NIST NCSTAR 1A

Federal Building and Fire Safety Investigation of the World Trade Center Disaster

Final Report on the Collapse of World Trade Center Building 7

Draft for Public Comment

NIST
National Institute of Standards and Technology
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Final Report on the Collapse of World Trade Center Building 7

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U.S. Department of Commerce
Carlos M. Gutierrez, Secretary

National Institute of Standards and Technology
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ABSTRACT

This is the final report on the National Institute of Standards and Technology (NIST) investigation of the collapse of World Trade Center Building 7 (WTC 7), conducted under the National Construction Safety Team Act. This report describes how the fires that followed the impact of debris from the collapse of WTC 1 (the north tower) led to the collapse of WTC 7; an evaluation of the building evacuation and emergency response procedures; what procedures and practices were used in the design, construction, operation, and maintenance of the building; and areas in current building and fire codes, standards, and practices that warrant revision. Extensive details are found in the companion reports, NIST NCSTAR 1-9 and NIST NCSTAR 1-9A.

Also in this report is a summary of how NIST reached its conclusions. NIST complemented in-house expertise with private sector technical experts; accumulated copious documents, photographs, and videos of the disaster; conducted first-person interviews of building occupants and emergency responders; analyzed the evacuation and emergency response operations in and around WTC 7; performed computer simulations of the behavior of WTC 7 on September 11, 2001; and combined the knowledge gained into a probable collapse sequence.

The report concludes with a list of 13 recommendations for action in the areas of increased structural integrity, enhanced fire endurance of structures, new methods for fire resistant design of structures, enhanced active fire protection, improved emergency response, improved procedures and practices, and education and training. One of these is new; the other 12 are reiterated from the investigation into the collapse of the WTC towers. Each of the 13 is relevant to WTC 7.

Keywords: building evacuation, emergency response, fire safety, structural collapse, tall buildings, World Trade Center.

EXECUTIVE SUMMARY

WORLD TRADE CENTER BUILDING 7 (WTC 7)

WTC 7 was a 47 story office building located immediately to the north of the main WTC Complex. It had been built on top of an existing Consolidated Edison of New York electric power substation, which was located on land owned by The Port Authority of New York and New Jersey. On September 11, 2001, WTC 7 endured fires for almost seven hours, from the time of the collapse of the north WTC tower (WTC 1) at 10:28:22 a.m. until 5:20:52 p.m., when WTC 7 collapsed. This was the first known instance of the total collapse of a tall building primarily due to fires.

WTC 7 was unlike the WTC towers in many respects. It was a more typical tall building in the design of its structural system. It was not struck by an airplane. The fires in WTC 7 were quite different from those in the towers. Since WTC 7 was not doused with thousands of gallons of jet fuel, large areas of any floor were not ignited simultaneously. Instead, the fires in WTC 7 were similar to those that have occurred in several tall buildings where the automatic sprinklers did not function or were not present. These other buildings did not collapse, while WTC 7 succumbed to its fires.

THIS REPORT

This is the final report of the National Institute of Standards and Technology (NIST) investigation into the collapse of WTC 7, conducted under the National Construction Safety Team Act. The report is the result of an extensive, state-of-the-art reconstruction of the events that affected WTC 7 and eventually led to its collapse. Numerous facts and data were obtained, then combined with validated computer modeling to produce an account that captures the key features of what actually occurred. However, the reader should keep in mind that the building and the records kept within it were destroyed, and the remains of all the WTC buildings were disposed of before congressional action and funding was available for this Investigation to begin. As a result, there are some facts that could not be discerned, and thus there are uncertainties in this accounting. Nonetheless, NIST was able to gather sufficient evidence and documentation to conduct a full investigation upon which to reach firm findings and recommendations.

This report summarizes how NIST reached its conclusions. NIST complemented in-house expertise with private sector technical experts; accumulated copious documents, photographs, and videos of the disaster; conducted first-person interviews of building occupants and emergency responders; analyzed the evacuation and emergency response operations in and around WTC 7; performed computer simulations of the behavior of WTC 7 on September 11, 2001; and combined the knowledge gained into a probable collapse sequence. Extensive details on the reconstruction effort for WTC 7, the uncertainties, the assumptions made, and the testing of these assumptions are documented in NIST NCSTAR 1-9 and NIST NCSTAR 1-9A.

PRINCIPAL FINDINGS OF THE INVESTIGATION

The fires in WTC 7 were ignited as a result of the impact of debris from the collapse of WTC 1, which was approximately 370 ft to the south. The debris also caused some structural damage to the southwest perimeter of WTC 7. The fires were ignited on at least 10 floors; however, only the fires on Floors 7 through 9 and 11 through 13 grew and lasted until the time of the building collapse. These uncontrolled fires had characteristics similar to those that have occurred previously in tall buildings. Their growth and spread were consistent with ordinary building contents fires. Had a water supply for the automatic sprinkler system been available and had the sprinkler system operated as designed, it is likely that fires in WTC 7 would have been controlled and the collapse prevented. However, the collapse of WTC 7 highlights the importance of designing fire-resistant structures for situations where sprinklers are not present, do not function (e.g., due to disconnected or impaired water supply, or are overwhelmed.

Eventually, the fires reached the northeast of the building. The probable collapse sequence that caused the global collapse of WTC 7 was initiated by the buckling of a critical interior column in that vicinity. This column had become unsupported over nine stories after initial local fire-induced damage led to a cascade of local floor failures. The buckling of this column led to a vertical progression of floor failures up to the roof and to the buckling of adjacent interior columns to the south of the critical column. An east-to-west horizontal progression of interior column buckling followed, due to loss of lateral support to adjacent columns, forces exerted by falling debris, and load redistribution from other buckled columns. The exterior columns then buckled as the failed building core moved downward, redistributing its loads to the exterior columns. Global collapse occurred as the entire building above the buckled region moved downward as a single unit. This was a fire-induced progressive collapse, also known as disproportionate collapse, which is defined as the spread of local damage, from an initiating event, from element to element, eventually resulting in the collapse of an entire structure or a disproportionately large part of it.

Factors contributing to the building failure were: thermal expansion occurring at temperatures hundreds of degrees below those typically considered in design practice for establishing structural fire resistance ratings; significant magnification of thermal expansion effects due to the long-span floors, which are common in office buildings in widespread use; connections that were designed to resist gravity loads, but not thermally induced lateral loads; and a structural system that was not designed to prevent fire-induced progressive collapse.

Within the building were emergency electric power generators, whose fuel supply tanks lay in and under the building. However, fuel oil fires did not play a role in the collapse of WTC 7. The worst-case scenarios associated with fires being fed by the ruptured fuel lines (a) could not have been sustained long enough, or could not have generated sufficient heat, to raise the temperature of the critical interior column to the point of significant loss of strength or stiffness, or (b) would have produced large amounts of visible smoke that would have emanated from the exhaust louvers. No such smoke discharge was observed.

Hypothetical blast events did not play a role in the collapse of WTC 7. NIST concluded that blast events did not occur, and found no evidence whose explanation required invocation of a blast event. Blast from the smallest charge capable of failing the critical column would have resulted in a sound level of 130 dB to 140 dB at a distance of at least half a mile. There were no witness reports of such a loud noise, nor was such a noise heard on the audio tracks of video recordings of the WTC 7 collapse.

There were no serious injuries or fatalities, because the estimated 4,000 occupants of WTC 7 reacted to the airplane impacts on the two WTC towers and began evacuating before there was significant damage to WTC 7. The occupants were able to use both the elevators and the stairs, which were as yet not damaged, obstructed, or smoke-filled. Evacuation of the building took just over an hour. The potential for injuries to people leaving the building was mitigated by building management personnel holding the occupants in the lobby until they identified an exit path that was safe from the debris falling from WTC 1. The decision not to continue evaluating the building and not to fight the fires was made hours before the building collapsed, so no emergency responders were in or near the building when the collapse occurred.

The design of WTC 7 was generally consistent with the New York City Building Code of 1968 (NYCBC), with which, by policy, it was to comply. The installed thickness of the thermal insulation on the floor beams was below that required for unsprinklered or sprinklered buildings, but it is unlikely that the collapse of WTC 7 could have been prevented even if the thickness had been consistent with building code requirements. The stairwells were narrower than those required by the NYCBC, but, combined with the elevators, were adequate for a timely evacuation on September 11, 2001, since the number of building occupants was only about half that expected during normal business hours.

The collapse of WTC 7 could not have been prevented without controlling the fires before most of the combustible building contents were consumed. There were two sources of water (gravity fed overhead tanks and the city water main) for the standpipe and automatic sprinkler systems serving Floor 21 and above, and some of the early fires on those upper floors might have actually been controlled in this manner. However, consistent with the NYCBC, both the primary and back-up source of water for the sprinkler system in the lower 20 floors of WTC 7 was the city water main. Since the collapses of the WTC towers had damaged the water main, there was no water available (such as from the gravity-fed overhead tanks that supplied water to Floor 21 and above) to control those fires that eventually led to the building collapse.

Other than initiating the fires in WTC 7, the damage from the debris from WTC 1 had little effect on initiating the collapse of WTC 7. The building withstood debris impact damage that resulted in seven exterior columns being severed and subsequently withstood conventional fires on several floors for almost seven hours. The debris damaged the spray-applied fire resistive material that was applied to the steel columns, girders, and beams, only in the vicinity of the structural damage from the collapse of WTC 1. This was near the west side of the south face of the building and was far removed from the buckled column that initiated the collapse. Even without the structural damage, WTC 7 would have collapsed from fires having the same characteristics as those experienced on September 11, 2001. The transfer elements such as trusses, girders, and cantilever overhangs that were used to support the office building over the Con Edison substation did not play a significant role in the collapse of WTC 7.

RECOMMENDATIONS

Based on the findings of this Investigation, NIST identified one new recommendation (B, below) and reiterated 12 recommendations from the Investigation of the WTC towers. These encompass increased structural integrity, enhanced fire endurance of structures, new methods for fire resistant design of structures, improved active fire protection, improved emergency response, improved procedures and practices, and education and training.

The urgency of these recommendations is substantially reinforced by their pertinence to the collapse of a tall building that was based on a structural system design that is in widespread use.

The partial or total collapse of a building due to fires is an infrequent event. This is particularly true for buildings with a reliably operating active fire protection system such as an automatic fire sprinkler system. A properly designed and operating automatic sprinkler system will contain fires while they are small and, in most instances, prevent them from growing and spreading to threaten structural integrity.

The intent of current practice, based on prescriptive standards and codes, is to achieve life safety, not collapse prevention. However, the key premise of NIST's recommendations is that buildings should not collapse in infrequent (worst-case) fires that may occur when active fire protection systems are rendered ineffective, e.g., when sprinklers do not exist, are not functional, or are overwhelmed by the fire, or where the water supply is impaired.

Fire scenarios for structural design based on single compartment or single floor fires are not appropriate representations of infrequent fire events. Such events have occurred in several tall buildings resulting in unexpected substantial losses. Instead, historical data suggests that infrequent fires which should be considered in structural design have characteristics that include: ordinary combustibles and combustible load levels, local fire origin on any given floor, no widespread use of accelerants, consecutive fire spread from combustible to combustible, fire-induced window breakage providing ventilation for continued fire spread and accelerated fire growth, concurrent fires on multiple floors, and active fire protection systems rendered ineffective. The fires in WTC 7 had all of these characteristics.

The subjects of the NIST recommendations are as follows:

A. Development of methods for prevention of progressive collapse and for reliable prediction of the potential for complex failures in structural systems subjected to multiple hazards.

B (New). Explicit evaluation of the fire resistance of structural systems in buildings under worst-case design fires with any active fire protection systems rendered ineffective. Of particular concern are the effects of thermal expansion in buildings with one or more of the following features: long-span floor systems[1], connections not designed for thermal effects, asymmetric floor framing, and composite floor systems.

C. Evaluation and improvement of the technical basis for determining appropriate construction classification and fire rating requirements (especially for tall buildings), and making of related code changes.

D. Improvement of the technical basis for the standard for fire resistance testing of components, assemblies, and systems.

E. Broadening the scope of the "structural frame" approach to fire resistance ratings by including, as part of the structural frame, floor systems and other bracing members that are essential to the vertical stability of the building under gravity loads.

[1] Typical floor span lengths in tall office buildings are in the range of 12 m to 15 m (40 ft to 50 ft); this range is considered to represent long-span floor systems. Thermal effects (e.g., thermal expansion) that may be significant in long-span buildings may also be present in buildings with shorter span lengths, depending on the design of the structural system.

F. Enhancement of the fire resistance of structures by requiring a performance objective that uncontrolled building fires result in burnout without partial or global (total) collapse.

G. Development of performance-based standards and code provisions to enable the design and retrofit of structures to resist real building fire conditions, and the tools necessary to perform the building evaluations.

H. Enhancement of the performance and redundancy of active fire protection systems to accommodate higher risk buildings.

I. Establishment and implementation of codes and protocols for ensuring effective and uninterrupted operation of the command and control system for large-scale building emergencies.

J. Requirement that building owners to retain building documents over the entire life of the building.

K. Inclusion of all appropriate technical professionals in the building design team.

L Development and implementation of continuing education curricula for training building professionals in each others' skills and practices.

M. Development and delivery of training materials in the use of computational fire dynamics and thermostructural analysis tools.

Building owners, operators, and designers should immediately act upon the new recommendation (B). Industry should also partner with the research community to fill critical gaps in knowledge about how structures perform in real fires.

Chapter 5
RECOMMENDATIONS

5.1 GENERAL

In its final report on the collapse of the World Trade Center towers (NIST NCSTAR 1), NIST made 30 recommendations for improving the safety of buildings, occupants, and emergency responders. These encompass increased structural integrity, enhanced fire endurance of structures, new methods for fire resistant design of structures, improved active fire protection, improved building evacuation, improved emergency response, improved procedures and practices, and education and training.

WTC 7 was unlike the WTC towers in many respects. It was a more typical tall building in the design of its structural system. It was not struck by an airplane. The fires in WTC 7 were quite different from those in the towers. Since WTC 7 was not doused with thousands of gallons of jet fuel, large areas of any floor were not ignited simultaneously. Instead, the fires in WTC 7 were similar to those that have occurred previously in several tall buildings where the sprinklers did not function or were not present. These other buildings did not succumb to their fires and collapse because they were of structural designs that differed from that of WTC 7.

The Investigation Team has compiled a list of key factors that enabled ordinary fires to result in an extraordinary outcome. In so doing, the Team recognized that there were additional aspects to be included in the content of some of the 30 earlier recommendations.

Based on the findings of this Investigation, NIST has identified one new recommendation and has reiterated 12 recommendations from the Investigation of the WTC towers.

The urgency of the prior recommendations is substantially reinforced by their pertinence to the collapse of a tall building that is based on a structural system design that is in widespread use. A few of the prior recommendations have been modified to reflect the findings of this Investigation.

The partial or total collapse of a building due to fires is an infrequent event. This is particularly true for buildings with a reliably operating active fire protection system such as an automatic fire sprinkler system. A properly designed and operating automatic sprinkler system will contain fires while they are small and, in most instances, prevent them from growing and spreading to threaten structural integrity.

The intent of current practice, based on prescriptive standards and codes, is to achieve life safety, not collapse prevention. However, the key premise of NIST's recommendations is that buildings should not collapse in infrequent (worst-case) fires that may occur when active fire protection systems are rendered ineffective, e.g., when sprinklers do not exist, are not functional, or are overwhelmed by the fire.

Fire scenarios for structural design based on single compartment or single floor fires are not appropriate representations of infrequent fire events. Such events have occurred in several tall buildings resulting in unexpected substantial losses. Instead, historical data suggests that infrequent fires which should be considered in structural design have characteristics that include: ordinary combustibles and combustible load levels, local fire origin on any given floor, no widespread use of accelerants, consecutive fire spread from combustible to combustible, fire-induced window breakage providing ventilation for continued fire spread and accelerated fire growth, concurrent fires on multiple floors, and active fire protection systems rendered ineffective. The fires in WTC 7 had all of these characteristics.

NIST believes the recommendations are realistic, appropriate, and achievable within a reasonable period of time. NIST strongly urges 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—with the goal of making buildings safer in future emergencies.

A complete listing of all 13 recommendations (Recommendations A through L) based on this Investigation follows. Under a few of the recommendations, the pertinent lesson from the reconstruction of the WTC 7 collapse is reflected in the form of a modification. For the 12 reiterated recommendations, the pertinent codes, standards, and organizations were listed in Table 9-1 and Tables 9-2a through 9-2c of NIST NCSTAR 1 and are not repeated here. For the one new recommendation, B, this information is provided in the text below.

NIST'S RECOMMENDATIONS FOR IMPROVING THE SAFETY OF BUILDINGS, OCCUPANTS, AND EMERGENCY RESPONDERS

5.1.1 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 A (NIST NCSTAR 1 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.**

Relevance to WTC 7: Had WTC 7 been expressly designed for prevention of fire-induced progressive collapse, it would have been sufficiently robust to withstand local failure due to the fires without suffering total collapse.

5.1.2 Group 2. 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 materials.

Recommendation B (New), **NIST recommends that buildings be explicitly evaluated to ensure the adequate performance of the structural system under worst-case design fires with any**

active fire protection system rendered ineffective. Of particular concern are the effects of thermal expansion in buildings with one or more of the following features: (1) long-span floor systems[6] which experience significant thermal expansion and sagging effects, (2) connection designs (especially shear connections) that cannot accommodate thermal effects, (3) floor framing that induces asymmetric thermally-induced (i.e., net lateral) forces on girders, (4) shear studs that could fail due to differential thermal expansion in composite floor systems, and (5) lack of shear studs on girders. Careful consideration should also be given to the possibility of other design features that may adversely affect the performance of the structural system under fire conditions.

Building owners, operators, and designers are strongly urged to act upon this recommendation. Engineers should be able to design cost-effective fixes to address any areas of concern that are identified by these evaluations. Several existing, emerging, or even anticipated capabilities could have helped prevent the collapse of WTC 7. The degree to which these capabilities improve performance remains to be evaluated. Possible options for developing cost-effective fixes include:

- More robust connections and framing systems to better resist the effects of thermal expansion on the structural system.
- Structural systems expressly designed to prevent progressive collapse. The current model building codes do not require that buildings be designed to resist progressive collapse.
- Better thermal insulation (i.e., reduced conductivity and/or increased thickness) to limit heating of structural steel and to minimize both thermal expansion and weakening effects. Currently, insulation is used to protect steel strength, but it could also be used to maintain a lower temperature in the steel framing to limit thermal expansion.
- Improved compartmentation in tenant areas to limit the spread of fires.
- Thermally resistant window assemblies which limit breakage, reduce air supply, and retard fire growth.

Industry should partner with the research community to fill critical gaps in knowledge about how structures perform in real fires, particularly considering: the effects of fire on the entire structural system; the interactions between subsystems, elements, and connections; and scaling of fire test results to full-scale structures, especially for structures with long span floor systems.

Affected Standards: ASCE 7, ASCE/SFPE 29, AISC Specifications, ACI 318. Development of performance objectives, design criteria, evaluation methods, design guidance, and computational tools should begin promptly, leading to new standards.

Model Building Codes: The new standard should be adopted in model building codes (IBC, NFPA 5000) by mandatory reference to, or incorporation of, the latest edition of the standard.

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[6] Typical floor span lengths in tall office buildings are in the range of 40 ft to 50 ft; this range is considered to represent long-span floor systems. Thermal effects (e.g., thermal expansion) that may be significant in long-span buildings may also be present in buildings with shorter span lengths, depending on the design of the structural system.

Relevance to WTC 7: The effects of restraint of free thermal expansion on the steel framing systems, especially for the long spans on the east side of WTC 7, were not considered in the structural design and led to the initiation of the building collapse.

<u>Recommendation C (NIST NCSTAR 1 Recommendation 4).</u> 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:[7]

- **timely access by emergency responders and full evacuation of occupants, or the time required for burnout without partial 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;[8]**
- **the need for redundancy in fire protection systems that are critical to structural integrity;[9]**
- **the ability of the structure and local floor systems to withstand a maximum credible fire scenario[10] without collapse, recognizing that sprinklers could be compromised, not operational, or non-existent;**
- **compartmentation requirements (e.g., 12,000 ft^2 [11]) 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.**

Relevance to WTC 7: The floor systems in WTC 7 failed at lower temperatures because thermal effects within the structural system, especially thermal expansion, were not considered in setting the fire rating requirements in the construction classification, which are determined using the ASTM E 119 or equivalent testing standard.

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[7] The construction classification and fire rating requirements should be *risk-consistent* with respect to the *design-basis hazards* and the *consequences* of those hazards. The fire rating requirements, which were originally developed based on experience with buildings fewer than 20 stories in height, have generally decreased over the past 80 years since historical fire data for buildings suggests considerable conservatism in those requirements. For tall buildings, the likely consequences of a given threat to an occupant on the upper floors are more severe than the consequences to an occupant on the first floor or the lower floors. For example, with non-functioning elevators, both the time requirements are much greater for full building evacuation from upper floors and emergency responder access to those floors. The current height and areas tables in building codes do not provide the technical basis for the progressively increasing risk to an occupant on the upper floors of tall buildings that are much greater than 20 stories in height.

[8] Occupant life safety, prevention of fire spread, and structural integrity are considered separate safety objectives.

[9] The passive fire protection system (including the application of SFRM, compartmentation, and firestopping) and the active sprinkler system each provide redundancy for maintaining structural integrity in a building fire, should one of the systems fail to perform its intended function.

[10] A maximum credible fire scenario includes conditions that are severe, but reasonable to anticipate, conditions related to building construction, occupancy, fire loads, ignition sources, compartment geometry, fire control methods, etc., as well as adverse, but reasonable to anticipate operating conditions.

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