EXECUTIVE SUMMARY FOR DESIGN, CONSTRUCTION, AND MAINTENANCE OF STRUCTURAL AND LIFE SAFETY SYSTEMS

E.1 INTRODUCTION

One of the four primary objectives of the National Institute of Standards and Technology (NIST) Investigation of the World Trade Center (WTC) disaster is to determine the procedures and practices that were used in the design, construction, operation, and maintenance of the structural, passive and active fire protection, and emergency and evacuation systems of WTC 1, 2, and 7 and the impacts these had on the buildings over their life, up to the attacks of September 11, 2001.

To accomplish this objective, relevant information was collected by reviewing design and construction documents, correspondence, and memoranda related to the building projects; and tenant alterations; interviewing individuals involved in the design, construction, and maintenance of the buildings; obtaining information from regulatory and emergency services agencies of New York City; and reviewing books and published journal and magazine articles related to the WTC building projects. Information obtained from various sources was synthesized and summarized in this report. Specifically, this report presents:

1. Provisions used to design and construct the structural, fire protection, and egress systems of the buildings;
2. Tests performed to support the design of these systems;
3. Criteria that governed the design of the structural and fire protection systems;
4. Methods used to proportion structural members and other components of the buildings;
5. Innovative features, technologies, and materials that were incorporated in the design and construction of the structural and fire protection systems;
6. Details of variances to the contract documents granted by the Port Authority of New York and New Jersey (PANYNJ or Port Authority);
7. Fabrication and inspection requirements at the fabrication yard; and
8. Inspection protocol during construction.
9. Alterations made to the buildings to accommodate specific needs of tenants or to respond to changes to the Building Code of New York City as implemented in Local Laws (LL) and interpreted in rules.

This report also addresses the fuel systems for the diesel generators that supplied emergency power to many of the tenants in WTC 7.

E.2 DESCRIPTION OF WTC 1, 2, AND 7

The WTC complex was located at lower west side of Manhattan, New York City, near the Hudson River. The complex was composed of seven buildings (referred to in this report as WTC 1 through WTC 7). The two towers, WTC 1 (North Tower) and WTC 2 (South Tower), were each 110 stories high. WTC 3 (Marriott Hotel) was 22 stories. WTC 4 (South Plaza Building) and WTC 5 (North Plaza Building) were both nine-story office buildings. WTC 6 (U.S. Customs House) was an eight-story office building. These six buildings were built around a 5 acre WTC Plaza. WTC 7 was a 47-story office building that was built just north of the six-building WTC site.

The first six buildings on the sixteen-acre site were developed by the Port Authority. Groundbreaking for WTC 1 and WTC 2 was in 1966, and the first tenant began to occupy WTC 1 in December 1970 and WTC 2 in January 1972. Construction of the other buildings continued during the 1970s and the 1980s. WTC 7 was developed by a consortium comprising the Seven World Trade Company, and Silverstein Development Corporation, and was completed in 1987.

The NIST Investigation is focused only on WTC 1, 2, and 7.

WTC 1 and WTC 2

Although the WTC towers were similar, they were not identical. The height of WTC 1 at the roof level was 1,368 ft above the Concourse level, was 6 ft taller than WTC 2, and supported a 360 ft tall antenna for television and radio transmission. Each tower had a square plan with the side dimension of approximately 207 ft. The corners of the tower were chamfered 6 ft 11 in. Each tower had a core service area of approximately 135 ft by 87 ft. All elevators and three egress stairs were located within the core, although on any given floor the arrangements of the elevators and the location of the stairs varied. Placing all service systems within the core provided a nearly column-free floor space of approximately 31,000 ft^2 per floor outside the core. The two towers had about 10 million ft^2 of rentable floor area.

The towers were designed as a “framed-tube” structural system with closely spaced exterior perimeter columns connected by spandrel beams around the perimeter at each floor level. The core was designed as a conventional frame with a grid of columns interconnected with beams.

The exterior walls were composed of box-shaped welded steel columns and spandrel beams comprised of a steel plate. Each building face consisted of 59 columns spaced at 3 ft 4 in. on center. As part of the framed-tube system, the exterior columns were designed structurally such that they resisted the total lateral loads and about 50 percent of gravity loads. Below floor 7, the columns were combined in groups of three to form single base columns which were spaced 10 ft on center and extended to the footings. An important architectural feature of the towers was the uniform look of the exterior walls, presented by the uniform width of the exterior columns up the height of the buildings. This was produced by maintaining a constant exterior dimension the columns and changing the strength of the steel with height. Thus, twelve different grades of steel, with yield strengths ranging from 36 ksi to 100 ksi, were used for the exterior columns. The external cladding, which covered the columns and spandrel beams, consisted of aluminum sheets. The window openings were infilled with glass fitted into aluminum covers and sealed with neoprene gaskets.

The core columns were of two types: welded box columns for the lower floors and rolled wide flange shapes for the upper floors. They were designed to support about 50 percent of gravity loads. Below floor 7 to the foundation, where there were fewer perimeter columns in the outer walls, bracings were used in the outer perimeter of the core area to increase lateral stiffness. In the lower part of the towers, the outer core columns were designed to resist a portion of the lateral forces. Hidden within the building, the core columns were thicker and larger on the lower floors. Thus, core columns used fewer grades of steel. The box columns were either 36 ksi or 42 ksi. Core wide flange columns were one of four grades, yield strengths ranging from 36 ksi to 50 ksi, but most (approximately 90 percent) were primarily 36 ksi or 42 ksi steel.

The floor system of WTC 1 and WTC 2 was composed of concrete-steel composite members. The area inside the cores and on the mechanical floors was framed with rolled structural steel shapes with welded shear studs acting compositely with normal-weight concrete slabs. The thickness of the slabs varied from 4.5 in. to 8 in. depending on design loads. The area outside the core, typically on tenant floors, was framed with steel trusses acting compositely with 4 in. thick lightweight concrete slabs cast on 1½ in., 22 gauge fluted metal deck. The trusses consisted of double angle top and bottom chords with round bar webs. Some floors, immediately adjacent to the mechanical floors, used a hybrid of beam and truss framing acting compositely with the concrete slab.

Fire protection of exposed structural steel members in the WTC towers was provided by applied fire resistive materials. They were either sprayed fire resistive materials (SFRMs), gypsum wallboards, or a combination of the two, depending upon the type of structural members, to meet the requirements of Construction Classification of 1B of the 1968 New York City (NYC) Building Code. All floor trusses and beams were protected with SFRM. The columns inside the core were either covered with gypsum wall board or a combination of gypsum wall board and SFRM. For the exterior columns, vermiculite plaster was applied to the side of the column facing the interior of the building, whereas SFRM was applied to other three faces. No fire resistive material was specified for the underside of the metal deck, which was in contact with the concrete slab above. For typical tenant floors, the ceiling was suspended from the steel trusses. The space between the ceiling and the floor above was used for the mechanical and electrical systems.

Elevators were the primary mode of routine ingress and egress from the towers for tens of thousands of people daily. In order to minimize the total floor space needed for elevators, each tower was divided vertically into three zones by skylobbies, which served to distribute passengers among express and local elevators. In this way, the local elevators within a zone were placed on top of one another within a common shaft. Local elevators serving the lower portion of a zone were terminated to return to the space occupied by those shafts to leasable tenant space. People transferred from express elevators to local elevators at the skylobbies which were located on the 44th and 78th floors in both towers. Each tower had 99 passenger and 7 freight elevators, all located within the core of the building.

WTC 7

WTC 7 was a 47-story commercial office building constructed by Silverstein Properties as a tenant alteration on land owned by the Port Authority. The overall dimensions of WTC 7 were approximately 330 ft long, 140 ft wide, and 610 ft high. It contained about 2 million ft^2 of rentable floor area. The building was constructed over a pre-existing electrical substation owned by Consolidated Edison

(Con Edison). The original plans for the Con Edison Substation included supporting a high-rise building, and the foundation was sized for the planned structure. However, the final design for WTC 7 had a larger footprint than originally planned.

Above floor 7, the building had typical steel framing for high-rise construction. The floor systems had composite construction with steel beams of 50 ksi yield strength supporting concrete slabs on metal deck, with a floor thickness of 5.5 in. The core and perimeter columns supported the floor system and carried their loads to the foundation. Above floor 7, the perimeter moment frame resisted wind forces. Below floor 7, a combination of moment and braced frames around the perimeter and a series of braced frames in the core resisted the wind load.

Columns above floor 7 did not align with the foundation columns, so braced frames, transfer trusses, and transfer girders were used to transfer loads between these column systems, primarily between floors 5 and 7. Floors 5 and 7 were heavily reinforced concrete slabs on metal decks, with thicknesses of 14 in. and 8 in., respectively.

Core columns were primarily rolled wide-flange shapes with a yield strength of either 36 ksi or 50 ksi, while the exterior columns were typically rolled W14 shapes with a yield strength of 36 ksi.

E.3 CODE PROVISIONS FOR STRUCTURAL DESIGN

The design of WTC 1, 2, and 7 was based on the 1968 edition of the NYC Building Code. As an interstate compact under the U.S. Constitution, the Port Authority was not subjected to any state or local building codes. In May 1963, the Port of New York Authority (PONYA or Port Authority) instructed the architect and structural engineer to prepare their designs for WTC 1 and WTC 2 in accordance with the NYC Building Code. At that time, the 1938 edition of that Code was in effect. In September of 1965, the PONYA instructed the architect and structural engineer to revise their designs for WTC 1 and WTC 2 to comply with the second and third drafts of the new NYC Building Code that was under development. Prior to issuance of this instruction, the Port Authority recognized that the draft version of the new NYC Building Code had incorporated advanced techniques and the Port Authority favored the use of advanced techniques in the design of the WTC towers. By adopting the draft versions of the new NYC Building Code, WTC 1 and WTC 2 could be classified as Type 1-B Construction, and several features related to egress such as the elimination of the fire tower and the reduction of the number of egress stairs required from six to three with narrower doors were incorporated into the final design.

The new Code was adopted on December 6, 1968. Subsequently, the NYC Building Code was amended by numerous Local Laws to improve safety requirements or to incorporate technological advances, some of which had impacts on the towers. When WTC 7 was designed, the 1968 Building Code was in effect and the Local Laws impacting fire, life safety, and structural arrangements were in place, so these were incorporated into the original design of that building.

To put the design of WTC 1, 2, and 7 into the context of building codes and practices of the time, the structural provisions of the 1968 edition of the NYC Building Code were compared with the structural provisions in a number of contemporaneous codes, as well as in the 2001 edition of the NYC Building Code, which is currently in effect. Specifically, the following codes were selected for comparison of the structural provisions: the 1964 New York State Building Construction Code (NYSBC 1964); the 1965 Building Officials and Code Administrators (BOCA) Basic Building Code (BOCA/BBC 1965); the 1967

Municipal Code of Chicago Relating to Buildings (MCC 1967); and the 2001 edition of the NYC Building Code (NYCBC 2001). The 1964 New York State Building Construction Code was selected for comparison, as it would have been a governing building code outside New York City limits. The 1965 BOCA Basic Building Code was selected, as it was typically adopted by local jurisdictions in the northeastern region of the United States. The 1968 NYC Building Code is compared with the 1967 Municipal Code of Chicago to see whether there are any substantial differences in the structural and fire safety requirements of the two codes. In the late 1960s and early 1970s, several tall buildings were built in Chicago, including the Sears Tower (110 stories) and the John Hancock Tower (100 stories). The 2001 edition of the NYC Building Code is compared with the 1968 version to examine the extent to which Local Laws have modified the code provisions.

Structural provisions include those concerning design loads, such as dead loads, live loads (including live load reduction), wind loads, earthquake loads, and other loads. They also include provisions concerning what is called “structural work” in the NYC Building Codes (this term is not used in the other codes). The scope of “structural work” includes, but is not limited to, materials and methods of construction, design methods including design load combinations, and the materials of construction including concrete, masonry, steel, and wood. Structural provisions also include those for foundation design and construction.

With respect to structural design provisions, the major changes from the 1968 to the 2001 edition of the NYC Building Code are the inclusion of seismic design requirements and updating of standards. Of the codes contemporaneous with the 1968 NYC Building Code examined for this investigation, only the BOCA Basic Building Code had seismic design requirements, which were adopted from the 1962 edition of the Uniform Building Code (UBC). Taller buildings have longer periods of vibration, which means lower seismic design forces. Also, since New York City is in an area of moderate seismicity (UBC Zone 2A), additional seismic detailing requirements are minimal to non-existent.

The alternate live load reduction provisions for columns, walls, and piers of the 1968 and 2001 NYC Building Codes are the same as in the Chicago Municipal Code. The New York State Building Code has more liberal live load reduction provisions for upper portions of buildings. The NYC Building Codes also have live load reduction provisions based on contributory floor area and live-to-dead load ratio. For live-to-dead load ratios of 0.625 or less, the New York City code provisions may yield higher live load reduction for columns, walls, and piers than allowed by the other codes. For beams and girders, the live load reduction provisions of the NYC Building Code are comparable to those of the New York State Building Code and the BOCA Basic Building Code. The Chicago Municipal Code has more conservative requirements. The maximum live load reduction allowed for beams and girders in the Chicago Municipal Code is 15 percent, compared with 40 percent in the other codes.

When the wind load provisions in the codes are compared, the largest shear force at the base of a building is obtained from the BOCA Basic Building Code when the height of the building is taken equal to 1,368 ft (i.e., the height of WTC 1). Similarly, the largest overturning moment at the base of a building with the height of the WTC towers is also obtained from the BOCA Basic Building Code. Thus, the NYC Building Code does not have the most stringent wind load provisions.

The 1968 NYC Building Code requires that weights of partitions be considered in two ways: (1) using line loads at locations shown on plans or (2) using the equivalent uniform load. Equivalent uniform loads must be used in areas where the locations of partitions are not shown on plans, or in areas where partitions can be relocated. The 1964 New York State Building Construction Code did not have a specific provision in this regard. The 1967 Municipal Code of Chicago prescribed a minimum partition load of 20 psf. The BOCA Basic Building Code required consideration of the actual weight of the partitions or an equivalent uniform load of at least 20 psf.

The primary materials design standards referenced by the 1968 NYC Building Code, the Chicago Municipal Code, and the BOCA Basic Building Code are the 1963 edition of the American Concrete Institute's (ACI's), *Building Code Requirements for Reinforced Concrete (ACI 318)*, and the American Institute of Steel Construction's, *Specifications for the Design, Fabrication and Erection of Structural Steel for Buildings (AISC 1963)*. The New York State Building Code, being a performance code, does not adopt any specific standards by reference. The 2001 NYC Building Code adopts the 1989 edition of ACI 318, AISC 1989, *Specifications for Structural Steel Buildings – ASD and Plastic Design*, and AISC-LRFD 1993, *Load and Resistance Factor Design Specifications for Structural Steel Buildings*.

The NYC Building Codes have extensive and quite rigorous foundation design and construction requirements. The foundation related provisions of the other codes are less extensive and typically less rigorous.

The NYC Building Codes prescribe testing and inspection requirements for all materials, assemblies, forms and methods of construction. The other three codes require that materials and methods of construction meet the criteria of generally accepted standards. With respect to foundations, only the NYC Building Codes have specific requirements for foundation inspection.

E.4 STRUCTURAL DESIGN OF WTC 1, 2, AND 7

For WTC 1 and WTC 2 the design criteria were established referencing provisions of the 1968 NYC Building Code as minimum. The design dead loads and live loads specified in the design criteria were greater than or equal to corresponding design loads in the Building Code. Live load reduction requirements given in the design criteria were equal to or more stringent than Code requirements.

Wind forces on the towers were determined based on a series of wind tunnel tests that were conducted at the Colorado State University and the National Physical Laboratory, Teddington, Middlesex, United Kingdom. Such tests were permitted by the Code to determine wind pressures in lieu of those tabulated in the Code. The code prescribed base shear and overturning moment occur simultaneously on the same face of the tower, and these values are the same for all four faces. The base shear and the overturning moment obtained from the wind tunnel tests represent the largest values related to most unfavorable wind direction; so, they may not occur simultaneously on the same face of the tower. Thus, the base shear value obtained from the wind tunnel tests is about 42 percent greater than that obtained using the code prescribed wind pressure values, whereas the overturning moments obtained from the wind tunnel tests is about 65 percent greater than that obtained using the code prescribed wind pressure values.

The allowable stress method in the 1963 American Institute of Steel Construction (AISC) *Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings* was used to proportion the exterior columns and spandrels for the combined effects of axial compression, bending moment, and shear due to gravity and wind forces. Composite floor trusses were designed based on the AISC Specification. The allowable stress method was also used to proportion the members in the hat trusses that were located between the 107th floor and the roof in WTC 1 and WTC 2. In the core area, composite steel beams, columns, and their connections were designed by the appropriate requirements in the 1963

AISC Specification. The ultimate strength method in the 1963 edition of the ACI *Building Code Requirements for Reinforced Concrete* was used to design the concrete floor slabs in WTC 1 and WTC 2.

For WTC 7, the project specifications required that the structural steel be designed in accordance with the 1968 edition of the NYC Building Code, edited and amended through January 1, 1985, and the 1978 edition of the AISC *Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings.* Design load criteria for WTC 7, listed on one of the structural drawings, show that the design values for the superimposed dead loads could not be ascertained, since the actual materials used for partitions, flooring, and ductwork were not specified. The live loads in the design criteria were equal to those in the 1968 NYC Building Code at the floors where the type of occupancy was noted. No documents were found that indicated what live load reduction was used.

No design criteria or calculations including wind load analysis of WTC 7 were available for this investigation. However, a wind tunnel study of WTC 7 was carried out in 1983 by the University of Western Ontario at the request of the structural engineer of record.

E.5 INNOVATIVE FEATURES INCORPORATED IN STRUCTURAL DESIGN

A number of innovative features were incorporated in the structural design of WTC 1 and WTC 2. They were incorporated in both the lateral-load-resisting system and the gravity-load-carrying system.

These features include the following:

- Application of the framed-tube system to resist lateral loads.
- Uniform exterior column geometry (14 in. by 14 in. cross-section) was maintained over most of the height of the 110-story buildings by using twelve different grades of steel.
- Use of deep spandrel plates as beam elements connecting perimeter columns.
- Use of long-span composite steel trusses for the floor systems. Composite action was achieved between the steel trusses and the concrete floor slab by extending the truss diagonals above the top chord into the slab.
- Application of viscoelastic dampers connecting the floor trusses to the perimeter framed tube system to control dynamic response.
- Use of wind tunnel test data to establish the wind loads used in the design of the towers.

E.6 FABRICATION AND CONSTRUCTION INSPECTIONS AND VARIANCES

The contract documents for WTC 1 and WTC 2 between the Port of New York Authority and the steel fabricators and erector, and the construction contract specifications for WTC 7, indicate that inspection programs were instituted at the steel fabrication sites. The inspection requirements were listed in the contract documents. However, the records of inspections for both the WTC 1 and WTC 2 and the WTC 7 projects were not available to the investigation. The records for WTC 1 and WTC 2, which were kept in WTC 1 were destroyed, and the records for WTC 7 were discarded by the general contractor after retaining them for 7 years.

WTC 1 and WTC 2

Fabrication and inspection requirements were contained in the contracts for the floor trusses, box core columns and built-up beams, members of the exterior wall, and rolled columns and beams. In general, the inspection requirements from the specifications for the various contracts were at a minimum equivalent to those in the 1968 NYC Building Code. The Code contains provisions that govern the fabrication and inspection of materials used in buildings. However, in a number of cases, the contract requirements were more comprehensive and stringent than the corresponding provisions in the Code The Code refers to the requirements in the 1963 AISC *Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings* (AISC 1963). The AISC Specification contained minimum fabrication requirements for the following:

- Straightening of materials
- Gas cutting
- Planing of edges
- Riveted and bolted construction – holes
- Riveted and high strength bolted construction – assembling
- Welded construction
- Finishing
- Tolerances

Specific inspection requirements during fabrication of various structural members were covered in the contract documents between PONYA and individual fabricators.

WTC 7

The contract specification for WTC 7 required that structural steel for WTC 7 was to be fabricated in accordance with the applicable requirements in the 1968 NYC Building Code, the 1963 AISC *Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings*, and other specifications related to bolts, welds, and painting. The specification also notes that there was a separate contract for testing and inspection. This contract was not found. However, specific requirements for inspection of shop and field welds by a testing agency were included in the specification.

E.7 INSPECTION PROTOCOL DURING CONSTRUCTION

WTC 1 and WTC 2

Karl Koch Erecting Co., the company that performed the structural steel erection work for WTC 1 and WTC 2, developed a quality control and safety program. This program included information on ten different key areas that were to be addressed during construction, including:

- Survey control
- Control of construction and erection loads
- Field welding
- Bolting of structural steel
- Control of stud welding operations
- Erection procedures
- Control of workmanship
- Control of erection tolerances
- As-built drawings
- Safety programs

WTC 7

The WTC 7 specifications contained general erection requirements for fasteners, anchor bolts, column bases, installation, and bracing. The specification did not include any requirements for inspection.

E.8 VARIANCES GRANTED BY PANYNJ

The Port Authority approved numerous variances in the fabrication and erection of structural members in WTC 1 and WTC 2. The Office of the Construction Manager at the Port Authority approved variances to the contract documents after the structural engineer of record; Skilling, Helle, Christiansen, and Robertson (SHCR), reviewed the details of the variances and recommended approval. In many cases, SHCR submitted alternative methods, which were incorporated into the variance.

The variances that were granted for the structural members and their materials may be categorized into the following groups:

- Variances relating to fabrication/erection tolerances (box columns, box beams, and floor trusses)

- Variances relating to defective components (column trees and floor trusses)
- Variances relating to alternative fabrication/erection procedures (core columns, floor trusses, exterior wall columns, and beam seats)
- Variances relating to product substitutions (exterior wall)
- Variances relating to inspection practice (exterior wall and welds).

Fabrication and erection inspections identified many deviations from the contract drawings and specifications. Many variance requests were based on inspection results.

E.9 STRUCTURAL MAINTENANCE AND MODIFICATIONS DURING OCCUPANCY

Both architectural and structural modifications were made to meet the occupancy needs of individual tenants throughout the history of occupancy of WTC 1, 2, and 7. PONYA, later PANYNJ, reviewed all modifications to maintain the structural integrity of the buildings and to ensure that modifications were compatible with existing building conditions. In order to guide tenants in their modification process, the PONYA issued *Tenant Alteration Review Manual* in 1971 and updated the manual periodically through 1997.

In anticipation of structural degradation, the PANYNJ issued in 1986 the *Standard for Structural Integrity Inspection of the World Trade Center Towers A & B* to guide periodic inspection of structural members. Deteriorated and damaged members were identified for repair. The standard was used by consultants who were retained by PANYNJ for systematic examination of WTC 1 and WTC 2.

In 1998, the PANYNJ issued the *Standards for Architectural and Structural Design* for modification works. The standards included not only the design guide, but also included specifications and standard details to be used in modification works. Tenants proposing any modifications were required to follow the specified standards.

Apart from the repairs following the 1993 bombing of WTC 1, most of the structural modifications in WTC 1 and WTC 2 were performed to accommodate tenant requirements. Openings were cut in existing floors to construct new stairways linking two or more floors, and floor systems were reconstructed over previously cut openings. In a number of cases, floor trusses outside of the core area and steel beams in the core area had to be reinforced due to heavy loads imposed by tenant requirements. All such modifications were reviewed and approved by the structural engineer of record (SHCR).

Similar to WTC 1 and WTC 2, most of the structural modifications in WTC 7 were done to accommodate tenant requirements. Horizontal members of the floor framing system were strengthened due to increased loading from high-density files. Strengthening of these beams and girders was achieved by welding cover plates to the bottom flanges, the underside of the top flanges, or both. In some cases, new beams were introduced to carry a portion of the new load.

Structural Integrity Inspection Program

In 1986, PANYNJ implemented an inspection program to detect, record, and correct any signs of distress, deterioration, or deformation that could signal structural problems. This structural integrity inspection program contained detailed guidelines on inspection, record-keeping, and follow-up procedures.

Inspection findings were to be categorized as “Immediate,” “Priority,” or “Routine.” Repairs falling into the “Immediate” category included possible closure of the area and/or structure affected until interim remedial action could be implemented. The “Priority” category was for those conditions where no immediate action was required, or for which immediate action had been completed, but for which further investigation, design, and implementation of interim or long-term repairs were to be undertaken on a priority basis (i.e., taking precedence over all other scheduled work). Repairs falling into the “Routine” or “non-priority” category were to be undertaken as part of a scheduled major work program or other scheduled project, or when routine facility maintenance was to be performed, depending on the type of repair that was required. An important requirement in the inspection program was that where inspection procedures involved the removal of fireproofing, such fireproofing was to be properly replaced on completion of inspection.

In general, the structural integrity inspections findings indicated that the structural systems of WTC 1, 2, and 7 were in good condition. The inspections resulted in numerous routine and some priority recommendations for repairs, as outlined in the inspection standard. According to the PANYNJ, all of the construction records on repairs following the inspections were lost on September 11, 2001. Thus, it cannot be determined whether all of the recommended repairs were performed.

Repair Work Following the 1993 Explosion

The explosion of February 26, 1993, occurred on Level B2 near the center of the south wall of WTC 1 and adjacent to WTC 3 (Vista Hotel). Structural steel columns, diagonal braces, and spandrel beams in the vicinity of the blast were damaged. Concrete floor slabs at Levels B1 and B2 and unreinforced masonry walls were also damaged over a large area.

The explosion severely bent and tore out the diagonal brace between columns. Spandrel beams at level B1 were also damaged by the blast. A crack developed along the field splice in a column. Ultrasonic testing determined that the crack extended across the full width of the weld on the south face of the column and at each end of the weld on the north face. Magnetic-particle testing procedure determined that the crack extended across the east face of the column. The explosion also damaged floor beams at levels B1 and B2. Concrete spandrel beams at level B3 also sustained damage. Masonry walls in WTC 1 were breached over distances of approximately 50 ft to the east and 120 ft to the west of the blast origin.

The diagonal bracing members between levels B1 and B2 that were damaged by the explosion were removed and replaced with new members. New plates were added to the damaged spandrel beam at level B1. Also, the cracked weld on the south face of the spandrel beam at level B1 was removed and replaced.

Six different inspections were performed before and after repairs were made to WTC 1. No anomalies were detected in the welds used to repair structural members.

E.10 CODE PROVISIONS FOR DESIGN OF THE FIRE SAFETY AND EGRESS SYSTEMS

The fire safety provisions of the 1968 NYC Building Code (NYCBC 1968) were compared with four other building codes: the 1964 New York State Building Construction Code (NYSBC 1964), the 1965 BOCA Basic Building Code (BOCA/BBC 1965), the 1967 Municipal Code of Chicago Relating to Buildings (MCC 1967), and the 2001 edition of the NYC Building Code (NYCBC 2001). In addition, comparisons were made to the 1966 edition of National Fire Protection Association (NFPA) 101, Code for Safety to Life in Buildings and Structures. While not a building code, NFPA 101 is widely adopted for its requirements for life safety in fires.

The NYC Building Code was regularly amended by local laws, two of which, Local Law 5 (1973) and Local Law 16 (1984), had a significant influence on WTC 1 and WTC 2, even though the buildings were completed and occupied at the time of adoption. It is normal practice not to apply building code changes to existing buildings, but the Port Authority chose to follow the revised provisions and to retrofit the buildings as required under the new provisions. The resulting changes to WTC 1 and WTC 2 are discussed primarily in the sections on modifications to the building systems.

While New York City developed its own building code, their code development committees were influenced by the same forces that bore on the model codes. Thus, there were relatively few differences between the NYC Building Code and the others.

Construction Classification

In Construction Classifications, the 1968 Building Code, the New York State Building Code, and the 1965 BOCA all recognized Class 1A or Class 1B (with the same fire resistance ratings for building elements) for most unsprinklered buildings of unlimited height, while the 1967 Chicago Code recognized only 1A. New York City imposed a 75 ft height limit on unsprinklered buildings with the adoption of Local Law 16 (1984).

Active Systems

At the time of construction, sprinklers were primarily for property protection and were rare even in high-rise buildings (except for underground spaces). Fire alarm systems were mostly manually initiated but there was concern about smoke being recirculated through the heating, ventilating, and air conditioning (HVAC) systems, so smoke detectors controlled dampers at return shafts to prevent this. This is the arrangement of the fire alarm system originally installed in the towers. Voice communication systems were a response to phased evacuation with the recognition that it was necessary to provide instructions to occupants who were relocated or held within the building at least until they were told to leave. Requirements for voice systems first appeared in national standards in the mid-1980s, at the same time as NYC adopted LL 16 (1984).

Technical Standards

All building codes rely on referenced technical standards to provide the details of design, installation, operation, and maintenance of required systems. Most building codes reference national (consensus) standards as published, but New York City cites their own reference standards that are based on these national standards but are often highly modified. For example, fire alarm systems and fire sprinkler systems are addressed in Reference Standard (RS) 17, with Class E fire alarm systems (required in office occupancies) covered in RS 17-3A and general fire alarm system requirements in RS 17-5. The former is entirely written by a NYC code committee, and the latter is based on NFPA 72 (National Fire Alarm Code) but highly modified by the deletion of many sections and modification of many others. One major modification is that RS 17 does not include the "Survivability" section for high-rise voice communication systems that requires duplicate communication trunks so that loss on one trunk does not result in loss of communication with a floor. However the voice communication system installed in WTC 1 and WTC 2 was consistent with the National Fire Alarm Code (NFPA 72) in addition to RS 17 and had redundant trunks run in Stairways A and C.

Egress Systems

Prior to 1988, all building codes determined egress capacity by the (22 in.) Units of Exit Width method, which New York City still uses. In 1988, other codes changed to a method involving an allowance of width per person, which provides credit for non-standard widths of corridors and doors, but for standard dimensioned components yields the same results. Another difference in egress design is that New York City applies the occupant load factor for business occupancies (100 ft^2 per person) to the net floor area while other codes use the gross floor area. Other codes use net for some and gross for others. The NYC Building Code allows doubling stair capacity allowances with one or tripling of the stair capacity on floors with two or more horizontal exits where other codes only allow doubling for one horizontal exit (see discussion of Windows on the World).

Miscellaneous Details

There are a number of detail differences between the NYC Building Code and the other building codes. The NYC Building Code has no requirements for fire extinguishers since they require occupant hose reels. The 1968 NYC Building Code was the first code to include smoke developed ratings for finish materials in addition to flame spread. Now, all of the codes have similar requirements.

Specifications for the Original Buildings

No contemporaneous documentation has been found that provides the rationale for the decision to select Class 1B for the WTC towers. This decision, however, appears to have been made by the architect-of-record on the basis of economics.

As stated above the primary occupancy group was Group B (Business) with the Windows on the World space in WTC 1 being Group F (Assembly). While there was a Port Authority cafeteria on the 44th floor, employee cafeterias not open to the public are specifically exempted from assembly classification because they do not increase occupant load and are only used intermittently. Incidental mercantile spaces such as news stands and coffee bars at the concourse level are also exempt from reclassification in most building codes.

The NYC Building Code and Port Authority practice required partitions to separate tenant spaces from each other and from common spaces such as the corridors that served the elevators, stairs, and other common spaces in the building core. Fire rated partitions are intended to limit fire spread on a floor, to prevent spread of fire in one tenant space to that of another, Partitions separating tenant space from exit access corridors were permitted to be 1 h, although the Port Authority specified them to be 2 h, allowing dead ends to extend to 100 ft (rather than 50 ft with 1 h partitions), which permitted more flexibility in tenant layouts. Partitions separating tenant spaces (so-called demising walls) were required to be 1 h (see Sec. 10.4.5). Enclosures for vertical shafts, including stairways and transfer corridors, elevator hoistways, and mechanical or utility shafts were required to be of 2 h fire rated construction. Protection of vertical shafts is intended to limit the spread of fire and smoke from floor to floor.

The primary egress system for the office spaces was the three stairways located in the building core. These included two 44 in. (designated A and C) and one 56 in. wide (designated B) stairs which provided exactly the code required capacity for an occupant load of 390 per floor (39,000 ft^2 net at 100 ft^2 per person). The layout within the building core was consistent with the Building Code requirements for maximum travel distance (200 ft unsprinklered, 300 ft sprinklered) and, while the separation was consistent with New York City requirements (15 ft and later 30 ft), it was short of the more common requirements found in all current building codes (one-half the diagonal of the space served if unsprinklered, or one-third the diagonal if sprinklered) on some of the floors where the transfer corridors brought the stair access closer together.

There were 99 passenger elevators in each tower, arranged in three vertical zones to move occupants in stages to skylobbies on the 44th and 78th floors. These were arranged as express (generally larger cars that moved at higher speeds) and local elevators in an innovative system first introduced in WTC 1 and WTC 2. There were 8 express elevators from the concourse to the 44th floor and 10 express elevators from the concourse to the 78th floor as well as 24 local elevators per zone, which served groups of floors in those zones. There were seven freight elevators, only one of which served all floors. All elevators had been upgraded to incorporate firefighter emergency operation per American Society of Mechanical Engineers (ASME) A17.1 and Local Law 5 (1973).

Consistent with practice at the time, the original fire alarm system in WTC 1 and WTC 2 was a manual system with four smoke detectors on each tenant floor, positioned to monitor for smoke entering the HVAC returns and arranged to stop the fans to prevent smoke circulation to non-fire areas. Local Law 5 (1973) included retroactive requirements for fire alarm systems and emergency voice communication systems in business occupancies over 100 ft in height. Subsequently, such systems were installed in WTC 1 and WTC 2 with the required fire command center located in the underground parking garage, where it was destroyed by the blast in the 1993 bombing, rendering most fire safety features inoperable. Following the 1993 bombing, the fire command stations were relocated to the tower building lobbies, with a third monitoring location in the Port Authority offices. The lobby location (within sight of the elevators) is specified in the NYC Building Code for fire command centers required in high-rise buildings. There are no code requirements for off-site monitoring of fire alarm systems in this occupancy.

Modifications to the Fire and Life Safety Systems

The general practice is that buildings are governed by the building code in force at the time the building permits are issued except in the rare case of the adoption of retroactive requirements. Local Laws 5 (1973) and 16 (1984) were adopted after completion of WTC 1 and WTC 2 but did contain some retroactive provisions. However, the Port Authority chose to implement virtually all of the provisions of

LL 5/73 and LL 16/84, which drove most of the modifications to the fire and life safety systems that occurred over the life of the buildings. These modifications included the complete sprinklering of the buildings and several upgrades to the fire alarm system.

After the passage of Local Law 5, the Port Authority implemented a program to retrofit sprinklers and to offer tenants the option of sprinklering or compartmentation consistent with Local Law 5 provisions. Sprinklering of WTC 1 and WTC 2 was undertaken in three phases: Phase 1 was the sprinklering of below grade spaces completed with the original construction. Phase 2 was begun after Local Law 5 was adopted and included the installation of sprinkler risers and other infrastructure and the installation of sprinklers in corridors, storage rooms, lobbies, and smaller tenant spaces for tenants not selecting the compartmentation option. Phase 3 involved sprinklering the remaining tenant spaces, initially as tenants changed, and later on negotiated schedules. This process was underway when, in 1984, Local Law 16 was adopted, which required sprinklers in new high-rise buildings, including offices. Under Local Law 16 (1984) all floor spaces had to either be subdivided in accordance with the compartmentation requirement or sprinklered by February 8, 1988. A 1997 report states that there were four floors and the skylobbies (all in WTC 1) left to be sprinklered and that the installation of sprinklers at these floors was underway (Coty 1997). An October 1999 report states that sprinklering of the tenant floors was completed and sprinklering of the skylobbies was "currently underway" (PANYNJ 1999).

Issues identified after completion of the buildings that were not related to amendments to the NYC Building Code that were addressed during the occupancy included the extension of the tenant separation walls to run slab to slab, upgrading of the fireproofing to 1½ in. on the floor trusses, and correction of the egress deficiencies for Windows on the World by creating three areas of refuge on each floor with 2 h separations, each including a stair. These issues were identified through various independent reviews conducted by PANYNJ and contractors hired by PANYNJ to conduct "due diligence" surveys. One example was the surveys conducted in 1996 by Rolf Jensen and Associates and Jaros, Gaum & Bolles which identified inconsistencies with the code and programs to address them, which are discussed in this report in detail.

Innovations in Fire and Life Safety Features

Little about the towers' fire and life safety features would be considered novel or innovative. The fire alarm systems as originally provided and as upgraded over the life of the buildings were of high quality and state-of-the-art, but followed accepted practice as it evolved in those years. Similarly, the fire sprinkler system was high quality and state-of-the-art, following accepted practice with a few features following New York City practice that differed from the rest of the nation. This included manually operated fire pumps with a so called "standpipe telephone system" to communicate with the pump operator. Most codes and standards specify automatic fire pumps.

Two features that were novel (and thus innovative) were the use of lightweight trusses in the floor system with fire protection of spray applied material on steel bars (rather than angles). Another was the shaft enclosure system of reinforced gypsum planks with applied steel channels that formed the framing. While gypsum shaft enclosure systems are now common, this particular arrangement was not used before or since.

Fuel System for Emergency Generators in WTC 7

Several of the tenants in WTC 7 installed generators to supply critical operations with continuous power. These generators were installed on several floors within the building (5, 7, 8, and 9) and fed from small (275 gal) "day tanks" near the generators. These day tanks were kept full by an automatic system of piping running to primary storage tanks (24,000 gal) located under the loading dock or a 6,000 gal tank in a 1st floor storage room associated with the generators for the Mayor's Office of Emergency Management on the 7th floor. Details of the system design and installation are found in NIST NCSTAR 1-1J.[1]

E.11 FINDINGS

The findings of this report are grouped into three categories: (1) general; (2) factors related to structural safety; and (3) factors related to fire safety.

E.11.1 General

Finding 1: 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. All six comments made by the NYC Department of Buildings dealt with egress issues, but none questioned the large occupant loads for Windows on the World in WTC 1 or Top of the World in WTC 2.

Finding 2: In 1993, the PANYNJ and the NYC Department of Buildings entered into a memorandum of understanding that restated the PANYNJ's longstanding stated policy to ensure 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 ensure that buildings owned or operated by the PANYNJ are in conformance with the Building Standards contained in the NYC Building Code. Some salient points included in this agreement and the 1995 enhancement to the agreement are:

- Each project would be reviewed and examined for compliance with the Code.
- All plans would be prepared, sealed, and reviewed by New York State licensed professional engineers or architects.
- The PANYNJ engineer or architect approving the plans would be licensed in the State of New York and would not have assisted in the preparation of the plans.
- The person or firm performing the review and certification of plans for WTC tenants may be the same person or firm providing certification that the project had been constructed in accordance with the plans and specifications unless the proposed alteration would "change the character of the occupancy group under paragraph 27-237 of the NYC Building Code

[1] This reference is to one of the companion documents from this Investigation. A list of these documents appears in the Preface to this report.

which would have been applicable to such space had such space been located in a privately owned building."

- Variances from the Code, acceptable to the PANYNJ, would be submitted to the NYC Department of Buildings for review and concurrence. Disagreements between the PANYNJ and the NYC Department of Buildings over such variances from the Code would be referred to the Port Authority Board of Commissioners for resolution.

Finding 3: 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 and sought review and concurrence as required by the agreements, the PANYNJ was not required to yield, and appears not have yielded, approval authority to New York City. The PANYNJ was created as an interstate entity "body corporate and politic," under its charter, pursuant to Article 1 Section 10 of the U.S. Constitution permitting compacts between states, and like many other nongovernmental and quasi-governmental entities in the United States is not subject to building and fire safety code requirements of any governmental jurisdiction.

Finding 4: State and local jurisdictions do not require retention of documents related to the design, construction, operation, maintenance, and modifications of buildings, with few exceptions. These documents are in the possession of building owners, contractors, architects, engineers, and consultants. Such documents are not archived for more than about 6 years to 7 years, and there are no requirements that they be kept in safe custody physically remote from the building throughout its service life. In the case of the WTC towers, the PANYNJ and its contractors and consultants maintained an unusually comprehensive set of documents, a significant portion of which had not been destroyed in the collapse of the buildings but could be assembled and provided to the investigation. In the case of WTC 7, several key documents could not be reviewed since they were lost in the collapse of the building.

Finding 5: Consistent with the practice at the time the (code) architect was responsible for specifying the fire protection and designing the egress system in accordance with the prescriptive provisions of the Building Code. The architect and owner engaged the services of structural engineers to perform the structural design and to ensure that his/her design was properly implemented. At that time the fire protection engineering profession was not sufficiently mature to require the same standard of care employed with the structural design. There is no reason to believe that the involvement of a fire protection engineer at that time would have resulted in any differences in the design or performance of the fire protection systems. However, the technical base and sophistication of the practice of fire protection engineering today is well advanced of where it was then. Today, particularly when designing a building employing innovative features, the involvement of a fire protection engineer in a role similar to the structural engineer, and under the overall coordination of the Design Professional in Responsible Charge is central to the standard of care. Further, when designing the structure of selected tall buildings or selected other buildings to resist fires, or evaluating the fire resistance of such structures, it is essential for the structural engineer and the fire protection engineer to jointly provide the needed standard of care.

E.11.2 Structural Safety

Applicable Building Codes

Finding 6: Although not required to conform to New York City codes, the PANYNJ adopted the provisions of the proposed 1968 edition of the NYC Building Code, more than 3 years before it went into effect. The proposed 1968 edition allowed the PANYNJ to take advantage of less restrictive provisions and of technological advances compared with the 1938 edition, which was in effect when design began for the WTC towers in 1962. The 1968 code:

- 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 wind tunnel tests using models to establish design values for the wind load.

Many of these newer requirements, instituted in the 1968 NYC Building Code, are contained in current model codes and building regulations.

Structural Integrity

Finding 7: Building codes lack explicit structural integrity provisions to mitigate progressive collapse. Federal agencies have developed guidelines to mitigate progressive collapse and routinely incorporate such requirements in the construction of new federal buildings. The United Kingdom incorporates such code requirements for all buildings. New York City adopted by rule in 1973 a requirement for buildings to resist progressive collapse under extreme local loads. The rules, which were adopted after the WTC towers were built but before WTC 7 was built, applied specifically to buildings that used precast concrete wall panels and not to other types of buildings.

Finding 8: Building codes lack minimum structural integrity provisions for the means of egress (stairwells and elevator shafts) in the building core that are critical to life safety. In most tall buildings the core is designed to be part of the vertical gravity load carrying system of the structure. However, in many of those buildings, especially in regions where earthquakes are not dominant, the core may not be part of the lateral load carrying system of the structure. Thus, the core may be designed to carry only vertical gravity loads with no capacity to resist lateral loads, i.e., overturning moment and shear loads. In such situations, the structural designer may prefer the use of partition walls over structural walls in the core area to reduce building weight. The decision to have the core carry a specified fraction of the lateral design loads or be made part of a dual system to carry lateral loads, each of which would enhance the structural integrity of the core if structural walls were used, is left to the discretion of the structural engineer. Alternatively, stairway/elevator cores built with concrete or reinforced concrete block, which are not part of the lateral load carrying system, may be able to provide sufficient structural integrity if they meet, for example, ASTM E1996-03, or other more appropriate test for impact resistance. In the case of the WTC towers, the core had 2 h fire-rated partition walls with little structural integrity and the core framing was required to carry only gravity loads. Had there been a minimum structural integrity requirement to satisfy normal building and fire safety considerations, it is conceivable that the damage to stairways, especially above the floors of impact, may have been less extensive.

Finding 9: Standards and code provisions for conducting wind tunnel tests and for the methods used in practice to estimate design wind loads from test results do not exist. Building codes allow the determination of wind pressures from wind tunnel tests for use in design. Such tests are frequently used in the design of tall buildings. Results of two sets of wind tunnel tests conducted for the WTC towers in 2002 by independent commercial laboratories as part of insurance litigation, and voluntarily provided to NIST by the parties to the litigation, show large differences, of as much as about 40 percent, in resultant forces on the structures, i.e., overturning moments and base shears. Independent reviews by a NIST expert on wind effects on structures and a leading engineering design firm contracted by NIST indicated that the documentation of the test results did not provide sufficient basis to reconcile the differences. Wind loads were a major governing factor in the design of structural components that made up the frame-tube steel framing system.

E.11.3 Fire Safety

Applicable Building Codes

Finding 10: Although not required to conform to New York City codes, the PANYNJ adopted the provisions of the proposed 1968 edition of the NYC Building Code, more than 3 years before it went into effect. The 1968 edition allowed the PANYNJ to take 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[2] as a required means of fire department access;
- 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.(by increasing stairway and door capacity allowances);
- Reduced the required fire rating of the shaft walls in the building core from 3 h to 2 h; 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) by allowing the owner/architect to select Class 1B construction for business occupancy and unlimited building height.

Many of these newer requirements, instituted in the 1968 NYC Building Code, are contained in current codes.

Finding 11: 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 the New York City Fire Department (FDNY), which reiterated the policy adopted by the PANYNJ, recognized the right of FDNY to conduct fire safety inspections of PANYNJ properties in the City of New York, provided guidelines for FDNY to communicate needed corrective actions to the PANYNJ, ensured that new or modified fire

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[2] 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.

safety systems are in compliance with local codes and regulations, and required third-party review of such systems by a New York State licensed architect or engineer.

Standard Fire-Resistance Tests

Finding 12: Code provisions with detailed procedures to analyze and evaluate data from fire resistance tests of other building components and assemblies to qualify an untested building element do not exist. Based on available data and records, no technical basis has been found for selecting the SFRM used (two competing materials were under evaluation) or its thickness for the large-span open-web floor trusses of the WTC towers. The assessment of the fireproofing thickness needed to meet the 2 h fire rating requirement for the untested WTC floor system evolved over time:

- In October 1969, the PANYNJ directed the fireproofing contractor to apply ½ in. of fireproofing to the floor trusses.
- In 1999, the PANYNJ issued guidelines requiring that fireproofing be upgraded to 1½ in. for full floors undergoing alterations.
- Unrelated to the WTC buildings, an International Conference of Building Officials Evaluation Service report (ER-1244), re-issued June 1, 2001, using the same SFRM recommends a minimum thickness of 2 in. for “unrestrained steel joists” with “lightweight concrete” slab.

Finding 13: Code provisions that 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 are needed. Instead, several alternate methods based on other fire-resistance designs or calculations or alternative protection methods are permitted with limited guidance on detailed procedures to be followed. Both the architect-of-record (in 1966) and the structural-engineer-of-record (in 1975) stated that the fire rating of the floor system of the WTC towers could not be determined without testing. NIST has not found evidence indicating that such a test was conducted to determine the fire rating of the WTC floor system. The PANYNJ has informed NIST that there are no such test records in its files.

Finding 14: Use of the “structural frame” approach, in conjunction with the prescriptive fire rating, would have required the floor trusses, the core floor framing, and perimeter spandrels in the WTC towers to be 3 h fire-rated, like the columns for Class 1B construction in the 1968 NYC Building Code. 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. The “structural frame” approach to fire resistance ratings 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. 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 model codes) which states: “The structural frame shall be considered to be the columns and the girders, beams, trusses and spandrels having direct connections to the columns and bracing members designed to carry gravity loads.” The WTC floor system was essential to the stability of the building as a whole since it provided lateral stability to the columns and diaphragm action to distribute wind loads to the columns of the frame-tube system.

Finding 15: A technical basis to establish whether the construction classification and fire rating requirements in modern building codes are risk-consistent with respect to the design-basis hazard and the consequences of that hazard is needed. The fire rating requirements, which were originally developed based on experience with buildings less than about 20 stories in height, have generally decreased over the past 80 years since historical fire data for buildings suggested considerable conservatism in those requirements. However, 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, say, on the first floor. 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 about 20 stories in height where access by firefighters without the availability of firefighter elevators is limited by physiological factors. The maximum required fire rating in current codes applies to any building more than about 12 stories in height. There are no additional categories for buildings above, for example, 40 stories and 80 stories, where different building classification and fire ratings requirements may be appropriate, recognizing factors such as the time required for stairwell evacuation without functioning elevators (e.g., due to power failure or major water leakage), the time required for first responder access without functioning elevators, the presence of skylobbies and/or refuge floors, and limitations on the height of elevator shafts. The 110-story WTC towers, initially classified as Class IA based on the 1938 NYC Building Code, were classified as Class 1B before being built to take advantage of the provisions in the 1968 edition of the code. This re-classification permitted a reduction of 1 h in the fire rating of the components (columns from 4 h to 3 h and floor framing members from 3 h to 2 h).

Fire Performance of Structures

Finding 16: Rigorous field application and inspection provisions and regulatory requirements to ensure 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 is needed. For example, provisions are not available to ensure that the as-applied average fireproofing thickness and variability (reflecting the quality of application) is thermally equivalent to the specified minimum fireproofing thickness. In addition, requirements are not available for in-service inspections of passive fire protection during the life of the building. The adequacy of the fireproofing of the WTC towers posed an issue of some concern to the PANYNJ over the life of the buildings, and the availability of accepted requirements and procedures for conducting in-service inspections would have provided useful guidance

Finding 17: Structural design does not consider fire as a design condition, as it does the effects of dead loads, live loads, wind loads, and earthquake loads. Current prescriptive code provisions for determining fire resistance of structures—used in the design of the WTC towers and WTC 7—are based on tests using a standard fire that may be adequate for many simple structures and for comparing the relative performance of structural components in more complex structures. A building system with 3 h rated columns and 2 h rated girders and floors could last longer than 3 h or shorter than 2 h depending upon the performance of the structure as a 3-dimensional system in a real fire. The standard tests cannot be used to evaluate the actual performance (i.e., load carrying capacity) in a real fire of the structural component, or the structure as a whole system, including the connections between components. Performance-based code provisions and standards are not available for use by engineers, as an alternative to the current prescriptive fire rating approach, to (1) evaluate the system performance of tall-building structures under real fire scenarios, and (2) enable risk consistent design with appropriate thickness of passive protection being provided where it is needed on the structure. Standards development organizations, including the

American Institute of Steel Construction, have initiated development of performance-based provisions to consider fire effects in structural design.

Finding 18: Detailed procedures to select appropriate design-basis fire scenarios to be considered in the performance-based design of the sprinkler system, compartmentation, and passive protection of the structure are needed. The standard fire in current prescriptive fire resistance tests is not adequate for use in performance-based design. While the NFPA 5000 model building code contains general guidance on design fire scenarios (the IBC Performance Code contains no such guidance), the details of the scenarios are left to the fire engineer and regulatory official. The three major scenarios that are not considered adequately are: frequent but low severity events (for design of sprinkler system), moderate but less frequent events (for design of compartmentation), and a maximum credible fire (for design of passive fire protection on the structure). The maximum credible fire scenario for passive protection of structures would assume that the sprinkler system is compromised or overwhelmed and that there is no active firefighting, as is explicitly considered for U.S. Department of Energy facilities. These building-specific representative fire scenarios are similar in concept, though not identical, to the approach used in building design where the performance objectives and design-basis of the hazard are better defined (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). The design-basis fire hazards for the WTC towers and WTC 7 are unknown, and it is difficult to evaluate the performance of the fire protection systems in these buildings under specific fire scenarios.

Finding 19: Code provisions to ensure that structural connections are provided the same degree of fire protection as the more restrictive protection of the connected elements are needed. The provisions that were used for the WTC towers and WTC 7 did not require specification of a fire-rating requirement for connections separate from those for the connected elements. It is not clear what the fire rating of the connections were when the connecting elements had different fire ratings and whether the applied fireproofing achieved that rating.

Finding 20: A technical basis to establish whether the minimum mechanical and durability related properties of SFRM are sufficient to ensure acceptable in-service performance in buildings is needed. 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. There are existing testing standards for determining many of these properties, but the technical basis is insufficient to establish serviceability requirements. Knowledge of such serviceability requirements is relevant to determine the post-impact fireproofing condition of the WTC towers.

Finding 21: 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 are needed. Existing tools are either too simplified to adequately capture the performance of interest or too complex and computationally demanding and lack adequate validation. While considerable progress has been made in recent years, significant work remains to be done before adequate tools are available for use in routine practice. NIST has had to further develop and validate existing tools to investigate the fire performance of the WTC towers and WTC 7.

Compartmentation and Sprinklers

Finding 22: Building fire protection is based on a four-level hierarchical strategy comprising detection, suppression (sprinklers and firefighting), compartmentation, and passive protection of the structure.

- Detectors are typically used to activate fire alarms and notify building occupants and emergency services.
- Sprinklers are designed to control small and medium fires and to prevent fire spread beyond the typical water supply design area of about 1,500 ft^2.
- Compartmentation mitigates the horizontal spread of more severe but less frequent fires and typically requires fire-rated partitions for areas of about 7,500 ft^2. Active firefighting measures also cover up to about 5,000 ft^2 to 7,500 ft^2.
- Passive protection of the structure seeks to ensure that a maximum credible fire scenario, with sprinklers compromised or overwhelmed and no active firefighting, results in burnout, not overall building collapse. The intent of building codes is also for the building to withstand local structural collapse until occupants can escape and the fire service can complete search and rescue operations.

Compartmentation of spaces is a key building fire safety requirement to limit fire spread. The WTC towers initially had 1 h fire-rated partitions separating tenants (demising walls) that extended from the floor to the suspended ceiling, not the floor above (the ceiling tiles were not fire rated). Over the years, these partitions were replaced with partitions that were continuous from floor to floor (separation wall) as required by the 1968 NYC Building Code. Some partitions had not been upgraded by 1997, and a consultant recommended to the PANYNJ that it develop and implement a survey program to ensure that the remediation process occurred as quickly as possible. It appears that with few exceptions, nearly all of the floors not upgraded were occupied by a single tenant, and it is not clear whether separation walls would have mattered in terms of meeting the 1968 code. The PANYNJ adopted guidelines in 1998 that required such partitions to provide a continuous fire barrier from top of floor to underside of slab.

Finding 23: Building codes typically require 1 h fire-rated tenant separations but do not impose minimum compartmentation requirements (e.g., 13,000 ft^2) for buildings with large open floor plans to mitigate the horizontal spread of fire. This is the case with both the 1968 NYC Building Code, which did not require sprinklers in occupied spaces on or above the ground floor, and the 2001 NYC Building Code, which requires sprinklers in Group E (Business) buildings over 100 ft in height. 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. Thus, if there was only one tenant on a WTC floor there would be no horizontal compartmentation requirement. Conversely, if there were a large number of tenants on a WTC floor, it would be highly compartmented with separation walls. 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 to 100 min prior to collapse of the WTC towers 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.

Finding 24: State and local building regulations are needed that require installation of sprinklers in existing buildings on a reasonable time schedule, not as an option in lieu of compartmentation. Functioning sprinklers can provide significant improvement in safety for most common building fires and prevent them from becoming large fires. NYC promulgated local laws in 1973 and 1984 to encourage installation of sprinklers in new buildings and is now considering a law to require sprinklers in existing buildings. The WTC towers were fully sprinklered by 2001, about 30 years after their construction. Sprinklering of the tenant floors in the WTC towers was completed by October 1999, while sprinklering of the skylobbies was still underway at that time. The sprinkler system was installed in three phases. Phase 1 was completed during initial building construction and included the sub-grade areas. Phase 2 was completed in 1976, in compliance with Local Law 5, and included sprinklering the corridors, storage rooms, lobbies, and certain tenant spaces. Phase 3 was begun in 1983 and completed in 2001 and resulted in fully sprinklering the buildings.

Finding 25: Modern building codes allow a lower fire rating for structural elements when a building is sprinklered. This trade-off provides an economic incentive to encourage installation of sprinklers. Sprinklers provide better intervention against small and medium fires, fires which are more likely to occur than a WTC disaster, as long as the water supply is not compromised and there is redundant technology in place. The required technical basis is not available to establish whether the “sprinkler trade-off” in current codes adequately considers fire safety risk factors such as: (1) the complementary functions of sprinklers and fire-protected structural elements, (2) the different fire scenarios for which each system is designed to provide protection, and (3) the need for redundancy should one system fail. It is noteworthy that the British Standards Institution has established a group to review all the sprinkler trade-offs contained in their standards. No such formal review has yet been initiated in the United States. Although the classification and fire rating of the WTC towers did not take advantage of the sprinkler-tradeoff since such provisions were not contained in the 1968 NYC Building Code, had such provisions existed, they would have permitted a lower fire rating for many WTC building elements.

Use of Elevators in Emergencies

Finding 26: With a few special exceptions, building codes in the United States do not permit the use of fire-protected elevators for routine emergency access by first responders or as a secondary method (after stairwells) for emergency evacuation of building occupants. The use of elevators by first responders would additionally mitigate counterflow problems in stairwells. While the United States conducted research on specially protected elevators in the late 1970s, the United Kingdom along with several other countries that typically utilize British standards have required such “firefighter lifts,” located in protected shafts, for a number of years. Without functioning elevators (e.g., due to a power failure or major water leakage), first responders carrying gear typically require about a minute per floor to reach an incident using the stairs. While it is difficult to maintain this pace for more than about the first 20 stories, it would take a first responder about an hour to reach, for example, the 60th floor of a tall building if that pace could be maintained. Such a delay, combined with the resulting fatigue and physical effects on first responders that were reported on September 11, 2001, would make firefighting and rescue efforts difficult even in tall building emergencies not involving a terrorist attack. Each of the WTC towers had 106 elevators, and WTC 7 had 38 elevators. By code, the elevators could not be used for fire service access or occupant egress during an emergency since they were not fire-protected, nor were they located in protected shafts. The elevators were equipped through normal modernization with fire service recall. Most were damaged by the aircraft impacts; though prior to the impact in WTC 2 the elevators were functioning and contributed greatly to the much faster initial evacuation rate in WTC 2.