

The first fire scenario assumes that a typical fire in a sprinklered building would either be controlled or extinguished by the automatic sprinkler system. It was assumed that the temperature in the zone of origin never exceeded the operation temperature of the sprinklers, which were assumed to have an activation temperature of 165 °F (74 °C). Given the large size of the majority of the office spaces in the towers, some of which encompassed an entire floor, the average temperature throughout the floor would be expected to be less than the assumed 165 °F.

The second fire scenario, the full-floor burnout scenario, is considered a worst-case design scenario for a fire involving the contents of a typical office building. In a fully-sprinklered building, a full-floor burnout would only be possible given some sort of catastrophic failure of the sprinkler system or given a fuel load that exceeded the capacity of the sprinkler system. The full floor burnout fire scenario evaluated in this report assumed a temperature on the floor of fire origin of 1,800 °F (1,000 °C). It was further assumed that 58 windows on each face were broken out.

The third fire scenario, the two-floor fire scenario, corresponds to a multi-floor event. The purpose of this fire scenario was to examine smoke management system performance for a multi-floor fire scenario of far less severity than the aircraft impact scenario that occurred on September 11, 2001. It was assumed that an explosion had opened up a 100 ft^2 (9.3 m^2) hole in the floor slab at the midpoint along one of the faces of the building. The average temperature on the two floors was assumed to be identical to that of the sprinklered fire scenario, 165 °F (74 °C).

The fourth fire scenario was a hypothetical fire scenario in which the majority of the structural damage occurring on September 11, 2001, was modeled, but with no shaft damage occurring in the building's core. This scenario, although unlikely, was modeled to estimate the performance of the candidate smoke management system approaches for a scenario involving a multi-floor fire event with high temperatures throughout the fire compartment and large openings in the exterior of the building.

The fifth fire scenario was an attempt to model smoke management system performance given conditions close to what actually may have existed in WTC 1 and WTC 2 on September 11, 2001. Estimates made as to the size of the exterior openings after aircraft impact, including impact damage and window breakage, were used along with the preliminary damage estimates to model the damage to shafts within the core of each building. Where the extent of damage was unknown, estimates had to be made with regard to the extent of damage. Temperatures of 750 °F (400 °C) and 1,800 °F (1,000 °C) were used to model the temperature throughout the impact zone. For all cases, the outside air temperature was modeled as 70 °F (21 °C) with the wind out of the north at 11.2 mi/h (5 m/s).

Results of the Analysis

Five candidate smoke management system approaches were evaluated to determine whether each of these approaches could provide adequate pressurization to contain smoke to the zone of fire origin for five postulated fire scenarios.

The smoke purge approach and the core pressurization approach were shown to create adequate pressure differentials for only the sprinklered fire scenario. Substantial negative pressure differentials, indicating flow of smoke from the zone of fire origin into the core, occurred for each of the other fire scenarios.

The building pressurization approach created high pressure differentials from the core to the perimeter office spaces for all fire scenarios except the multi-floor September 11 aircraft impact scenarios. Positive pressures were demonstrated for both the undamaged core and shaft damage September 11 scenarios in WTC 1, but sufficient airflow velocity was not created to prohibit smoke spread via large openings in ventilation shafts and in the core/office space boundaries resulting from aircraft impact damage. Use of the building pressurization method could potentially create excessive door opening forces that could hinder or prohibit the egress of building occupants. The magnitude of the door opening forces is a function of the fire scenario, size of interior and exterior openings, and location of the floor(s) of fire origin relative to the location of the MER.

The zoned smoke control with stair pressurization approach was shown to be effective for the sprinklered fire scenario, the full-floor burnout, and the two-floor fire. For each of these fire scenarios, however, stack effect was shown to have a substantial impact on the performance of the system, in some cases causing airflow from the floor of fire origin into the core. Therefore, this approach might not be effective using a single speed fan, or set airflow quantity. It is likely that fan speed would have to be adjusted based on differential pressure readings to ensure the success of a smoke management system using this approach. Because the zoned smoke control method involves exhausting from a single floor of the building, it was not effective for the multi-floor aircraft impact scenarios. In addition, stair pressurization did not prohibit smoke spread into the stairs when large openings in the stairway walls were present due to aircraft impact damage.

The sandwich pressurization approach was determined to be effective for the sprinklered fire, full-floor burnout, and two-floor fire scenarios, even in the presence of stack effect. Positive pressures were demonstrated in the model scenarios for both the undamaged core and shaft damage September 11 scenarios in WTC 1, but sufficient airflow velocity was not created to prohibit smoke spread via large openings into ventilation shafts or the core resulting from aircraft impact damage.

SUMMARY OF RESULTS

The following is a summary of findings based upon the review of the building designs and analysis of various smoke management systems as documented in the detailed report (NIST NCSTAR 1-4D):

- The smoke management systems in WTC 1 and WTC 2, which provided the capability for a manual smoke purge (required by the BCNYC for post-fire smoke venting) within an individual HVAC zone on a quadrant-by-quadrant basis, were not initiated on September 11, 2001.
- Had the smoke purge sequence been initiated in WTC 1 or WTC 2, it is unlikely the system would have functioned as designed, due to loss of electrical power and/or damage to the HVAC shafts and other structural elements in the impact zone that were an integral part of the smoke purge system.
- WTC 1 and WTC 2 were not required by the 1968 BCNYC, as amended by Local Law 5 and Local Law 86, to have active smoke and heat venting and/or stair pressurization because they contained automatic sprinklers throughout.
- None of the potential smoke management system configurations evaluated would have provided sufficient pressure differentials to contain smoke for the postulated aircraft impact damage scenarios, even if these systems were capable of operation after the building sustained damage from the aircraft impact.
- During the events occurring on September 11, 2001, stair pressurization would have been ineffective in improving conditions for occupants trying to exit the building due to the extensive damage to the stair shafts.
- Installation of combination fire/smoke dampers in HVAC ductwork, which was not required in WTC 1 or WTC 2 at the time the WTC was constructed, may have acted to slow the development of hazardous conditions on the uppermost floors of the building, but would likely not have had a significant effect on the ability of occupants to egress the building due to the impassibility of the exit stairways.

REFERENCES

Adler, J. 2002. Five Who Survived. Newsweek, September 9.

Beyler, C. 2002. Analysis of the Fire Aspects of the World Trade Center Terrorist Attacks: 11 September 2001. Hughes Associates Inc. Baltimore, MD, July 31.

Dols, W. and G. Walton 2002. CONTAM 2.0 User Manual: Multizone airflow and containment transport analysis software. NISTIR 6921, National Institute of Standards and Technology, U.S. Department of Commerce, Washington, DC.

Fahy, R. and G. Proulx 2003. Database of First-Person Accounts from Survivors of the World Trade Center Evacuation on September 11, 2001 conducted as part of report NIST NCSTAR 1-7a (2005).

HAI (Hughes Associates, Inc.) and DCE (Dillon Consulting Engineers). 1996. Smoke Management Evaluation Study of The World Trade Center Complex Excluding the Concourse and Plaza. Prepared for the PANYNJ (Port Authority of New York and New Jersey). New York, NY.

Lathrop, J. 1975. World Trade Center Fire, New York, New York. Fire Journal. July.

Murphy, D. 2002. September 11: An Oral History. Doubleday, New York.

New York City 1968. The City of New York Building Code. City Publishing Center Department of General Services. December 6.

New York City 1973. Fire Safety in Office Buildings, New York City - Local Law 5, The City of New York. January 18.

New York City 1979. Revised Compliance Dates for Local Law 5/1973, New York City - Local Law 86, The City of New York. December 13.

NIST. 2005. NIST NCSTAR 1: Final Report on the Collapse of the World Trade Center Towers. Gaithersburg, MD. National Institute of Standards and Technology, U.S. Department of Commerce.

NIST. 2005. NIST NCSTAR 1-4: Active Fire Protection Systems. Gaithersburg, MD. National Institute of Standards and Technology, U.S. Department of Commerce.

NIST. 2005. NIST NCSTAR 1-4d: Smoke Management Systems. Gaithersburg, MD. National Institute of Standards and Technology, U.S. Department of Commerce.

NIST. 2005. NIST NCSTAR 1-7: Occupant Behavior, Egress, and Emergency Communications. Gaithersburg, MD. National Institute of Standards and Technology, U.S. Department of Commerce.

PANYNJ (Port Authority of New York and New Jersey). 1986. World Trade Center Instruction Manual No. 23: Operation and Maintenance of Fire Protection Systems. New York, NY, February.

PANYNJ 1995. The Port Authority of NY & NJ World Trade Center Fire Safety Plan (Towers One and Two), The Port Authority of New York and New Jersey, New York. WTCI-13-NYC.

Powers, W. R. 1975. One World Trade Center Fire, New York, N.Y., February 13, 1975. National Fire Protection Association, Boston, MA, pp. 1-15.