# EXECUTIVE SUMMARY

## Background

In response to the terrorist attacks of September 11, 2001, the National Institute of Standards and Technology (NIST) initiated a formal federal building and fire safety investigation of the World Trade Center disaster on August 21, 2002. NIST issued two written updates on its WTC investigation activities (December 2002 and December 2003) and a detailed technical progress report in May 2003.

In addition, NIST held a public meeting in New York City on February 12, 2004 to solicit comments on (1) specific technical aspects of the investigation, (2) additional information that NIST might consider in the time remaining; and (3) areas that NIST should consider, within the scope of its investigation, in making recommendations for specific improvements to building and fire practice, standards, and codes, and their timely adoption.

The present report provides details of the technical progress made since the May 2003 report was published. NIST expects to release the draft of the final investigation report for public comment in December 2004. NIST's investigation is still ongoing. Current findings may be revised and additional findings will be presented in the December 2004 report. **NIST is not making any recommendations at this time. All recommendations will be made in the final report.**

## Status of Progress

This report includes:

- A comprehensive summary of interim findings and accomplishments for each of the independent investigation objectives.
- A working hypothesis for the collapse of the WTC towers that identifies the chronological sequence of major collapse events and allows for different possible load redistribution paths and damage scenarios currently under analysis. The hypothesis will be refined on the basis of these analyses to determine the most probable collapse sequence for each building.
- A working hypothesis for the collapse of the 47-story WTC 7 based on an initiating event, a vertical progression at the east side of the building, a subsequent horizontal progression from the east to the west side of the building, and global collapse.
- Key visual observations on the building, fire, and smoke conditions in all three WTC buildings (the WTC towers and WTC 7) from analysis of a large collection of photographic and videographic images.
- A summary of major progress in building comprehensive models for analyzing the most probable collapse sequence, from aircraft impact to collapse initiation, and simplified analytical models with results to supplement those from detailed models.

- Results from experimental work to (1) analyze the recovered WTC structural steel, (2) support the fire dynamics and thermal modeling, and (3) conduct fire endurance testing of typical floor systems of the WTC towers based on ASTM E 119.

- Reports on the inventory and identification of the steels recovered from the WTC buildings and on the contemporaneous (1960s era) structural steel and welding specifications used to construct the WTC towers.

- First-person interviews of nearly 1,200 WTC occupants, first responders, and families of victims to collect data on occupant behavior, evacuation, and emergency response with some early results from analysis of that data.

- Review of the New York City 911 tapes and logs and the transcripts of about 500 interviews with Fire Department of New York (FDNY) employees involved in WTC emergency response activities with analysis still in progress.

- Preliminary analysis of emergency responder communication tapes recorded by the Port Authority, including the high-rise radio repeater, and by the New York Police Department (NYPD), including internal department operations.

- Analysis of building and fire codes and practices, including: a review of available documents related to the design, construction, operation, maintenance, and modifications to the three WTC buildings; and a comparison of selected building regulatory and code requirements.

- Analysis of the design, capabilities, and performance of the installed active fire protection systems for all three WTC buildings (i.e., fire alarm, sprinkler, and smoke management systems) with documentation of the fire history of the WTC towers.

- Progress on both the research and development and the dissemination and technical assistance programs related to the WTC Investigation.

- Seventeen appendices with detailed interim reports on specific technical tasks within the eight investigation projects where significant progress has been made.

NIST has received large amounts of data and information related to the design, construction, operation, inspection, maintenance, repair, alterations, emergency response, and evacuation of the WTC complex. NIST has received considerable cooperation from the Port Authority of New York and New Jersey (PANYNJ or Port Authority), the City of New York, the National Commission on Terrorist Attacks Upon the United States (9-11 Commission), designers, leaseholders, contractors, suppliers, insurers, news media, tenants, first responders, survivors, and families of victims.

NIST has received all of the essential information it needs for the WTC Investigation. NIST has made a few requests for materials that are lost, currently pending, or not yet located; NIST is making efforts to assemble this information from various sources since much of it was lost when the buildings collapsed. NIST continues to pursue other materials that can further clarify some aspects of the Investigation.

The Web site http://wtc.nist.gov provides comprehensive information on the WTC investigation and related work to improve the safety of buildings, their occupants, and first responders.

## Investigation Objectives and Key Questions

The key interim findings are summarized below in subsections that relate to the investigation objectives contained in the NIST investigation plan (see Chapter 1 for a comprehensive discussion of all interim findings). The investigation objectives are:

1. To determine (a) why and how the WTC 1 and WTC 2 collapsed following the initial impact of the aircraft, and (b) why and how the 47-story WTC 7 collapsed.

2. To determine why the loss of life and injuries were so low or so high depending on location, including technical aspects of fire protection, occupant behavior, evacuation, and emergency response.

3. To determine the procedures and practices which were used in the design, construction, operation, and maintenance of the WTC buildings.

4. To identify, as specifically as possible, areas in national building and fire codes, standards, and practices that warrant revision.

Among the specific questions that NIST is investigating within the above four objectives are the following:

- How and why did WTC 1 stand nearly twice as long as WTC 2 before collapsing (103 min versus 56 min), though they were hit by virtually identical aircraft?

- What factors related to normal building and fire safety considerations not unique to the terrorist attacks of September 11, 2001, if any, could have delayed or prevented the collapse of the WTC towers?

- Would the undamaged WTC towers have remained standing in a normal major building fire?

- What factors related to normal building and fire safety considerations, if any, could have saved additional WTC occupant lives or could have minimized the loss of life among the ranks of first responders on September 11, 2001?

- How well did the procedures and practices used in the design, construction, operation, and maintenance of the WTC buildings conform to accepted national practices, standards, and codes?

## Context for Findings

When reviewing these interim findings, the following should be considered:

- Buildings are not specifically designed to withstand the impact of fuel-laden commercial airliners. While documents from the PANYNJ indicate that the impact of a Boeing 707 flying at 600 mph, possibly crashing into the 80th floor, was analyzed during the design of the WTC towers in February/March 1964, the effect of the subsequent fires was not considered. Building codes do not require building designs to consider aircraft impact.

- Buildings are not designed for fire protection and evacuation under the magnitude and scale of conditions similar to those caused by the terrorist attacks of September 11, 2001.

- The load conditions induced by aircraft impact and the extensive fires on September 11, 2001, which triggered the collapse of the WTC towers, fall outside the norm of design loads considered in building codes.

- Prior evacuation and emergency response experience in major events did not include the total collapse of tall buildings such as the WTC towers and WTC 7 that were occupied and in everyday use; instead, that experience suggested that major tall building fires result in burnout conditions, not global building collapse.

- The PANYNJ was created as an interstate entity, under a clause of the U.S. Constitution permitting compacts between states, and is not bound by the authority of any local, state, or federal jurisdiction, including local building and fire codes. The PANYNJ's longstanding policy is to meet and, where appropriate, exceed the requirements of local building and fire codes.

## Collapse of the WTC Towers

***Working Hypothesis.*** The following chronological sequence of major events led to the eventual collapse of the towers; specific load redistribution paths and damage scenarios are currently under analysis to determine the most probable collapse sequence for each building:

- Aircraft impact damage to perimeter columns, resulting in redistribution of column loads to adjacent perimeter columns and to the core columns via the hat truss;

- After breaching the building's exterior, the aircraft continued to penetrate into the buildings, damaging core columns with redistribution of column loads to other intact core and perimeter columns via the hat truss and floor systems;

- The subsequent fires, influenced by the post-impact condition of the fireproofing, weakened columns and floor systems (including those that had been damaged by aircraft impact), triggering additional local failures that ultimately led to column instability; and

- Initiation and horizontal progression of column instability resulted when redistributing loads could not be accommodated any further. The collapses then ensued.

The working hypothesis (see Chapter 1 and Appendix Q for a detailed description) is consistent with all evidence currently held by NIST, including photographs and videos, eyewitness accounts, and emergency communication records. In addition to evidence of hanging floor slabs on the east and north faces of WTC 2 that were reported previously, new evidence has been found showing inward bowing of perimeter columns several minutes (less than 10 min) prior to collapse in both WTC towers. Inward bowing of about a quarter to a third of the perimeter columns was observed in photographs on the south face of WTC 1 and the east face of WTC 2 in regions that contained active fires. Further, initiation of global collapse was first observed by the tilting of building sections above the impact regions of both WTC towers. WTC 1 tilted to the south (observed via antenna tilting in a video recording) and WTC 2 tilted to the east and south and twisted in a counterclockwise motion.

Discussed below are interim findings for several factors relevant to the condition and collapse of the WTC towers, including the innovative structural system, aircraft impact and the ensuing fires, post-impact condition of the fireproofing, and the quality and properties of the structural steel used in the WTC towers. In addition to the role played by these factors in the collapse of the WTC towers, NIST continues to investigate the relative roles of the perimeter and core columns and the composite floor system, including connections.

***Innovative Structural System.*** The WTC tower structures represented an innovative structural system when they were built, incorporating many new and unusual features. Among them, two features require additional consideration: the composite floor system, using open-web bar joist elements, to provide lateral stability and diaphragm action, and the use of wind tunnel testing to estimate lateral wind loads—which were a major governing factor in the design of the WTC tower structures.

The performance of the former under fire conditions, which is relevant to evaluating the collapse of the WTC towers, was of some concern to the building owner and designers throughout the life of the buildings. The concern stemming from the latter, identified by the leaseholder and insurers in litigation after September 11, 2001, is representative of the still evolving state-of-knowledge in the field of wind engineering and is relevant to establishing the baseline performance of the WTC towers and to assessing the practices and procedures used in design.

The fire protection of a truss-supported floor system by directly applying spray-on fireproofing to the steel trusses was innovative and not consistent with prevailing practice at the time the WTC towers were designed and constructed. The fireproofing thickness required to meet the 2 h fire rating evolved from the specified 1/2 in. when the WTC towers were built to 1-1/2 in. for use in upgrading the fireproofing some years prior to September 11, 2001. Unrelated to the WTC buildings, a model code evaluation service recommended in June 2001 a minimum thickness of 2 in. for a similar floor system. This three to four fold difference in specifying the fireproofing thickness to meet the required fire rating for a structural assembly is extraordinarily large and confirms the lack of technical basis in the selection of thickness.

While the benefits of conducting a full-scale fire endurance test to determine the required fireproofing thickness were recognized by the building designers, no tests were conducted on the floor system used in the WTC towers to establish a fire endurance rating. NIST has awarded a contract to Underwriters Laboratories (UL) to determine the fire resistance rating of typical WTC floor systems under both as-specified and as-built conditions. The tests, expected to be conducted in August 2004, are also designed to evaluate the effects of test scale, fireproofing thickness, and thermal restraint.

Further, use of the "structural frame" approach, in conjunction with the prescriptive fire rating, would have required the floor system trusses, the core floor framing, and perimeter spandrels in the WTC towers—essential to the stability of the building as a whole—to be 3 h fire-rated as the columns were required to be rated by the 1968 New York City (NYC) Building Code. This approach, which appeared in the Uniform Building Code (a model building code) as early as 1953, was carried into the 2000 International Building Code (one of two current national model codes). Neither the 1968 edition of the NYC Building Code which was used in the design of the WTC towers, nor the 2001 edition of the code, adopted the "structural frame" requirement.

Results of two sets of wind tunnel tests conducted for the WTC towers in 2002 by independent laboratories, and voluntarily provided to NIST by the parties to an insurance litigation, show large differences, of as much as about 40 percent, in resultant forces on the structures, i.e., overturning moments and base shears. In addition, the wind loads estimated from these tests are about 20 percent to 60 percent higher than those apparently used in the original design of the WTC towers, also obtained from wind tunnel testing. NIST is conducting an independent analysis to establish the baseline performance of the WTC towers under the original design wind loads and will compare those wind load estimates with then-prevailing code requirements. Wind loads were a major governing factor in the design of structural components that made up the frame-tube steel framing system.

***Relative Roles of Aircraft Impact and Fires.*** The two WTC towers withstood the initial impact of virtually identical aircraft (Boeing 767-200ER) during the terrorist attacks of September 11, 2001. The robustness of the perimeter frame-tube system and large dimensional size of the WTC towers helped the buildings withstand the aircraft impact. The WTC towers displayed significant reserve capacity, vibrating immediately following impact with amplitudes that were about half the amplitudes for design wind conditions expected by the building designers and an oscillation period nearly equal to that measured for the undamaged building.

Preliminary aircraft impact damage analysis indicates that the impact of a fuel-filled wing section results in extensive damage to the exterior wall panel, including complete failure of the perimeter columns. A normal impact of the exterior wall by an empty wing segment produces significant damage to the perimeter columns, not necessarily complete failure. Also, engine impact against an exterior wall panel results in a penetration of the exterior wall and failure of impacted perimeter columns. The residual velocity and mass of the engine after penetration of the exterior wall is sufficient to fail a core column in the event of a direct impact.

Fires played a major role in further reducing the structural capacity of the buildings, initiating collapse. While aircraft impact damage did not, by itself, initiate building collapse, it contributed greatly to the subsequent fires by:

- Compromising the sprinkler and water supply systems;
- Dispersing jet fuel and igniting building contents over large areas;
- Creating large accumulations of combustible matter containing aircraft and building contents;

- Increasing the air supply into the damaged buildings that permitted significantly higher energy release rates than would normally be seen in ventilation limited building fires, allowing the fires to spread rapidly within and between floors; and

- Damaging ceilings that enabled "unabated" heat transport over the floor-to-ceiling partition walls and to structural components.

The jet fuel, which ignited the fires, was mostly consumed within the first few minutes after impact. The fires that burned for almost the entire time that the buildings remained standing were due mainly to burning building contents and, to a lesser extent, aircraft contents, not jet fuel.

By contrast, typical office furnishings were able to sustain intense fires for at least an hour on a given WTC floor. The typical WTC office floor using modern workstation furnishings had on average about 4 pounds per square foot (psf) of combustible materials on floors without unusual file rooms, film storage, etc. Further, the mass of aircraft solid combustibles was significant relative to the building combustibles in the immediate impact region of both WTC towers.

Consistent with available photographic and videographic evidence, computer simulations conducted by NIST have been able to capture the broad patterns of fire movement around the floors, with the flames in a given location lasting for about 20 min before spreading to adjacent, yet unburned combustibles. This spread is generally continuous due to the relatively even distribution of combustibles and the paucity of interior partitions. There are some observed instances where fires persisted over longer durations in regions with accumulated combustible debris and other instances of sudden or interrupted fire spread.

Applying the 1968 NYC Building Code, the WTC towers were required to have 1 h fire-rated tenant separations, but the code did not impose any minimum compartmentation requirements (e.g., 7,500 $ft^2$) to mitigate the horizontal spread of fire in buildings with large open floor plans. The sprinkler option was chosen for the WTC towers in preference to the compartmentation option in meeting the subsequent requirements of Local Law 5, adopted by New York City in 1973. The affected floors in the WTC towers were mostly open—with a modest number of perimeter offices and conference rooms and an occasional special purpose area. Some floors had two tenants, and those spaces, like the core areas, were partitioned (slab to slab). Photographic and videographic evidence confirms that even non-tenant space partitions (such as those that divided spaces to provide corner conference rooms) provided substantial resistance to fire spread in the affected floors. For the duration of about 50 min to 100 min prior to building collapse that the fires were active, the presence of undamaged 1 h fire-rated compartments may have assisted in mitigating fire spread and consequent thermal weakening of structural components.

***Role of Fireproofing Conditions.*** NIST has developed a rigorous technical approach (see Appendix I for details) to evaluate the role fireproofing conditions may have played in the collapse of the WTC towers. The approach considers both the thickness and variability of fireproofing and the extent to which fireproofing may have been damaged due to aircraft impact.

In general, the floor systems in WTC 1 subject to aircraft impact and subsequent fires on September 11, 2001 had upgraded or thicker fireproofing (1.5 in. specified), while the affected floors in WTC 2 had the original fireproofing (0.5 in. specified).

The response of a structural component to fires is sensitive to variability in fireproofing thickness along its length. For the original fireproofing in the WTC towers, the as-applied fireproofing thickness on the floor trusses (0.75 in. average and 0.4 coefficient of variation) was found to be thermally equivalent to a uniform thickness of 0.6 in., which is greater than the specified minimum thickness of 0.5 in. For the upgraded fireproofing in some floors of the WTC towers, the as-applied upgraded fireproofing thickness (2.5 in. average and 0.24 coefficient of variation) was found to be thermally equivalent to a uniform thickness of 2.2 in., which is greater than the specified minimum thickness of 1.5 in. An alternative criterion for determining the equivalent thickness is currently being examined to confirm these findings.

Based on simplified analytical models, it was found that acceleration of a structural element, on the order of 100 to 150 times the acceleration due to gravity (or 100 g to 150 g), would be required to dislodge fireproofing similar to that used in the WTC towers with a typical thickness of about 1 in. from the structural component. Experiments are underway to verify the results of these simplified analyses. Similarly, analytical studies are underway to estimate the magnitude of accelerations of the structural members due to aircraft impact, from which the regions where fireproofing may have been dislodged will be identified. Those results are being used to analyze the role of the post-impact condition of the fireproofing, including its thickness, on the collapse of the WTC towers.

***Analysis of Recovered WTC Steel.*** NIST has 236 pieces of steel in its possession; this collection of steel is adequate for purposes of determining the quality and properties of steel for the investigation. The regions of impact and fire damage were emphasized in the selection of steel pieces for the investigation. As a result, pieces of all 14 specified steel grades for exterior panels in the WTC towers are available, as well as the two specified grades that represent 99 percent of the core columns and both specified grades for the steel trusses that comprised the composite floor truss system.

Analysis of steel recovered from the WTC towers, based on stampings on the steel and mechanical tests, indicates that the correct specified materials were provided for the specified elements. When these data were combined with pre-collapse photographic images of damaged steel, it was found that aircraft impacted pieces of steel recovered from WTC 1 were in the precise locations as specified in the design drawings. Metallography and mechanical property tests indicate that the strength and quality of the steel used in the towers was as specified, typical of the era, and likely met all qualifying test requirements.

The room-temperature strength of the steel used in the towers met the relevant standards and, in many instances, exceeded the requirements by 5 percent to 10 percent. Work is ongoing to analyze the performance of the steel building components under impact and fire conditions up to initiation of global building collapse.

## Collapse of the 47-Story WTC 7 Building

***Working Hypothesis.*** The working hypothesis for the collapse of the 47-story WTC 7 building, if it remains viable upon further analysis, suggests that it was a classic progressive collapse including: an initiating event, a vertical progression at the east side of the building, a subsequent horizontal progression

from the east to the west side of the building, and global collapse. The chronological sequence of major events under analysis is:

- An initial local failure at the lower floors (below Floor 13) of the building due to fire and/or debris induced structural damage of a critical column (the initiating event), which supported a large span floor bay with an area of about 2,000 $ft^2$;

- Vertical progression of the initial local failure up to the east penthouse, as large floor bays were unable to redistribute the loads, bringing down the interior structure below the east penthouse; and

- Horizontal progression of the failure across the lower floors (in the region of Floors 5 and 7, that were much thicker than the rest of the floors), triggered by damage due to the vertical failure, resulting in disproportionate collapse of the entire structure.

***Visual Observations.*** The working hypothesis (see Chapter 1 and Appendix L for a detailed description) is consistent with all evidence currently held by NIST, including photographs and videos, eyewitness accounts, and emergency communication records. Specifically, the evidence indicates:

- The sequence of failures associated with the sinking of the east penthouse roof structure into the building, the near simultaneous window breakage along the east side of the north face, the sinking of the other roof structures, the near simultaneous breakage of a second set of windows along the west side of the north face, and the entire north façade above the 13th floor appearing to drop as an intact unit.

- Structural damage on the south face and southwest corner from WTC 1 debris that included (1) a multi-story gash across approximately a quarter to a third of the lower portion of the south face and extending inwards to the core, (2) approximately two columns in the southwest corner and related floor areas missing from Floors 8 to 18, and (3) severed spandrels between exterior columns near the southwest corner from the roof level for at least 5 to 10 floors.

- The sequence of fires in WTC 7—which began soon after WTC 1 collapsed—was observed (1) on the south face and near the southwest corner on Floors 22, 29, and 30, (2) across Floors 11 and 12 on the east face, from the south to the north, (3) on Floors 7 and 12 along the north face, (4) on Floors 8 and 13, with the fire on Floor 8 moving from west to east and the fire on Floor 13 moving from east to west, and (5) finally, on Floors 7, 8, 9, and 11 near the middle about half an hour before collapse; Floor 12 was burned out by this time. Interview responses indicate that there was no water in the standpipe system supplying the sprinklers in WTC 7.

***Fuel System for Emergency Power.*** Based on a review of the fuel system for emergency power in WTC 7, Floor 5—which did not have any exterior windows and contained the only pressurized fuel distribution system on the south, west and north floor areas—is considered a possible fire initiation location, subject to further data and/or analysis that improve knowledge of fire conditions in this area.

## Evacuation and Emergency Response

***Building Population Characteristics.*** Based on information and data gathered during the first-person interviews of WTC surviving occupants:

- It is estimated that 17,400 occupants (± 1,200) were present in the WTC towers on the morning of September 11, 2001. The initial population of each tower was similar: 8,900 (± 750) in WTC 1 and 8,500 (± 900) in WTC 2. Of those present on September 11, 2001, 16 percent were also present during the 1993 bombing.

- About 6 percent of the surviving occupants reported a pre-existing limitation to their mobility. These limitations included obesity, heart condition, needing assistance to walk, pregnancy, asthma, being elderly, chronic condition, recent surgery or injury, and other.

- About 7 percent of the surviving occupants reported having special knowledge about the building. These included fire safety staff, floor wardens, searchers, building maintenance, and security staff. Searchers assist the floor wardens in facilitating evacuation.

***Evacuation.*** Two-thirds of surviving occupants reported having participated in a fire drill in the 12 months prior to September 11, 2001, while 17 percent reported that they received no training during that same period. Of those participating in fire drills, 93 percent were instructed about the location of the nearest stairwell. Overall, slightly over half of the survivors, however, had never used a stairwell at the WTC prior to September 11, 2001.

Approximately 87 percent of the WTC tower occupants, including more than 99 percent of those below the floors of impact, were able to evacuate successfully. Two-thousand one-hundred fifty-nine building occupants (1,560 in WTC 1 and 599 in WTC 2) and an additional 433 first responders, including security guards but not aircraft passengers and crew or bystanders, were reported to have lost their lives on September 11, 2001.

Rough initial estimates indicate that about 20 percent or more of those who were in the WTC towers and lost their lives may have been alive in the buildings just prior to their collapse. This estimate, which will be refined as data analysis is completed, assumes that nearly all of the first responders and 76 building occupants below the floors of impact, but none of the people at or above the floors of impact, may have been alive. It is estimated that there were a total of 2,592 building occupants and first responders who were in the WTC towers and lost their lives.

Overall, about 7,900 survivors evacuated WTC 2 in 73 min (i.e., from the instant the WTC 1 was struck by aircraft until WTC 2 collapsed) while about 7,500 survivors evacuated WTC 1 in 103 min. Thus, the overall evacuation rate in WTC 2 (108 survivors per min) was about 50 percent faster than that in WTC 1 (73 survivors per min). Functioning elevators allowed many survivors to evacuate WTC 2 prior to aircraft impact. Most of the elevators in WTC 1 were not functioning, and survivors could only use the stairways. The stairwells, with partition wall enclosures that provided a 2 h fire-rating but little structural integrity, were damaged in the region of the aircraft impacted floors.

- After the first airplane struck WTC 1 and before the second airplane struck WTC 2, the survivors in WTC 2 were twice as likely as those in WTC 1 to have already exited the

building (41 percent versus 21 percent). The rate of evacuation completion in WTC 2 was twice the rate in WTC 1 during that same period.

- Soon after WTC 2 was struck by the airplane until about 20 min before each building collapsed, the survivors in WTC 2 and WTC 1 had exited at about the same rate (the prior evacuation rate of WTC 1).

- During the last 20 min before each building collapsed, the evacuation rate in both buildings had slowed to about one-fifth the immediately prior evacuation rate. This suggests that for those seeking and able to reach and use undamaged exits and stairways, the egress capacity (number and width of exits and stairways) was adequate to accommodate survivors.

Preliminary results from application of existing computer egress models for a full capacity evacuation of a single WTC tower with 25,000 occupants and visitors indicate a movement time of 2 h and 15 min. This is a minimum time estimate; the simulation assumed that there was no survivor delay, continual movement on the stairs, and no damage to the egress system. It was also assumed that elevators were not available. The egress model estimate for a September 11, 2001 capacity evacuation under the same assumptions is about 50 min, which is 2.5 times less than the time estimate for evacuating 25,000 people.

Given that the actual evacuation time on September 11, 2001 was about 100 min without elevator use, a full capacity evacuation of each WTC tower with 25,000 people would have required about 4 h (2.5 times 100 min). To achieve a significantly faster total evacuation at full capacity would have required increases in egress capacity (number and width of exits and stairways).

In addition to the full evacuation of the WTC towers on September 11, 2001, a full evacuation was ordered during the 1993 bombing at the WTC site and during a 1977 terrorist threat associated with bombings in two remote midtown Manhattan buildings. Sufficient data do not exist on the frequency with which full evacuations are conducted in buildings not at risk for terrorist attacks and whether this frequency has increased since September 11, 2001 among the general population that did not directly experience the events on that day.

***Roof Evacuation.*** A preliminary evaluation indicates that the PANYNJ's standard occupant evacuation procedures and drills required the use of stairways to exit at the bottom of the WTC towers. The standard procedures were to keep the doors to the roof locked with a key being required to gain roof access. The PANYNJ reports that it never advised tenants to evacuate upward.

There were at least two decedents who had tried to get to the roof and found the roof access locked to both the WTC towers. In addition, a PANYNJ employee trapped on Floor 105 of WTC 2 was unable to walk down the stairs, or go to the roof as instructed on radio by another PANYNJ employee.

The NYPD aviation unit arrived at the WTC site soon after WTC 1 was attacked. Despite repeated attempts to examine the possibility of roof rescue, smoke and heat conditions at the top of the WTC towers prevented the conduct of safe roof evacuation operations.

Considering the capacity of typical helicopters and travel times, it is not clear what fraction of the large number of occupants could have been evacuated from the WTC towers prior to their collapse had roof rescue been possible on September 11, 2001.

***Emergency Communication Systems.*** A partial analysis of emergency responder communications (see Appendix P for details) has been completed, including:

- Audio communications tapes recorded by the PANYNJ, including a recording of the FDNY's city-wide high-rise Channel 7 (Port Authority Police Department's [PAPD] Channel 30) radio repeater that was located at the WTC.

- Audio tapes copied from original NYPD communications tapes, including NYPD internal department operations.

FDNY communications recordings from the WTC location on September 11, 2001, are not available because the primary field communication truck was in the shop for repairs. A back-up field-communications van used in its place—which did not have a recording capability—was destroyed when the WTC towers collapsed.

The best record of radio communications reflecting fire department operations came from the FDNY Channel 7/PAPD Channel 30 and first person accounts provided by FDNY personnel during their interviews. The PANYNJ installed the radio repeater system for use by FDNY after the 1993 bombing.

The analysis of the emergency responder communication tapes indicates that:

- After the first aircraft struck WTC 1, there was an approximate factor of 5 peak increase in traffic level over the normal level of emergency responder radio communications, followed by an approximate factor of 3 steady increase in the level of subsequent traffic.

- A surge in communications traffic volume made it more difficult to handle the flow of communications and delivery of information.

- Roughly a third to a half of the radio messages transmitted during these radio traffic surge conditions were not complete messages or understandable.

- FDNY's city-wide high-rise Channel 7 (PAPD Channel 30) radio repeater at the WTC site was operating.

- NYPD aviation unit personnel reported critical information about the impending collapse of the WTC towers several minutes prior to their collapse. No evidence has been found to suggest that the information was further communicated to all emergency responders at the scene.

Several FDNY personnel at the incident site did not think that the high-rise radio repeater was working. This is based on radio communications tests that were conducted by two chief officers working inside WTC 1 when the first command post was being set up in that lobby. Following this radio test, a chief officer involved in the test chose to use different channels for command and tactical communications during the incident. However, as FDNY operations increased in WTC 2, it was determined by FDNY members that the high-rise repeater was functioning, and use of the channel developed.

While the preliminary analysis indicates that the repeater was operating, there also appears to have been some type of malfunction with the communications equipment that was detected, but not identified, by

FDNY officers during the initial test. NIST continues to evaluate the repeater system and its operations, as well as the handheld radios, which were used on September 11, 2001. These findings will be updated and additional findings will be documented when the investigation is complete.

***Command and Control.*** Based on face-to-face interviews, NIST has determined that first responders—including key incident commanders—did not have adequate information (voice, video, and data) on, nor an overall perspective of, the conditions in the WTC buildings and what was happening elsewhere at the WTC site. Interagency information sharing was inadequate.

The three FDNY suitcase-based, magnetic Command Boards that were set up at the incident site—on which a record is kept of the identification of the units on site, their assignment, location, and activities—were damaged and lost with the collapse WTC 2. Since there was no back-up capability for the Command Boards, all information related to command, control, and accountability was lost.

***Active Fire Protection Systems.*** Investigation of the design, capabilities, and performance of the active fire protection systems in the WTC towers and WTC 7 indicates that:

- The smoke management systems in the WTC towers were not activated during the fires on September 11, 2001. It was determined that the likelihood of these systems being functional was very low due to the damage inflicted by the aircraft impacts.

- The analysis of smoke flow in WTC 1 and WTC 2 on September 11, 2001 shows that HVAC (heating, ventilation, and air-conditioning) ductwork was a major path for vertical smoke spread in the buildings. Fire dampers were installed in the systems, but not smoke dampers that could have provided a barrier to hot gas and smoke penetration into the vertical HVAC shafts. However, smoke dampers were not available when the towers were built.

- Modeling results show that stair pressurization systems would have provided minimal resistance to the passage of smoke in WTC 1 and WTC 2 had they been installed on September 11, 2001. While the existence of such systems was known when the WTC towers were built, the alternative smoke purge system used in the WTC towers was considered to be equivalent.

- The fire alarm system in WTC 7 sent only one signal (at 10:00:52 a.m. shortly after the collapse of WTC 2) to the monitoring company indicating a fire condition. The signal did not contain any specific information about the location of the fire within the building. Since the system was placed on TEST for a period of 8 h beginning at 6:47:03 a.m. on September 11, 2001, alarm signals would not have been shown on the operator's display; instead, they would have to be recorded into the history file.

- The resistance to failure of the fire alarm system communications paths between the fire command station and occupied WTC tower floors could have been enhanced if fiber optic communications cable had been used instead of copper lines. Fiber optic cable is not susceptible to electric short-circuits and would have provided full communications with fire alarm system components, including voice communications systems, to the point where the cable was severed. Electric shorts in the voice communications disable that communication system over the entire cable length affected by the electric short-circuit. During initial design

of the system, the PANYNJ requested, but did not receive, approval of the City of New York for use of fiber optic communication cable in the system. The NYC code required copper wiring.

- There was adequate multiple point redundancy in the water supply to the sprinkler system, and the water flow rate exceeded the minimum requirement by a considerable margin. However, the potential for single point failure of the water supply to the fire sprinklers existed at each floor due to lack of redundancy in the sprinkler riser system that provided only one water supply connection on each floor. While this lack of redundancy may not have had an impact on September 11, 2001 because the sprinkler system was damaged by aircraft impact, it could have made a difference in other building emergencies.

## Procedures and Practices

The 110-story WTC towers were among the world's tallest buildings, while the 47-story WTC 7 represented a more typical tall building. These buildings provide case studies to document, review, and, if needed, improve the procedures and practices used in the design, construction, operation, and maintenance of tall buildings. This investigation objective is independent of other objectives which are focused specifically on the consequences of the attack on September 11, 2001, viz., the building collapses, evacuation, and emergency response. While some findings under this objective are directly relevant to the events of September 11, 2001, others are concerned with general building and fire safety procedures and practices.

***Applicable Building Codes.*** Although not required to conform to NYC codes, the PANYNJ adopted the provisions of the proposed 1968 edition of the NYC Building Code, more than three years before it went into effect. The 1968 edition allowed the PANYNJ to take economic advantage of less restrictive provisions compared with the 1938 edition that was in effect when design began for the WTC towers in 1962. The 1968 code:

- Eliminated a fire tower[1] as a required means of egress;
- Reduced the number of required stairwells from 6 to 3 and the size of doors leading to the stairs from 44 in. to 36 in.;
- Reduced the fire rating of the shaft walls in the building core from 3 h to 2 h;
- Changed partition loads from 20 psf to one based on weight of partitions per unit length (that reduced such loads for many buildings including the WTC buildings); and
- Permitted a 1 h reduction in fire rating for all structural components (columns from 4 h to 3 h and floor framing members from 3 h to 2 h).

[1] A fire tower (also called a smoke-proof stair) is a stairway that is accessed through an enclosed vestibule that is open to the outside or to an open ventilation shaft providing natural ventilation that prevents any accumulation of smoke without the need for mechanical pressurization.

The NYC Department of Buildings reviewed the WTC tower drawings in 1968 and provided comments to the PANYNJ concerning the plans in relation to the 1938 NYC Building Code. The architect-of-record submitted to the PANYNJ responses to those comments, noting how the drawings conformed to the 1968 NYC Building Code.

In 1993, the PANYNJ and the NYC Department of Buildings entered into a memorandum of understanding that restated the PANYNJ's longstanding policy to assure that its facilities in the City of New York meet and, where appropriate, exceed the requirements of the NYC Building Code. The agreement also provided specific commitments to the NYC Department of Buildings regarding procedures to be undertaken by the PANYNJ to assure that buildings owned or operated by the PANYNJ are in conformance with the Building Standards contained in the NYC Building Code.

In 1993, the PANYNJ adopted a policy providing for implementation of fire safety recommendations made by local government fire departments after a fire safety inspection of a PANYNJ facility and for the prior review by local fire safety agencies of fire safety systems to be introduced or added to a facility. Later that year, the PANYNJ entered into an agreement with FDNY which reiterated the policy adopted by the PANYNJ and set forth procedures to assure that new or modified fire safety systems are in compliance with local codes and regulations.

***Standards, Codes, and Regulations.*** NIST has reviewed the then-prevailing and current standards, codes, and regulations relevant to assessing the procedures and practices used in the design, construction, operation, and maintenance of the WTC buildings. That review raises the following issues that merit further consideration (see Chapter 1 for a discussion and WTC-related rationale):

- Code provisions that would detail procedures to analyze and evaluate data from fire resistance tests of other building components and assemblies to qualify an untested building element.

- Code provisions that would require the conduct of a fire resistance test if adequate data do not exist from other building components and assemblies to qualify an untested building element.

- Regulations that would adopt code provisions using the "structural frame" approach to fire resistance ratings which requires structural members, other than columns, that are essential to the stability of the building as a whole to be fire protected to the same rating as columns.

- Code provisions that would ensure that structural connections are provided the same degree of fire protection as the more restrictive protection of the connected elements.

- Code provisions and standards that would establish whether the minimum mechanical and durability related properties of spray-applied fire resistive materials (SFRM) are sufficient to ensure acceptable in-service performance in buildings. While minimum bond strength requirements exist, there are no serviceability requirements for such materials to withstand typical shock, impact, vibration, or abrasion effects over the life of a building.

- Rigorous field application and inspection provisions and regulatory requirements that would assure that the as-built condition of the passive fire protection, such as SFRM, conforms to conditions found in fire resistance tests of building components and assemblies.

- Rigorous provisions and regulatory requirements for in-service inspections of passive fire protection during the life of the building.
- Early installation of sprinklers in existing buildings, not as an option in lieu of compartmentation.
- Standards and code provisions that would provide minimum structural integrity for the means of egress (stairwells and elevator shafts) in the building core which are critical to life safety.
- Standards and code provisions that would permit the installation of fire-protected elevators and their use for routine emergency access by first responders or as a secondary method (after stairwells) for emergency evacuation of building occupants.
- Explicit standards and code provisions for structural integrity that would mitigate progressive collapse.
- Standards and code provisions for conducting wind tunnel tests and for the methods used in practice to estimate design wind loads from test results.
- Regulatory requirements for retention of documents related to the design, construction, operation, maintenance, and modifications of buildings, including retention off-site. For example, there are few, if any, requirements for retention of documents throughout the service life of a building.

***Fire Safety and Egress Design Methods.*** Historical fire loss data over more than half a century, for different high-rise building occupancies, suggests that prescriptive requirements in standards and codes have considerable built-in conservatism to adequately protect building occupants. As a result, there has been a trend in recent decades to reduce fire rating and egress requirements, sometimes in conjunction with addition of other new and complementary fire protection requirements (e.g., detectors and sprinklers). The lower fire rating requirements when combined with the considerable increases in building design efficiency that have been achieved, have also led to reductions in the thermal mass of buildings—an indicator of how much heat energy a building can absorb passively without damage.

The empirical rules and test methods used in prescriptive design, which have evolved with experience over the years, do not lend themselves readily to evaluate whether the performance of building fire safety and egress systems is risk-consistent, considering both the hazards and the consequences of the hazards. Performance-based methods that explicitly define the design objectives and specific design-basis fire hazards or evacuation events are better suited to risk analysis, enabling appropriate protection to be provided where it is needed.

The increasing use of performance-based methods, as an alternative to prescriptive design, in fire safety and egress design, raises the following issues that merit further consideration (see Chapter 1 for a detailed discussion and rationale related to the WTC investigation):

- Considering fire as a design condition in structural design, including evaluation of the fire performance of the structure as a whole system. This design approach is already being used in building design practice for earthquake and wind hazards (e.g., a two-level design that

includes an operational event with a 10 percent probability of occurrence in 50 years and a life safety event with a 2 percent probability of occurrence in 50 years).

- Detailed procedures to select appropriate design-basis fire scenarios for performance-based design of the sprinkler system (e.g., a frequent but low severity fire), compartmentation (e.g., a moderate severity but less frequent fire), and passive protection of the structure (e.g., a maximum credible fire).

- Validated and verified tools for use in performance-based design practice to analyze the dynamics of building fires and their effects on the structural system that would allow engineers to evaluate structural performance under alternative fire scenarios and fire protection strategies. While considerable progress has been made in recent years in advancing the tools that will help to improve the fire-safe design of new structures and analyze conditions of existing structures, significant work remains to be done before adequate tools are available for use in routine practice.

- The technical basis to establish whether the construction classification and fire rating requirements are risk-consistent. Specifically, it is not apparent how the current height and area tables in building codes consider the technical basis for the progressively increasing risk to an occupant on the upper floors of tall buildings that are much greater than 200 ft in height. The maximum fire rating in current codes applies to any building more than about 12 stories in height.

- Sprinklers improve safety in most common building fires and prevent them from becoming large fires. The technical basis to establish the "sprinkler trade-off" in current codes, considering fire safety risk factors such as: (1) the complementary functions of sprinklers and fire-protected structural elements, (2) the different design-basis fire scenarios for which each system is designed to provide protection, and (3) the need for redundancy should one system fail to function as intended is not available. The sprinkler trade-off provides an economic incentive to encourage installation of sprinklers by allowing a lower fire rating for sprinklered buildings.

- The design of egress systems to achieve a target performance (e.g., evacuation rate or time) for a given occupant population by adequately considering travel distance, remoteness requirements, and human factors such as occupant size, stairwell environmental conditions, visibility, and congestion.

***Building Practices.*** While the PANYNJ entered into agreements with the NYC Department of Buildings in the 1990s with regard to conformance of PANYNJ buildings constructed in New York City to the NYC Building Code, the PANYNJ did not yield jurisdictional authority for regulatory and enforcement oversight to the NYC Department of Buildings. The PANYNJ was created as an interstate entity, under a clause of the U.S. Constitution permitting compacts between states, and is not bound by the authority of any local, state, or federal jurisdiction.

The architect is responsible for specifying the fire protection in current building practice. The structural engineer is not required to evaluate and certify that the passive fire protection is adequate to protect the structural system. In accordance with established practice, the structural engineer was not responsible for

the passive fire protection in the design of the WTC tower structures. In addition, there is no requirement to involve a fire protection engineer in the design and evaluation of a building's fire protection system. In some cases, architects retain fire protection engineers to assist with the fire protection design for a building. There are only a few academic degree programs or continuing education programs that qualify engineers (or architects) to evaluate the fire performance of structures. The current state-of-practice is not sufficiently advanced for engineers to routinely analyze the performance of a whole structural system under a prescribed design-basis fire scenario.

## Approach to Recommendations

In the United States, state and local governments are responsible for promulgating and enforcing building and fire regulations. With some exceptions, the state and local regulations are based on national model building and fire codes developed by private sector organizations. The model codes, in turn, reference voluntary consensus standards developed by a large number of private sector standards development organizations (SDOs) accredited by the American National Standards Institute (ANSI).

NIST is a non-regulatory agency of the U.S. Department of Commerce. NIST does not set building codes and standards, but provides technical support to the private sector and other government agencies in the development of U.S. building and fire practices, standards, and codes. NIST recommendations are given serious consideration by private sector organizations that develop national standards and model codes – which provide minimum requirements for public welfare and safety.

The NIST building and fire safety investigation of the WTC disaster has not yet formulated recommendations. However, in formulating its recommendations, NIST will consider the following:

- Findings from the first three independent investigation objectives related to building performance, evacuation and emergency response, and procedures and practices.
- Whether findings relate to the unique circumstances surrounding the terrorist attacks of September 11, 2001, or to normal building and fire safety considerations, including evacuation and emergency response.
- What technical solutions are needed, if any, to address potential risks to buildings, occupants, and first responders, considering both identifiable hazards and the consequences of those hazards?
- Whether the risk is in all buildings or limited to certain building types (e.g., height and area, structural system), buildings that contain specific design features, iconic/signature buildings, or buildings that house critical functions.

NIST urges organizations responsible for building and fire safety at all levels to carefully consider the interim findings contained in this report. NIST welcomes comments from technical experts and the public on the interim findings presented herein. Comments can be sent by e-mail to wtc@nist.gov, facsimile to (301) 975-6122, or regular mail to WTC Technical Information Repository, Stop 8610, 100 Bureau Drive, Gaithersburg, MD 20899-8610.

In its final report, a draft which is expected to be released in December 2004, NIST will recommend appropriate improvements in the way buildings are designed, constructed, maintained and used. It will be important for those recommendations to be thoroughly and promptly considered by the many organizations responsible for building and fire safety. As part of NIST's overall WTC response plan, the Institute has begun to reach out to these organizations to pave the way for timely, expedited consideration of recommendations stemming from this investigation. NIST also has expanded its research in areas of high priority need.