Statement of

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on

The Building and Fire Safety Investigation into the World Trade Center Collapse

before the

Committee on Science
House of Representatives

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Mr. Chairman, and members of the Committee, I am William Jeffrey, Director of the National Institute of Standards and Technology. I am pleased to appear today and testify on the building and fire safety investigation of the World Trade Center disaster carried out by the National Institute of Standards and Technology (NIST).

NIST announced its building and fire safety investigation of the World Trade Center (WTC) disaster on August 21, 2002.[1] This WTC Investigation was then conducted under the authority of the National Construction Safety Team (NCST) Act, which was signed into law on October 1, 2002.

The goals of the investigation of the WTC disaster were:

- To investigate the building construction, the materials used, and the technical conditions that contributed to the outcome of the WTC disaster after terrorists flew large jet-fuel laden commercial airliners into the WTC towers.

- To serve as the basis for:

  — Improvements in the way buildings are designed, constructed, maintained, and used;

  — Improved tools and guidance for industry and safety officials;

  — Recommended revisions to current codes, standards, and practices; and

  — Improved public safety

The specific objectives were:

1. Determine why and how WTC 1 and WTC 2 collapsed following the initial impacts of the aircraft and why and how WTC 7 collapsed;

2. Determine why the injuries and fatalities were so high or low depending on location, including all technical aspects of fire protection, occupant behavior, evacuation, and emergency response; and

3. Determine what procedures and practices were used in the design, construction, operation, and maintenance of WTC 1, 2, and 7.

4. Identify, as specifically as possible, areas in current building and fire codes, standards, and practices that warrant revision

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[1] NIST is a nonregulatory agency of the U.S. Department of Commerce. The purposes of NIST investigations are to improve the safety and structural integrity of buildings in the United States and the focus is on fact finding. NIST investigative teams are required to assess building performance and emergency response and evacuation procedures in the wake of any building failure that has resulted in substantial loss of life or that posed significant potential of substantial loss of life. NIST does not have the statutory authority to make findings of fault or negligence by individuals or organizations. Further, no part of any report resulting from a NIST investigation into a building failure or from an investigation under the National Construction Safety Team Act may be used in any suit or action for damages arising out of any matter mentioned in such report (15 USC 281a, as amended by P.L. 107-231).

APPROACH

To meet these goals, NIST complemented its in-house expertise with an array of specialists in key technical areas. In all, over 200 staff contributed to the investigation. NIST and its contractors compiled and reviewed tens of thousand of pages of documents; conducted interviews with over a thousand people who had been on the scene or who had been involved with the design, construction, and maintenance of the WTC; analyzed 236 pieces of steel that were obtained from the wreckage; performed laboratory tests that measured material properties, and performed computer simulations of the sequence of events that happened from the instant of aircraft impact to the initiation of collapse for each tower.

Cooperation in obtaining the resource materials and in interpreting the results came from a large number of individuals and organizations, including The Port Authority of New York and New Jersey and its contractors and consultants, Silverstein Properties and its contractors and consultants, the City of New York and its departments, the manufacturers and fabricators of the building components, the companies that insured the WTC towers, the building tenants, the aircraft manufacturers, the airlines, and the media.

The scarcity of physical evidence that is typically available in place for reconstruction of a disaster led to the following approach:

- Accumulation of copious photographic and video material. With the assistance of the media, public agencies and individual photographers, NIST acquired and organized nearly 7,000 segments of video footage, totaling in excess of 150 hours and nearly 7,000 photographs representing at least 185 photographers. This guided the Investigation Team's efforts to determine the condition of the buildings following the aircraft impact, the evolution of the fires, and the subsequent deterioration of the structure.

- Establishment of the baseline performance of the WTC towers, i.e., estimating the expected performance of the towers under normal design loads and conditions. The baseline performance analysis also helped to estimate the ability of the towers to withstand the unexpected events of September 11, 2001. Establishing the baseline performance of the towers began with the compilation and analysis of the procedures and practices used in the design, construction, operation, and maintenance of the structural, fire protection, and egress systems of the WTC towers. The additional components of the performance analysis were the standard fire resistance of the WTC truss-framed floor system, the quality and properties of the structural steels used in the towers, and the response of the WTC towers to the design gravity and wind loads.

- Conduct simulations of the behavior of each tower on September 11, 2001, in four steps:

    1. The aircraft impact into the tower, the resulting distribution of aviation fuel, and the damage to the structure, partitions, thermal insulation materials, and building contents.
    2. The evolution of multi-floor fires.
    3. The heating and consequent weakening of the structural elements by the fires.
    4. The response of the damaged and heated building structure, and the progression of structural component failures leading to the initiation of the collapse of the towers.

For such complex structures and complex thermal and structural processes, each of these steps stretched the state of the technology and tested the limits of software tools and computer hardware. For example, the investigators advanced the state-of-the-art in the measurement of construction material properties and in structural finite element modeling. New modeling capability was developed for the mapping of fire-generated environmental temperatures onto the building structural components.

The output of the four-step simulations was subject to uncertainties in the as-built condition of the towers, the interior layout and furnishings, the aircraft impact, the internal damage to the towers (especially the thermal insulation for fire protection of the structural steel, which is colloquially referred to as *fireproofing*), the redistribution of the combustibles, and the response of the building structural components to the heat from the fires. To increase confidence in the simulation results, NIST used the visual evidence, eyewitness accounts from inside and outside the buildings, laboratory tests involving large fires and the heating of structural components, and formal statistical methods to identify influential parameters and quantify the variability in analysis results.

- Combination of the knowledge gained into probable collapse sequences for each tower,[2] the identification of factors that contributed to the collapse, and a list of factors that could have improved building performance or otherwise mitigated the loss of life.

- Compilation of a list of findings that respond to the first three objectives and a list of recommendations that responds to the fourth objective.

SUMMARY OF FINDINGS

Objective 1: Determine why and how WTC 1 and WTC 2 collapsed following the initial impacts of the aircraft.

- The two aircraft hit the towers at high speed and did considerable damage to principal structural components (core columns, floors, and perimeter columns) that were directly impacted by the aircraft or associated debris. However, the towers withstood the impacts and would have remained standing were it not for the dislodged insulation (fireproofing) and the subsequent multi-floor fires. The robustness of the perimeter frame-tube system and the large size of the buildings helped the towers withstand the impact. The structural system redistributed loads from places of aircraft impact, avoiding larger scale damage upon impact. The hat truss, a feature atop each tower which was intended to support a television antenna, prevented earlier collapse of the building core. In each tower, a different combination of impact damage and heat-weakened structural components contributed to the abrupt structural collapse.

- In WTC 1, the fires weakened the core columns and caused the floors on the south side of the building to sag. The floors pulled the heated south perimeter columns inward, reducing their capacity to support the building above. Their neighboring columns quickly became overloaded as columns on the south wall buckled. The top section of the building tilted to the

[2] The focus of the Investigation was on the sequence of events from the instant of aircraft impact to the initiation of collapse for each tower. For brevity, this sequence is referred to as the "probable collapse sequence," although it includes little analysis of the structural behavior of the tower after the conditions for collapse initiation were reached and collapse became inevitable.

south and began its descent. The time from aircraft impact to collapse initiation was largely determined by how long it took for the fires to weaken the building core and to reach the south side of the building and weaken the perimeter columns and floors.

- In WTC 2, the core was damaged severely at the southeast corner and was restrained by the east and south walls via the hat truss and the floors. The steady burning fires on the east side of the building caused the floors on that side to sag. The floors pulled the heated east perimeter columns inward, reducing their capacity to support the building above. Their neighboring columns quickly became overloaded as columns on the east wall buckled. The top section of the building tilted to the east and to the south and began its descent. The time from aircraft impact to collapse initiation was largely determined by the time needed for the fires to weaken the perimeter columns and floor assemblies on the east and the south sides of the building. WTC 2 collapsed more quickly than WTC 1 because there was more aircraft damage to the building core, including one of the heavily loaded corner columns, and there were early and persistent fires on the east side of the building, where the aircraft had extensively dislodged insulation from the structural steel.

- The WTC towers likely would not have collapsed under the combined effects of aircraft impact damage and the extensive, multi-floor fires that were encountered on September 11, 2001 if the thermal insulation had not been widely dislodged or had been only minimally dislodged by aircraft impact.

- NIST found no corroborating evidence for alternative hypotheses suggesting that the WTC towers were brought down by controlled demolition using explosives planted prior to September 11, 2001. NIST also did not find any evidence that missiles were fired at or hit the towers. Instead, photographs and videos from several angles clearly showed that the collapse initiated at the fire and impact floors and that the collapse progressed from the initiating floors downward, until the dust clouds obscured the view.

Objective 2: Determine why the injuries and fatalities were so high or low depending on location, including all technical aspects of fire protection, occupant behavior, evacuation, and emergency response.

- Approximately 87 percent of the estimated 17,400 occupants of the towers, and 99 percent of those located below the impact floors, evacuated successfully. In WTC 1, where the aircraft destroyed all escape routes, 1,355 people were trapped in the upper floors when the building collapsed. One hundred seven people who were below the impact floors did not survive. Since the flow of people from the building had slowed considerably 20 minutes before the tower collapsed, the stairwell capacity was adequate to evacuate the occupants on that morning.

- In WTC 2, before the second aircraft strike, about 3,000 people got low enough in the building to escape by a combination of self-evacuation and use of elevators. The aircraft destroyed the operation of the elevators and the use of two of the three stairways. Eighteen people from above the impact zone found a passage through the damaged third stairway (Stairwell A) and escaped. The other 619 people in or above the impact zone perished. Eleven people who were below the impact floors did not survive. As in WTC 1, shortly

before collapse, the flow of people from the building had slowed considerably, indicating that the stairwell capacity was adequate that morning.

- About 6 percent of the survivors described themselves as mobility impaired, with recent injury and chronic illness being the most common causes; few, however, required a wheelchair. Among the 118 decedents below the aircraft impact floors, investigators identified seven who were mobility impaired, but were unable to determine the mobility capability of the remaining 111.

- A principal factor limiting the loss of life was that the buildings were only one-third to one-half occupied at the time of the attacks. NIST estimated that if the towers had been fully occupied with 20,000 occupants each, it would have taken just over 3 hours to evacuate the buildings and about 14,000 people might have perished because the stairwell capacity would not have been sufficient to evacuate that many people in the available time. Egress capacity required by current building codes is determined by single floor calculations that are independent of building height and does not consider the time for full building evacuation.

- Due to the presence of assembly use spaces at the top of each tower (Windows on the World restaurant complex in WTC 1 and the Top of the Deck observation deck in WTC 2) that were designed to accommodate over 1,000 occupants per floor, the New York City Building Code would have required a minimum of four independent means of egress (stairs), one more than the three that were available in the buildings. Given the low occupancy level on September 11, 2001, NIST found that the issue of egress capacity from these places of assembly, or from elsewhere in the buildings, was not a significant factor on that day. It is conceivable that such a fourth stairwell, depending on its location and the effects of aircraft impact on its functional integrity, could have remained passable, allowing evacuation by an unknown number of additional occupants from above the floors of impact. If the buildings had been filled to their capacity with 20,000 occupants, however, the required fourth stairway would likely have mitigated the insufficient egress capacity for conducting a full building evacuation within the available time.

- Evacuation was assisted by participation in fire drills within the previous year by two-thirds of survivors and perhaps hindered by a Local Law that prevented employers from *requiring* occupants to practice using the stairways. The stairways were not easily navigated in some locations due to their design, which included “transfer hallways,” where evacuees had to traverse from one stairway to another location where the stairs continued. Additionally, many occupants were unprepared for the physical challenge of full building evacuation.

- The functional integrity and survivability of the stairwells was affected by the separation of the stairwells and the structural integrity of stairwell enclosures. In the impact region of WTC 1, the stairwell separation was the smallest over the building height—clustered well within the building core—and all stairwells were destroyed by the aircraft impact. By contrast, the separation of stairwells in the impact region of WTC 2 was the largest over the building height—located along different boundaries of the building core—and one of three stairwells remained marginally passable after the aircraft impact. The shaft enclosures were fire rated but were not required to have structural integrity under typical accidental loads:

there were numerous reports of stairwells obstructed by fallen debris from damaged enclosures.

- The active fire safety systems (sprinklers, smoke purge, fire alarms, and emergency occupant communications) were designed to meet or exceed current practice. However, with the exception of the evacuation announcements, they played no role in the safety of life on September 11 because the water supplies to the sprinklers were damaged by the aircraft impact. The smoke purge systems, operated under the direction of the fire department after fires, were not turned on, but they also would have been ineffective due to aircraft damage. The violence of the aircraft impact served as its own alarm. In WTC 2, contradictory public address announcements contributed to occupant confusion and some delay in occupants beginning to evacuate.

- For the approximately 1,000 emergency responders on the scene, this was the largest disaster they had even seen. Despite attempts by the responding agencies to work together and perform their own tasks, the extent of the incident was well beyond their capabilities. Communications were erratic due to the high number of calls and the inadequate performance of some of the gear. Even so, there was no way to digest, test for accuracy, and disseminate the vast amount of information being received. Their jobs were complicated by the loss of command centers in WTC 7 and then in the towers after WTC 2 collapsed. With nearly all elevator service disrupted and progress up the stairs taking about 2 min per floor, it would have taken hours for the responders to reach their destinations, assist survivors, and escape had the towers not collapsed.

Objective 3: Determine what procedures and practices were used in the design, construction, operation, and maintenance of WTC 1 and WTC 2.

- Because of The Port Authority's establishment under a clause of the United States Constitution, its buildings were not subject to any state or local building regulations. The buildings were unlike any others previously built, both in their height and in their innovative structural features. Nevertheless, the actual design and approval process produced two buildings that generally were consistent with nearly all of the provisions of the New York City Building Code and other building codes of that time that were reviewed by NIST. The loads for which the buildings were designed exceeded the New York City code requirements. The quality of the structural steels was consistent with the building specifications. The departures from the building codes and standards identified by NIST did not have a significant effect on the outcome of September 11.

- For the floor systems, the fire rating and insulation thickness used on the floor trusses, which together with the concrete slab served as the main source of support for the floors, were of concern from the time of initial construction. NIST found no technical basis or test data on which the thermal protection of the steel was based. On September 11, 2001, the minimum specified thickness of the insulation was adequate to delay heating of the trusses; the amount of insulation dislodged by the aircraft impact, however, was sufficient to cause the structural steel to be heated to critical levels.

- Based on four standard fire resistance tests that were conducted under a range of insulation and test conditions, NIST found the fire rating of the floor system to vary between 3/4 hour and 2 hours; in all cases, the floors continued to support the full design load without collapse for over 2 hours.

- The wind loads used for the WTC towers, which governed the structural design of the external columns and provided the baseline capacity of the structures to withstand abnormal events such as major fires or impact damage, significantly exceeded the requirements of the New York City Building Code and other building codes of the day that were reviewed by NIST. Two sets of wind load estimates for the towers obtained by independent commercial consultants in 2002, however, differed by as much as 40 percent. These estimates were based on wind tunnel tests conducted as part of insurance litigation unrelated to the Investigation.

RECOMMENDATIONS

The tragic consequences of the September 11, 2001, attacks were directly attributable to the fact that terrorists flew large jet-fuel laden commercial airliners into the WTC towers. Buildings for use by the general population are not designed to withstand attacks of such severity; building regulations do not require building designs to consider aircraft impact. In our cities, there has been no experience with a disaster of such magnitude, nor has there been any in which the total collapse of a high-rise building occurred so rapidly and with little warning.

While there were unique aspects to the design of the WTC towers and the terrorist attacks of September 11, 2001, NIST has compiled a list of recommendations to improve the safety of tall buildings, occupants, and emergency responders based on its investigation of the procedures and practices that were used for the WTC towers; these procedures and practices are commonly used in the design, construction, operation, and maintenance of buildings under normal conditions. Public officials and building owners will need to determine appropriate performance requirements for those tall buildings, and selected other buildings, that are at higher risk due to their iconic status, critical function, or design.

The topics of the recommendations in eight groups are listed in Table 1. A complete listing of the 30 recommendations is provided in Appendix A. The ordering does not reflect any priority.

The eight major groups of recommendations are:

- Increased Structural Integrity: The standards for estimating the load effects of potential hazards (e.g., progressive collapse, wind) and the design of structural systems to mitigate the effects of those hazards should be improved to enhance structural integrity.

- Enhanced Fire Endurance of Structures: The procedures and practices used to ensure the fire endurance of structures should be enhanced by improving the technical basis for construction classifications and fire resistance ratings, improving the technical basis for standard fire resistance testing methods, use of the “structural frame” approach to fire resistance ratings, and developing in-service performance requirements and conformance criteria for sprayed fire-resistive material.

- New Methods for Fire Resistant Design of Structures: The procedures and practices used in the fire resistant design of structures should be enhanced by requiring an objective that uncontrolled fires result in burnout without local or global collapse. Performance-based methods are an alternative to prescriptive design methods. This effort should include the development and evaluation of new fire resistive coating materials and technologies and evaluation of the fire performance of conventional and high-performance structural materials.

- Improved Active Fire Protection: Active fire protection systems (i.e., sprinklers, standpipes/ hoses, fire alarms, and smoke management systems) should be enhanced through improvements to design, performance, reliability, and redundancy of such systems.

- Improved Building Evacuation: Building evacuation should be improved to include system designs that facilitate safe and rapid egress, methods for ensuring clear and timely emergency communications to occupants, better occupant preparedness for evacuation during emergencies, and incorporation of appropriate egress technologies.

- Improved Emergency Response: Technologies and procedures for emergency response should be improved to enable better access to buildings, response operations, emergency communications, and command and control in large-scale emergencies.

- Improved Procedures and Practices: The procedures and practices used in the design, construction, maintenance, and operation of buildings should be improved to include encouraging code compliance by nongovernmental and quasi-governmental entities, adoption and application of egress and sprinkler requirements in codes for existing buildings, and retention and availability of building documents over the life of a building.

- Education and Training: The professional skills of building and fire safety professionals should be upgraded though a national education and training effort for fire protection engineers, structural engineers, architects, regulatory personnel, and emergency responders.

The recommendations call for action by specific entities regarding standards, codes and regulations, their adoption and enforcement, professional practices, education, and training; and research and development. Only when each of the entities carries out its role will the implementation of a recommendation be effective.

The recommendations do not prescribe specific systems, materials, or technologies. Instead, NIST encourages competition among alternatives that can meet performance requirements. The recommendations also do not prescribe specific threshold levels; NIST believes that this responsibility properly falls within the purview of the public policy setting process, in which the standards and codes development process plays a key role.

NIST believes the recommendations are realistic and achievable within a reasonable period of time. Only a few of the recommendations call for new requirements in standards and codes. Most of the recommendations deal with improving an existing standard or code requirement, establishing a standard for an existing practice without one, establishing the technical basis for an existing requirement, making a current requirement risk-consistent, adopting or enforcing a current requirement, or establishing a performance-based alternative to a current prescriptive requirement.

NEXT STEPS

We have strongly urged that immediate and serious consideration be given to these recommendations by the building and fire safety communities in order to achieve appropriate improvements in the way buildings are designed, constructed, maintained, and used and in evacuation and emergency response procedures—with the goal of making buildings, occupants, and first responders safer in future emergencies.

We are also strongly urging building owners and public officials to (1) evaluate the safety implications of these recommendations to their existing inventory of buildings and (2) take the steps necessary to mitigate any unwarranted risks without waiting for changes to occur in codes, standards, and practices.

We are urging state and local agencies to rigorously enforce building codes and standards since such enforcement is critical to ensure the expected level of safety. Unless they are complied with, the best codes and standards cannot protect occupants, emergency responders, or buildings.

I have assigned top priority for NIST staff to work vigorously with the building and fire safety communities to assure that there is a complete understanding of the recommendations and to provide needed technical assistance in getting the recommendations implemented. We have identified specific codes, standards, and practices affected by each of the recommendations in its summary report for the WTC towers and already begun to reach out to the responsible organizations to pave the way for a timely, expedited consideration of the recommendations. Toward this end, we held a conference September 13-15, 2005 that was attended by over 200 people, including all of the major standards and codes development organizations.

We have also awarded a contract to the National Institute of Building Sciences (NIBS) to turn many of the recommendations into code language suitable for submission of code change proposals to the two national model code developers.

In addition, we will implement a web-based system so that the public can track progress on implementing the recommendations. The web site will list each of the recommendations, the specific organization or organizations (e.g., standards and code developers, professional groups, state and local authorities) responsible for its implementation, the status of its implementation by organization, and the plans or work in progress to implement the recommendations.

We are releasing the final versions of the 43 reports on NIST's investigation of the WTC towers, totaling some 10,000 pages, today. Our current plans are to release next spring an additional five reports as drafts for public comment on the investigation of WTC 7.

Mr. Chairman, I want to thank you and the Committee again for allowing me to testify today about NIST's building and fire safety investigation of the World Trade Center disaster. I would be happy to answer any questions at this time.

Table 1. Topics of NIST recommendations for improved public safety in tall and high-risk buildings.

Recommendation Group	Recommendation Topic	Responsible Community					Application		Relation to 9/11 Outcome	
		Practices	Standards, Codes, Regulations	Adoption & Enforcement	R&D/Further Study	Education & Training	All Tall Buildings	Selected Other High-Risk Buildings	Related[a]	Unrelated[b]
Increased Structural Integrity	Prevention of progressive collapse and failure analysis of complex systems	✓	✓	✓	✓	✓	✓	✓	✓	
	Estimation of wind loads and their effects on tall buildings	✓	✓		✓		✓	✓		✓
	Allowable tall buildings sway	✓	✓		✓		✓			✓
Enhanced Fire Endurance of Structures	Fire resistance rating requirements and construction classification	✓	✓		✓		✓			✓
	Fire resistance testing of building components and extrapolation of test data to qualify untested building components		✓		✓		✓			✓
	In-service performance requirements and inspection procedures for sprayed fire-resistive material (SFRM or spray-on fireproofing)	✓	✓	✓	✓		✓			✓
	"Structural frame" approach (structural members connected to columns carry the higher fire resistance rating of the columns)		✓	✓		✓	✓	✓		✓
New Methods for Fire Resistant Design of Structures	Burnout without partial or global (total) structural collapse in uncontrolled building fires	✓	✓	✓	✓	✓	✓	✓	✓	
	Performance-based design and retrofit of structures to resist fires	✓	✓		✓	✓	✓	✓		✓
	New fire-resistive coating materials, systems, and technologies	✓	✓		✓		✓	✓	✓	
	Evaluation of high performance structural materials under conditions expected in building fires	✓			✓		✓	✓		✓
Improved Active Fire Protection	Performance and redundancy of active fire protection systems to accommodate the greater risks associated with tall buildings	✓	✓		✓		✓	✓	✓	
	Advanced fire alarm and communication systems that provide continuous, reliable, and accurate information on life safety conditions to manage the evacuation process.		✓		✓		✓		✓	
	Advanced fire/emergency control panels with more reliable information from the active fire protection systems to provide tactical decision aids		✓		✓		✓	✓	✓	
	Improved transmission to emergency responders, and off-site or black box storage, of information from building monitoring systems	✓	✓		✓		✓	✓	✓	✓

Recommendation Group	Recommendation Topic	Responsible Community					Application		Relation to 9/11 Outcome	
		Practices	Standards, Codes, Regulations	Adoption & Enforcement	R&D/Further Study	Education & Training	All Tall Buildings	Selected Other High-Risk Buildings	Related[a]	Unrelated[b]
Improved Building Evacuation	Public education and training campaigns to improve building occupants' preparedness for evacuation	✓	✓		✓	✓	✓		✓	✓
	Tall building design for timely full building emergency evacuation of occupants	✓	✓		✓	✓	✓	✓	✓	✓
	Design of occupant-friendly evacuation paths that maintain functionality in foreseeable emergencies	✓	✓				✓		✓	
	Planning for communication of accurate emergency information to building occupants	✓	✓			✓	✓	✓	✓	
	Evaluation of alternative evacuation technologies, to allow all occupants equal opportunity for evacuation and to facilitate emergency response access	✓	✓		✓		✓	✓	✓	
Improved Emergency Response	Fire-protected and structurally hardened elevators	✓	✓		✓		✓		✓	
	Effective emergency communications systems for large-scale emergencies	✓	✓	✓	✓	✓	✓		✓	
	Enhanced gathering, processing, and delivering of critical information to emergency responders	✓	✓	✓	✓	✓	✓	✓	✓	
	Effective and uninterrupted operation of the command and control system for large-scale building emergencies	✓	✓	✓	✓	✓	✓		✓	
Improved Procedures and Practices	Provision of code-equivalent level of safety and certification of as-designed and as-built safety by nongovernmental and quasi-governmental entities	✓	✓	✓			✓	✓		✓
	Egress and sprinkler requirements for existing buildings	✓		✓			✓	✓		✓
	Retention and off-site storage of design, construction, maintenance, and modification documents over the entire life of the building; and availability of relevant building information for use by responders in emergencies	✓	✓	✓			✓	✓	✓	
	Design professional responsibility for innovative or unusual structural and fire safety systems	✓	✓			✓	✓	✓	✓	
Education and Training	Professional cross training of fire protection engineers, architects, structural engineers, code enforcement officials, and fire service personnel.	✓	✓			✓	✓	✓	✓	
	Training in computational fire dynamics and thermostructural analysis	✓				✓	✓	✓		✓

a. If in place, could have changed the outcome on September 11, 2001.

b. Would not have changed the outcome, yet is an important building and fire safety issue that was identified during the course of the Investigation.

Appendix A. List of Recommendations

Group 1. Increased Structural Integrity

The standards for estimating the load effects of potential hazards (e.g., progressive collapse, wind) and the design of structural systems to mitigate the effects of those hazards should be improved to enhance structural integrity.

Recommendation 1. NIST recommends that: (1) *progressive collapse* be prevented in buildings through the development and nationwide adoption of consensus standards and code provisions, along with the tools and guidelines needed for their use in practice; and (2) a standard methodology be developed—supported by analytical design tools and practical design guidance—to reliably predict the potential for *complex failures* in structural systems subjected to multiple hazards.

Recommendation 2. NIST recommends that nationally accepted performance standards be developed for: (1) conducting *wind tunnel testing* of prototype structures based on sound technical methods that result in repeatable and reproducible results among testing laboratories; and (2) *estimating wind loads* and their effects on tall buildings for use in design, based on wind tunnel testing data and directional wind speed data.

Recommendation 3. NIST recommends that an appropriate criterion be developed and implemented to enhance the performance of tall buildings by *limiting how much they sway* under lateral load design conditions (e.g., winds and earthquakes).

Group 2. Enhanced Fire Endurance of Structures

The procedures and practices used to ensure the fire endurance of structures be enhanced by improving the technical basis for construction classifications and fire resistance ratings, improving the technical basis for standard fire resistance testing methods, use of the "structural frame" approach to fire resistance ratings, and developing in-service performance requirements and conformance criteria for sprayed fire-resistive materials.

Recommendation 4. NIST recommends evaluating, and where needed improving, the technical basis for determining appropriate construction classification and fire rating requirements *(especially for tall buildings)*—and making related code changes now as much as possible—by explicitly considering factors including:

- timely access by emergency responders and *full evacuation* of occupants, or the time required for burnout without local collapse;
- the extent to which *redundancy* in active fire protection (sprinkler and standpipe, fire alarm, and smoke management) systems should be credited for occupant life safety;
- the need for *redundancy* in fire protection systems that are critical to structural integrity;
- the ability of the structure and local floor systems to withstand a *maximum credible fire scenario without collapse*, recognizing that sprinklers could be compromised, not operational, or non-existent;

- *compartmentation* requirements (e.g., 12,000 ft$^{2\,(1)}$) to protect the structure, including fire rated doors and automatic enclosures, and limiting air supply (e.g., thermally resistant window assemblies) to retard fire spread in buildings with large, open floor plans;
- the effect of spaces containing *unusually large fuel concentrations* for the expected occupancy of the building; and
- the extent to which fire control systems, including suppression by automatic or manual means, should be credited as part of the prevention of fire spread.

Recommendation 5. NIST recommends that the technical basis for the century-old *standard for fire resistance testing* of components, assemblies, and systems be improved through a national effort. Necessary guidance also should be developed for extrapolating the results of tested assemblies to prototypical building systems. A key step in fulfilling this recommendation is to establish a capability for studying and testing the components, assemblies, and systems under realistic fire and load conditions.

Recommendation 6. NIST recommends the development of criteria, test methods, and standards: (1) for the *in-service performance* of sprayed fire-resistive materials (SFRM, also commonly referred to as fireproofing or insulation) used to protect structural components; and (2) to ensure that these materials, *as-installed*, conform to conditions in tests used to establish the fire resistance rating of components, assemblies, and systems.

Recommendation 7. NIST recommends the adoption and use of the "structural frame" approach to fire resistance ratings. This approach requires that structural members—such as girders, beams, trusses and spandrels having direct connection to the columns, and bracing members designed to carry gravity loads—be fire protected to the same fire resistance rating as columns.

Group 3. New Methods for Fire Resistant Design of Structures

The procedures and practices used in the fire resistant design of structures should be enhanced by requiring an objective that uncontrolled fires result in burnout without partial or global (total) collapse. Performance-based methods are an alternative to prescriptive design methods. This effort should include the development and evaluation of new fire-resistive coating materials and technologies and evaluation of the fire performance of conventional and high-performance structural materials.

Recommendation 8. NIST recommends that the fire resistance of structures be enhanced by requiring a performance objective that uncontrolled building fires result in burnout without partial or global (total) collapse.

Recommendation 9. NIST recommends the development of: (1) performance-based standards and code provisions, as an alternative to current prescriptive design methods, to enable the design and retrofit of structures to resist real building fire conditions, including their ability to achieve the performance objective of burnout without structural or local floor collapse: and (2) the tools, guidelines, and test methods necessary to evaluate the fire performance of the structure as a whole system.

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[1] Or a more appropriate limit, which represents a reasonable area for active firefighting operations.

Recommendation 10. NIST recommends the development and evaluation of *new fire-resistive coating materials, systems, and technologies* with significantly enhanced performance and durability to provide protection following major events.

Recommendation 11. NIST recommends that the performance and suitability of advanced structural steel, reinforced and pre-stressed concrete, and other high-performance material systems be evaluated for use under conditions expected in building fires.

Group 4. Improved Active Fire Protection

Active fire protection systems (i.e., sprinklers, standpipes/hoses, fire alarms, and smoke management systems) should be enhanced through improvements to design, performance, reliability, and redundancy of such systems.

Recommendation 12. NIST recommends that the performance and possibly the redundancy of active fire protection systems (sprinklers, standpipes/hoses, fire alarms, and smoke management systems) in buildings be enhanced to accommodate the *greater risks* associated with increasing building height and population, increased use of open spaces, high-risk building activities, fire department response limits, transient fuel loads, and higher threat profile.

Recommendation 13. NIST recommends that fire alarm and communications systems in buildings be developed to provide continuous, reliable, and accurate information on the status of life safety conditions at a level of detail sufficient to *manage the evacuation process* in building fire emergencies; all communication and control paths in buildings need to be designed and installed to have the same resistance to failure and increased survivability above that specified in present standards.

Recommendation 14. NIST recommends that control panels at fire/emergency command stations in buildings be adapted to accept and interpret a larger quantity of more reliable information from the active fire protection systems that *provide tactical decision aids to fireground commanders*, including water flow rates from pressure and flow measurement devices, and that standards for their performance be developed.

Recommendation 15. NIST recommends that systems be developed and implemented for: (1) *real-time off-site secure transmission of valuable information* from fire alarm and other monitored building systems for use by emergency responders, at any location, to enhance situational awareness and response decisions and maintain safe and efficient operations; and (2) preservation of that information either off-site or in a *black box that will survive a fire or other building failure* for purposes of subsequent investigations and analysis. Standards for the performance of such systems should be developed, and their use should be required.

Group 5. Improved Building Evacuation

Building evacuation should be improved to include system designs that facilitate safe and rapid egress, methods for ensuring clear and timely emergency communications to occupants, better occupant preparedness regarding their roles and duties for evacuation during emergencies, and incorporation of appropriate egress technologies.

Recommendation 16. NIST recommends that public agencies, non-profit organizations concerned with building and fire safety, and building owners and managers develop and carry

out *public education and training campaigns*, jointly and on a nationwide scale, to improve building occupants' preparedness for evacuation in case of building emergencies.

Recommendation 17. NIST recommends that tall buildings be designed to accommodate *timely full building evacuation* of occupants due to building-specific or large-scale emergencies such as widespread power outages, major earthquakes, tornadoes, hurricanes without sufficient advanced warning, fires, explosions, and terrorist attack. Building size, population, function, and iconic status should be taken into account in designing the egress system. Stairwell capacity and stair discharge door width should be adequate to accommodate counterflow due to emergency access by responders.

Recommendation 18. NIST recommends that egress systems be designed: (1) to *maximize remoteness of egress* components (i.e., stairs, elevators, exits) without negatively impacting the average travel distance; (2) to maintain their functional *integrity and survivability* under foreseeable building-specific or large-scale emergencies; and (3) with consistent layouts, standard signage, and guidance so that systems become *intuitive and obvious* to building occupants during evacuations.

Recommendation 19. NIST recommends that building owners, managers, and emergency responders develop a joint plan and take steps to *ensure that accurate emergency information is communicated* in a timely manner to enhance the situational awareness of building occupants and emergency responders affected by an event. This should be accomplished through better coordination of information among different emergency responder groups, efficient sharing of that information among building occupants and emergency responders, more robust design of emergency public address systems, improved emergency responder communication systems, and use of the Emergency Broadcast System (now known as the Integrated Public Alert and Warning System) and Community Emergency Alert Networks.

Recommendation 20. NIST recommends that the full range of current and *next generation evacuation technologies* should be evaluated for future use, including protected/hardened elevators, exterior escape devices, and stairwell descent devices, which may allow all occupants an equal opportunity for evacuation and facilitate emergency response access.

Group 6. Improved Emergency Response

Technologies and procedures for emergency response should be improved to enable better access to buildings, response operations, emergency communications, and command and control in large-scale emergencies.

Recommendation 21. NIST recommends the *installation of fire-protected and structurally hardened elevators* to improve emergency response activities in tall buildings by providing timely emergency access to responders and allowing evacuation of mobility impaired building occupants. Such elevators should be installed for exclusive use by emergency responders during emergencies. In tall buildings, consideration also should be given to installing such elevators for use by all occupants. The use of elevators for these purposes will require additional operating procedures and protocols, as well as a requirement for release of elevator door restrictors by emergency response personnel.

Recommendation 22. NIST recommends the installation, inspection, and testing of *emergency communications systems, radio communications, and associated operating protocols* to ensure that the systems and protocols: (1) are effective for large-scale

emergencies in buildings with challenging radio frequency propagation environments; and (2) can be used to identify, locate, and track emergency responders within indoor building environments and in the field. The federal government should coordinate its efforts that address this need within the framework provided by the SAFECOM program of the Department of Homeland Security.

Recommendation 23. NIST recommends the establishment and implementation of detailed procedures and methods for gathering, processing, and delivering critical information through *integration of relevant voice, video, graphical, and written data* to enhance the situational awareness of all emergency responders. An *information intelligence sector*[2] should be established to coordinate the effort for each incident.

Recommendation 24. NIST recommends the establishment and implementation of codes and protocols for ensuring *effective and uninterrupted operation of the command and control system* for large-scale building emergencies.

Group 7. Improved Procedures and Practices

The procedures and practices used in the design, construction, maintenance, and operation of buildings should be improved to include encouraging code compliance by nongovernmental and quasi-governmental entities, adoption and application of egress and sprinkler requirements in codes for existing buildings, and retention and availability of building documents over the life of a building.

Recommendation 25. *Nongovernmental and quasi-governmental entities* that own or lease buildings—and are not subject to building and fire safety code requirements of any governmental jurisdiction—should provide a level of safety that *equals or exceeds* the level of safety that would be provided by strict compliance with the code requirements of an appropriate governmental jurisdiction. To gain broad public confidence in the safety of such buildings, NIST further recommends that as-designed and as-built safety be *certified by a qualified third party*, independent of the building owner(s). The process *should not use self-approval* for code enforcement in areas including interpretation of code provisions, design approval, product acceptance, certification of the final construction, and post-occupancy inspections over the life of the buildings.

Recommendation 26. NIST recommends that state and local jurisdictions adopt and *aggressively enforce available provisions in building codes to ensure that egress and sprinkler requirements are met* by existing buildings. Further, occupancy requirements should be modified where needed (such as when there are assembly use spaces within an office building) to meet the requirements in model building codes.

Recommendation 27. NIST recommends that building codes should incorporate a provision that requires building owners to *retain documents,* including supporting calculations and test data, related to building design, construction, maintenance and modifications over the entire life of the building[3]. Means should be developed for offsite storage and maintenance of the

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[2] A group of individuals that is knowledgeable, experienced, and specifically trained in gathering, processing, and delivering information critical for emergency response operations and is ready for activation in large and/or dangerous events.

[3] The availability of inexpensive electronic storage media and tools for creating large searchable databases make this feasible.

documents. In addition, NIST recommends that relevant building information should be made available in suitably designed hard copy or electronic format for use by emergency responders. Such information should be *easily accessible by responders* during emergencies.

Recommendation 28. NIST recommends that the role of the "Design Professional in Responsible Charge"[4] be clarified to ensure that: (1) *all appropriate design professionals* (including, e.g., the fire protection engineer) are part of the design team providing the standard of care when designing buildings employing innovative or unusual fire safety systems, and (2) *all appropriate design professionals* (including, e.g., the structural engineer and the fire protection engineer) are part of the design team providing the standard of care when designing the structure to resist fires, in buildings that employ innovative or unusual structural and fire safety systems.

Group 8. Education and Training

The professional skills of building and fire safety professionals should be upgraded though a national education and training effort for fire protection engineers, structural engineers, and architects. The skills of the building regulatory and fire service personnel should also be upgraded to provide sufficient understanding and the necessary skills to conduct the review, inspection, and approval tasks for which they are responsible.

Recommendation 29. NIST recommends that *continuing education curricula* be developed and programs should be implemented for (1) training fire protection engineers and architects in structural engineering principles and design, and (2) training structural engineers, architects, fire protection engineers, and code enforcement officials in modern fire protection principles and technologies, including fire-resistance design of structures, and (3) training building regulatory and fire service personnel to upgrade their understanding and skills to conduct the review, inspection, and approval tasks for which they are responsible.

Recommendation 30. NIST recommends that academic, professional short-course, and web-based training materials in the use of computational fire dynamics and thermostructural analysis tools be developed and delivered to strengthen the base of available technical capabilities and human resources.

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[4] In projects involving a design team, the "Design Professional in Responsible Charge"—usually the lead architect—ensures that the team members use consistent design data and assumptions, coordinates overlapping specifications, and serves as the liaison to the enforcement and reviewing officials and to the owner. The term is defined in the International Building Code and in the ICC Performance Code for Buildings and Facilities (where it is the Principal Design Professional).

William Jeffrey, Director

William Jeffrey is the 13th Director of the National Institute of Standards and Technology (NIST), sworn into the office on July 26, 2005. He was nominated by President Bush on May 25, 2005, and confirmed by the U.S. Senate on July 22, 2005.

As director of NIST, Dr. Jeffrey oversees an array of programs that support U.S. industry and science with measurement research, standards, technology, and technical assistance that strengthen the nation's innovation infrastructure and competitiveness. The goal is to improve manufacturing, services, trade, safety and security, and quality of life. Operating in fiscal year 2005 on a budget of about $858 million, NIST is headquartered in Gaithersburg, Md., and has additional laboratories in Boulder, Colo. NIST also jointly operates research organizations in three locations, which support world-class physics, cutting-edge biotechnology, and environmental research. NIST employs about 3,000 scientists, engineers, technicians, and support personnel. An agency of the U.S. Commerce Department's Technology Administration, NIST has extensive cooperative research programs with industry, academia, and other government agencies. Its staff is augmented by about 1,600 visiting researchers.

Dr. Jeffrey has been involved in federal science and technology programs and policy since 1988. Previous to his appointment to NIST he served as senior director for homeland and national security and the assistant director for space and aeronautics at the Office of Science and Technology Policy (OSTP) within the Executive Office of the President. Earlier, he was the deputy director for the Advanced Technology Office and chief scientist for the Tactical Technology Office with the Defense Advanced Research Projects Agency (DARPA). While at DARPA, Dr. Jeffrey advanced research programs in communications, computer network security, novel sensor development, and space operations.

Prior to joining DARPA, Dr. Jeffrey was the assistant deputy for technology at the Defense Airborne Reconnaissance Office, where he supervised sensor development for the Predator and Global Hawk Unmanned Aerial Vehicles and the development of common standards that allow for cross-service and cross-agency transfer of imagery and intelligence products. He also spent several years working at the Institute for Defense Analyses performing technical analyses in support of the Department of Defense.

Dr. Jeffrey received his Ph.D. in astronomy from Harvard University and his B.Sc. in physics from the Massachusetts Institute of Technology.