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5 WTC 7

5.1 Introduction

WTC 7 collapsed on September 11, 2001, at 5:20 p.m. There were no known casualties due to this collapse. The performance of WTC 7 is of significant interest because it appears the collapse was due primarily to fire, rather than any impact damage from the collapsing towers. Prior to September 11, 2001, there was little, if any, record of fire-induced collapse of large fire-protected steel buildings.

The structural design and construction features of this building, potential fuel loads, fire damage, and the observed sequence of collapse are presented to provide a better understanding of what may have happened. However, confirmation will require additional study and analysis. Information about the structural design and construction features and the observed sequence of events is based upon a review of structural drawings, photographs, videos, eyewitness reports, and a 1986 article about the construction features of WTC 7 (Salvarinas 1986). In addition, the following information and data were obtained from the indicated sources:

- Annotated floor plans and riser diagrams of the emergency generators and related diesel oil tanks and distribution systems (Silverstein Properties 2002)
- Engineering explanation of the emergency generators and related diesel oil tanks and distribution systems (Flack and Kurtz, Inc. 2002)
- Information on the continuity of power to WTC 7 (Davidowitz 2002)
- Summary of diesel oil recovery and spillage (Rommel 2002)
- Information on WTC 7 fireproofing (Lombardi 2002)
- Information on the New York City Office of Emergency Management (OEM) tanks at WTC 7 (Odermatt 2002)

The 47-story office building had 1,868,000 square feet of office space. The top 40 stories of the building (floors 8 to 47) were office type occupancies. Table 5.1 lists the larger tenants of WTC 7. WTC 7 was completed in 1987 by a development team composed of the following parties:

- Owner/Developer: Seven World Trade Company, Silverstein Development Corporation, General Partner
- Construction Manager: Tishman Construction Corporation of New York
- Design Architect: Emery Roth & Sons, P.C.
- Structural Consultant: The Office of Irwin G. Cantor, P.C.
- Mechanical/Electrical Consultant: Syska & Hennessy, P.C.
- Structural Consultant (Con Ed Substation): Leslie E. Robertson Associates

As shown in Figure 1-1 (WTC site map in Chapter 1), WTC 7 was located north of the main WTC complex, across Vesey Street, and was linked to the WTC Plaza by two pedestrian bridges: the large Plaza bridge and a smaller, glass-enclosed pedestrian bridge. The bridges spanned 95 feet across Vesey Street, connecting the Plaza and the 3rd floor of WTC 7. In addition to the office occupancies, WTC 7 also contained an electrical substation, and the WTC Complex shipping ramp, as shown in Figure 5-1.

The substation and shipping ramp occupied major portions of the WTC 7 site. The substation was built prior to the office tower, supplied electrical power to lower Manhattan, and covered approximately half the site. The shipping ramp (5,200 square feet in area, approximately 10 percent of the WTC 7 site) was used by the entire WTC complex.

Table 5.1 WTC 7 Tenants

Floor	Tenant
46-47	Mechanical Floors
28-45	Salomon Smith Barney (SSB)
26-27	Standard Chartered Bank
25	Internal Revenue Service (IRS) Department of Defense (DOD) Central Intelligence Agency (CIA)
24	Internal Revenue Service (IRS)
23	Office of Emergency Management (OEM)
22	Federal Home Loan Bank of New York
21	First State Management Group
19-21	ITT Hartford Insurance Group
19	National Association of Insurance Commissioners (NAIC) Securities Valuation Office
18	Equal Employment Opportunity Commission (EEOC)
14-17	Vacant
13	Provident Financial Management
11-13	Securities and Exchange Commission
9-10	U.S. Secret Service
7-8	American Express Bank International
7 part	OEM generators and day tank
6	Switchgear, storage
5	Switchgear, generators, transformers
4	Upper level of 3rd floor lobby, switchgear
3	Lobby, SSB Conference Center, rentable space, management offices
2	Open to 1st floor lobby, transformer vault upper level, upper level switchgear
1	Lobby, loading docks, existing Con Ed transformer vaults, fuel storage, lower level switchgear

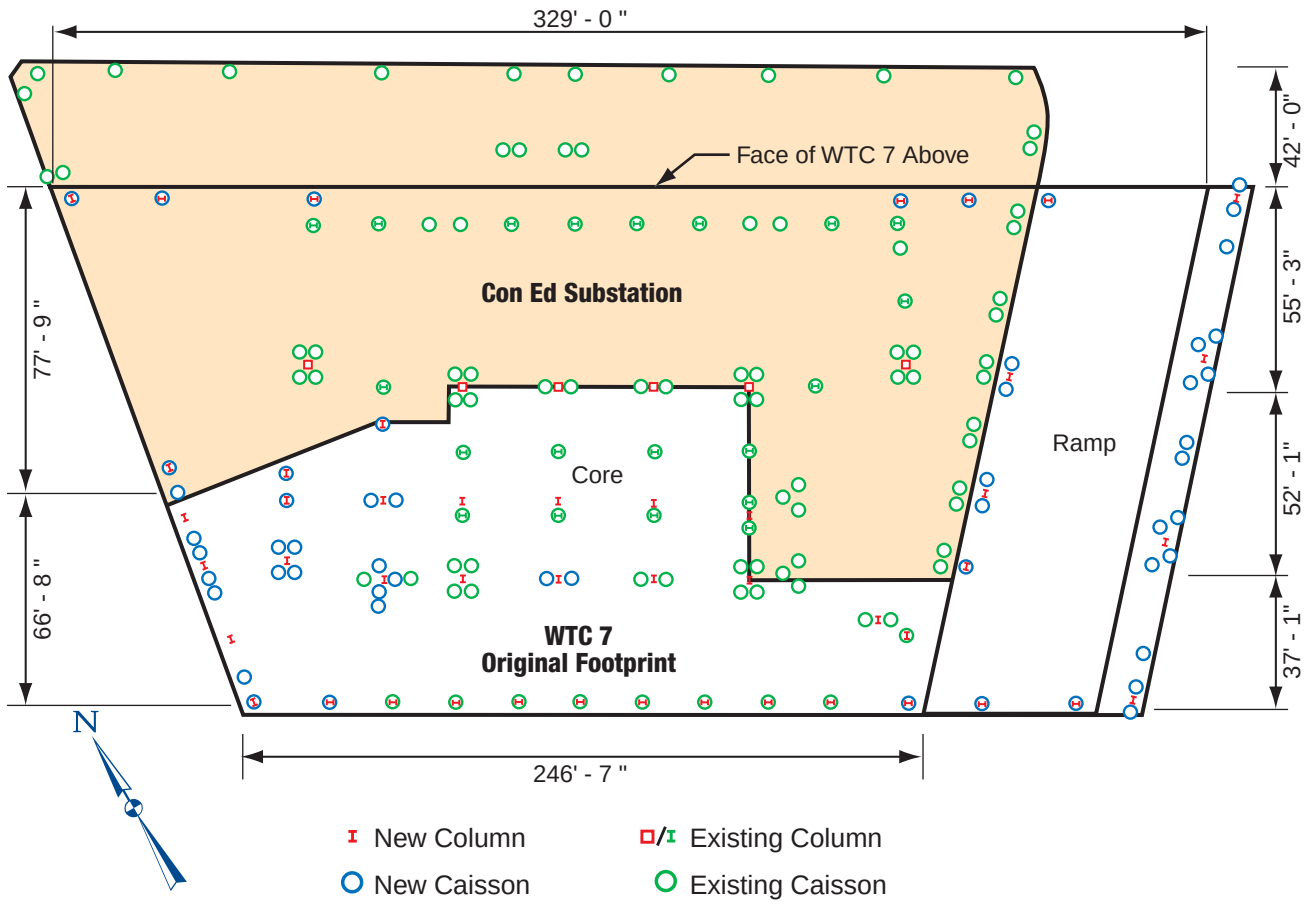


Figure 5-1 Foundation plan – WTC 7.

5.2 Structural Description

5.2.1 Foundations

With the development of an office tower in mind, the Port Authority of New York and New Jersey (hereafter referred to as the Port Authority) installed caissons intended for future construction. However, Seven World Trade Company, Silverstein Development Corporation, General Partner, decided to construct a building much larger in both height and floor area. The designers combined the existing caissons inside the substation with new caissons inside and outside the substation to create the foundation for WTC 7. Figure 5-1 shows the location of pre-existing caissons built when the Con Ed substation was constructed along with new caissons that were installed for the support of the building. The discrepancy in the column locations between the substation and the office tower required transfers to carry loads from the office tower to the substation and finally into the foundation. Old and new caissons, as well as old and new columns, also can be seen in the foundation plan shown in Figure 5-1.

5.2.2 Structural Framing

The typical floor framing shown in Figure 5-2 was used for the 8th through the 45th floors. The gravity framing consisted of composite beams (typically W16x26 and W24x55) that spanned from the core to the perimeter. The floor slab was an electrified composite 3-inch metal deck with 2-1/2-inch normal-weight concrete fill spanning between the steel beams. Below the 8th floor, floors generally consisted of formed slabs

with some limited areas of concrete-filled metal decks. There were numerous gravity column transfers, the more significant of these being three interior gravity column transfers between floors 5 to 7 and eight cantilever column transfers in the north elevation at the 7th floor. The column transfers in the exterior walls are shown in the bracing elevations (Figure 5-3).

The lateral load resisting system consisted of four perimeter moment frames, one at each exterior wall, augmented by two-story belt trusses between the 5th and 7th floors and between the 22nd and 24th floors. There were additional trusses at the east and west elevations below the 7th floor. An interior braced core extended from the foundation to the 7th floor. The horizontal shear was transferred into the core at the 5th and the 7th floors. The 5th floor diaphragm (plan shown in Figure 5-4) consisted of a reinforced concrete 14-inch-thick slab with embedded steel T-sections. The 7th floor was an 8-inch-thick reinforced concrete slab.

The 5th and 7th floors contained the diaphragm floors, belt trusses, and transfer girders. A 3-D rendering of Truss 1, Truss 2, Truss 3, and several cantilever transfer girders is shown in Figure 5-5.

5.2.3 Transfer Trusses and Girders

The transfer trusses and girders, shown in Figure 5-6, were located between the 5th and 7th floors. The function and design of each transfer system are described below.

Truss 1 was situated in the northeast sector of the core, and spanned in the east-west direction. As shown in Figure 5-7, this truss was a two-story double transfer structure that provided load transfers between nonconcentric columns above the 7th floor to an existing column and girder at the 5th floor. The girder then provided a second load transfer to an additional two columns. The 7th floor column supported 41 floors and part of the east mechanical penthouse. Its load was transferred through the triangular truss into a column located above an existing substation column and girder at the 5th floor. The 36.5-ton built-up double web girder spanned in the north-south direction between two new columns that started at the foundation and terminated at the 7th floor. The truss diagonals were W14 shapes and the horizontal tie was a 22-ton, built-up shape.

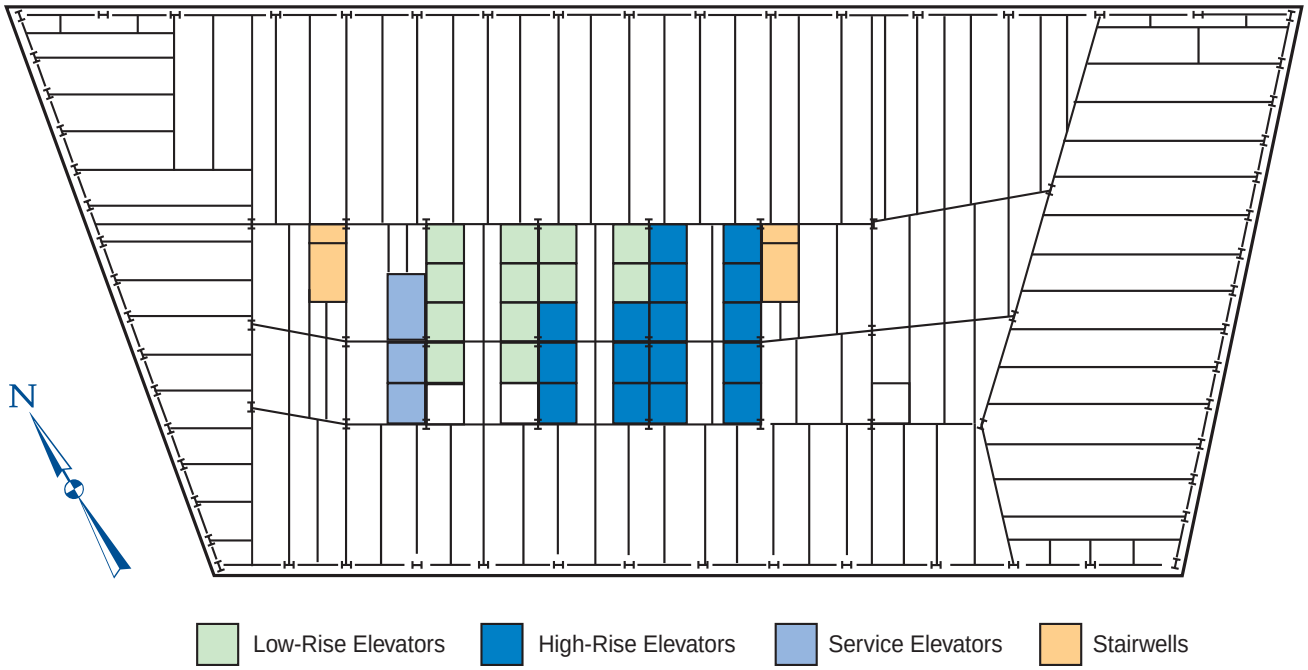
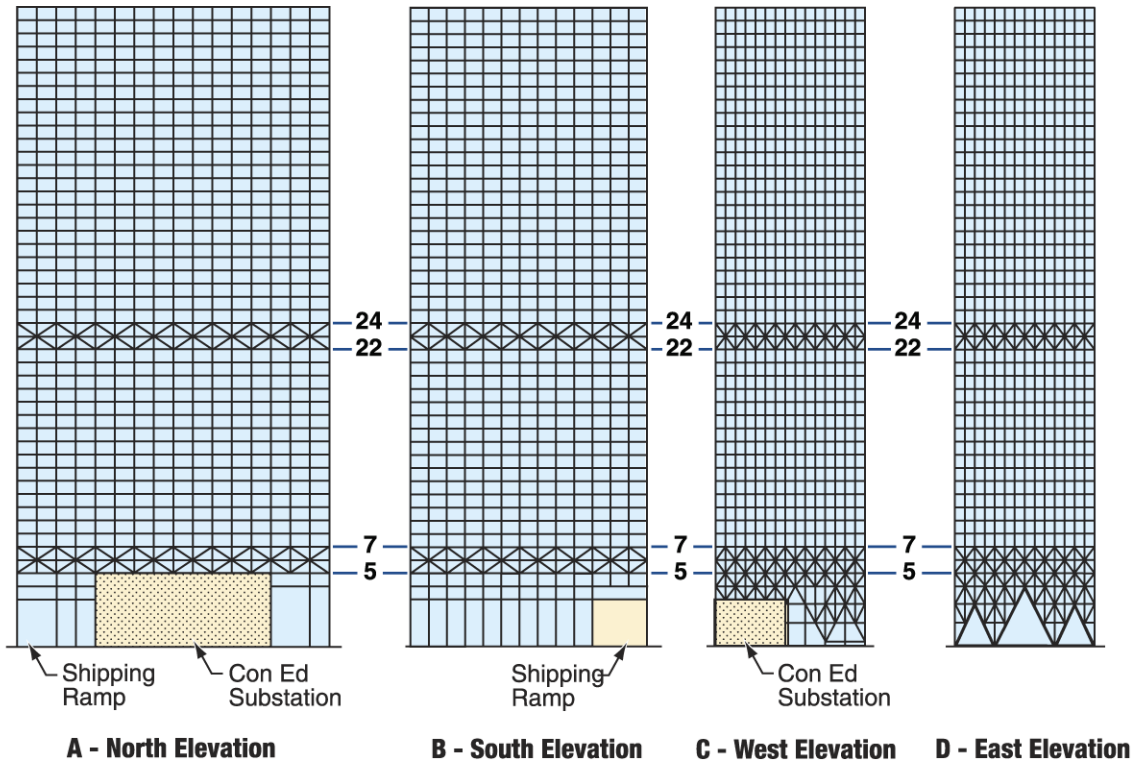


Figure 5-2 Plan view of typical floor framing for the 8th through 45th floors.



NOTE: Belt trusses located at floors 5-7 and 22-24.

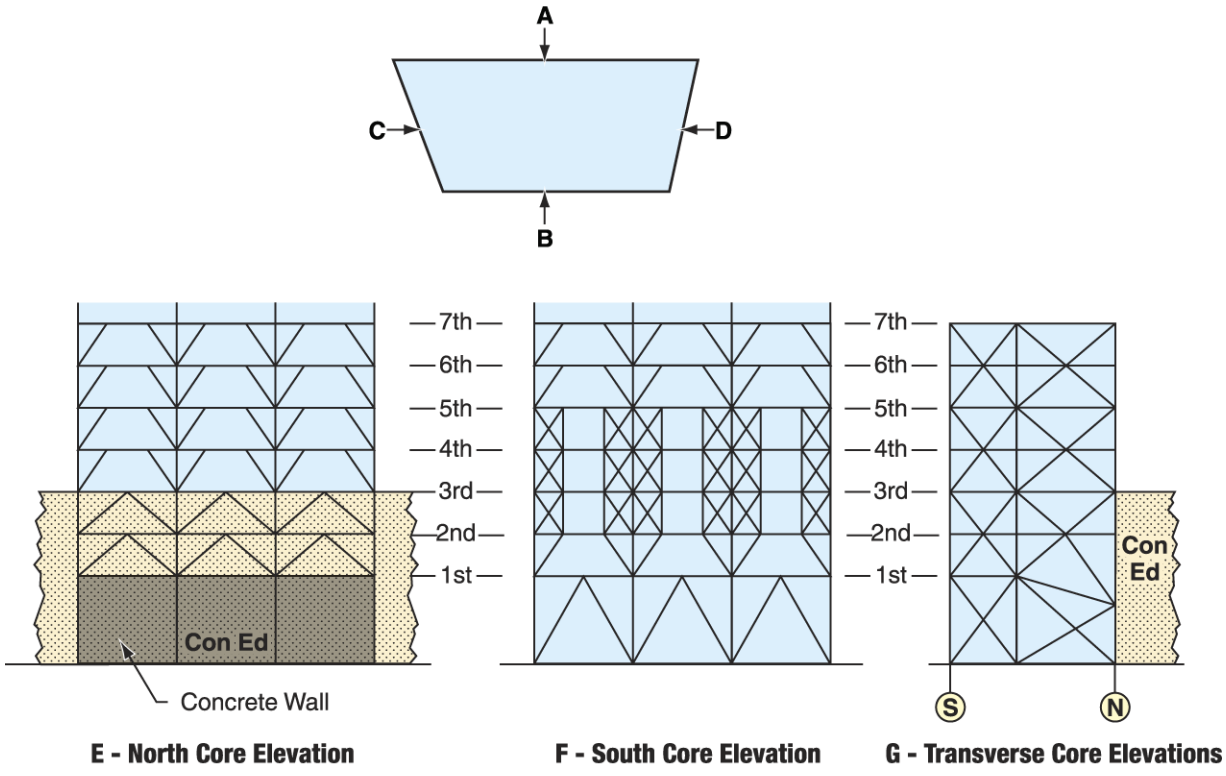


Figure 5-3 Elevations of building and core area.

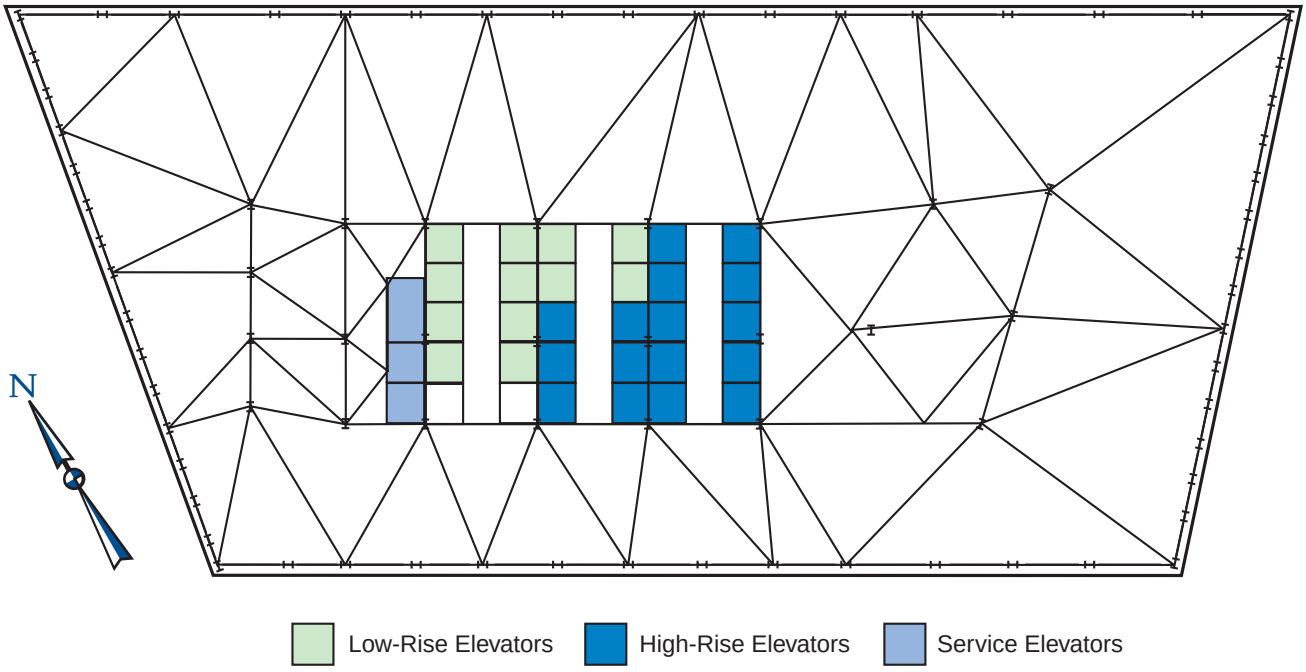


Figure 5-4 Fifth floor diaphragm plan showing T-sections embedded in 14-inch slab.

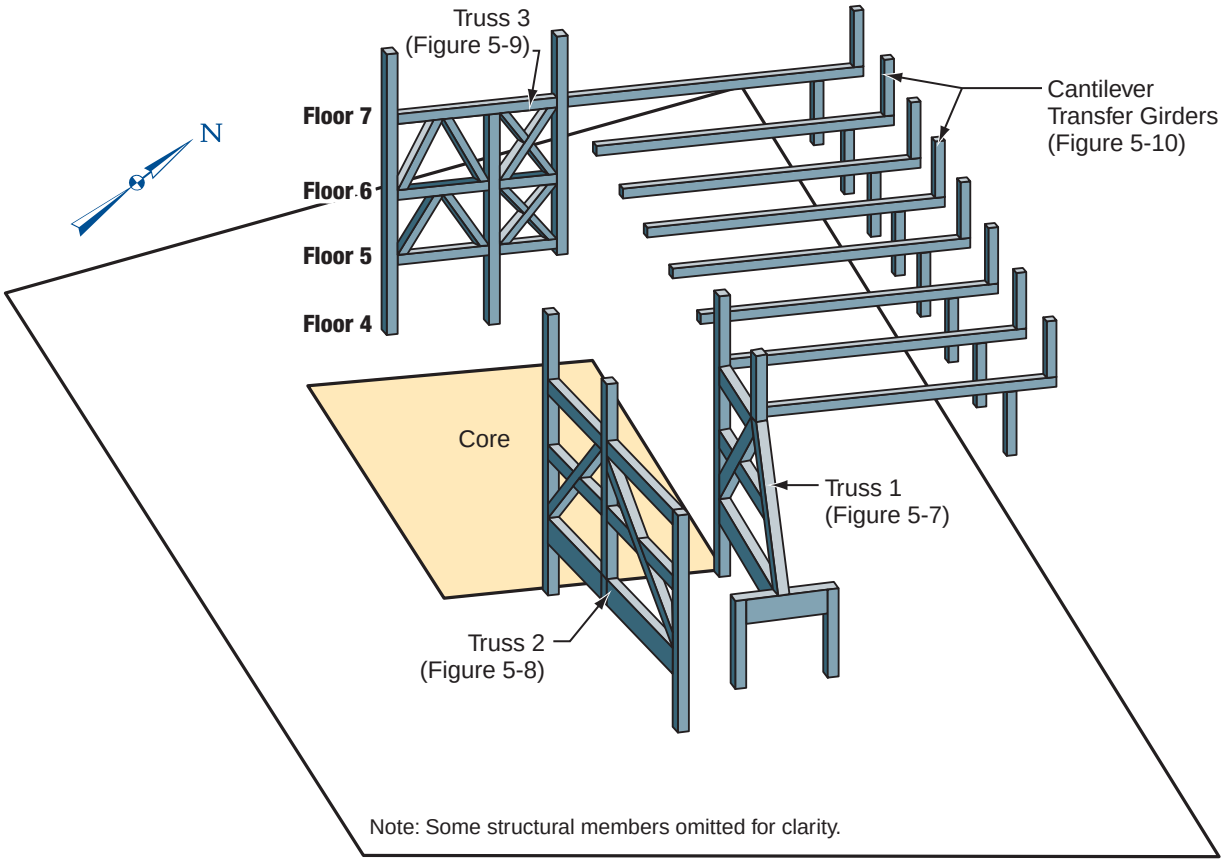


Figure 5-5 3-D diagram showing relation of trusses and transfer girders.

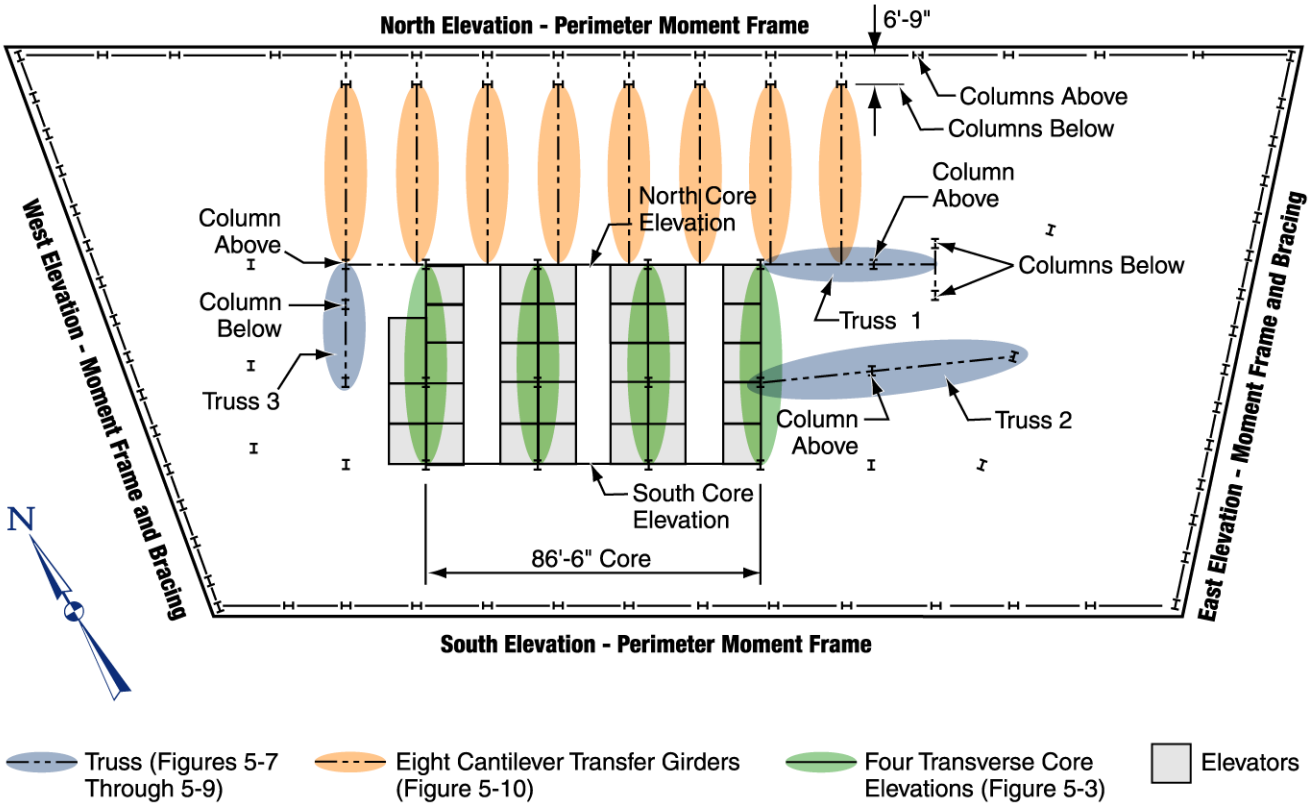


Figure 5-6 Seventh floor plan showing locations of transfer trusses and girders.

Truss 2 was a single transfer located south of Truss 1. As shown in Figure 5-8, Truss 2 transferred the column load from the 7th floor through a triangular truss into two existing columns at the 5th floor. Large gusset plates were provided at the connection between the diagonals, the columns, and the horizontal tie. The diagonals and the built-up horizontal tie were field-welded.

Truss 3 was a cantilevered two-story transfer structure in the north-south direction between the 5th and 7th floors at the western end of the core area. As shown in Figure 5-9, Truss 3 transferred the loads between columns. The upper columns carried 41 floors of load and were cantilevered to the north of the column that went from the foundation to the 7th floor.

The cantilever transfer girders, shown in Figure 5-10, spanned between the core and the north elevation at the 7th floor. There were eight transfer girders to redirect the load of the building above the 7th floor into the columns that went through the Con Ed substation. These girders cantilevered 6 feet 9 inches between the substation and the north façade of the building above. The girders extended an additional 46 feet to the core. The two transfer girders at the east end of the building were connected to Truss 1, creating a double transfer. The girders varied in depth from 9 feet at the north end, to a tapered portion in the middle, and to 4 feet 6 inches at the southern section closest to the core. Each transfer girder weighed approximately 52 tons. At the north wall, between the 7th and 5th floors, transferred columns were also part of the belt truss that circled the building as part of the lateral-load-resisting system and acted as a transfer for the columns above the shipping ramp.

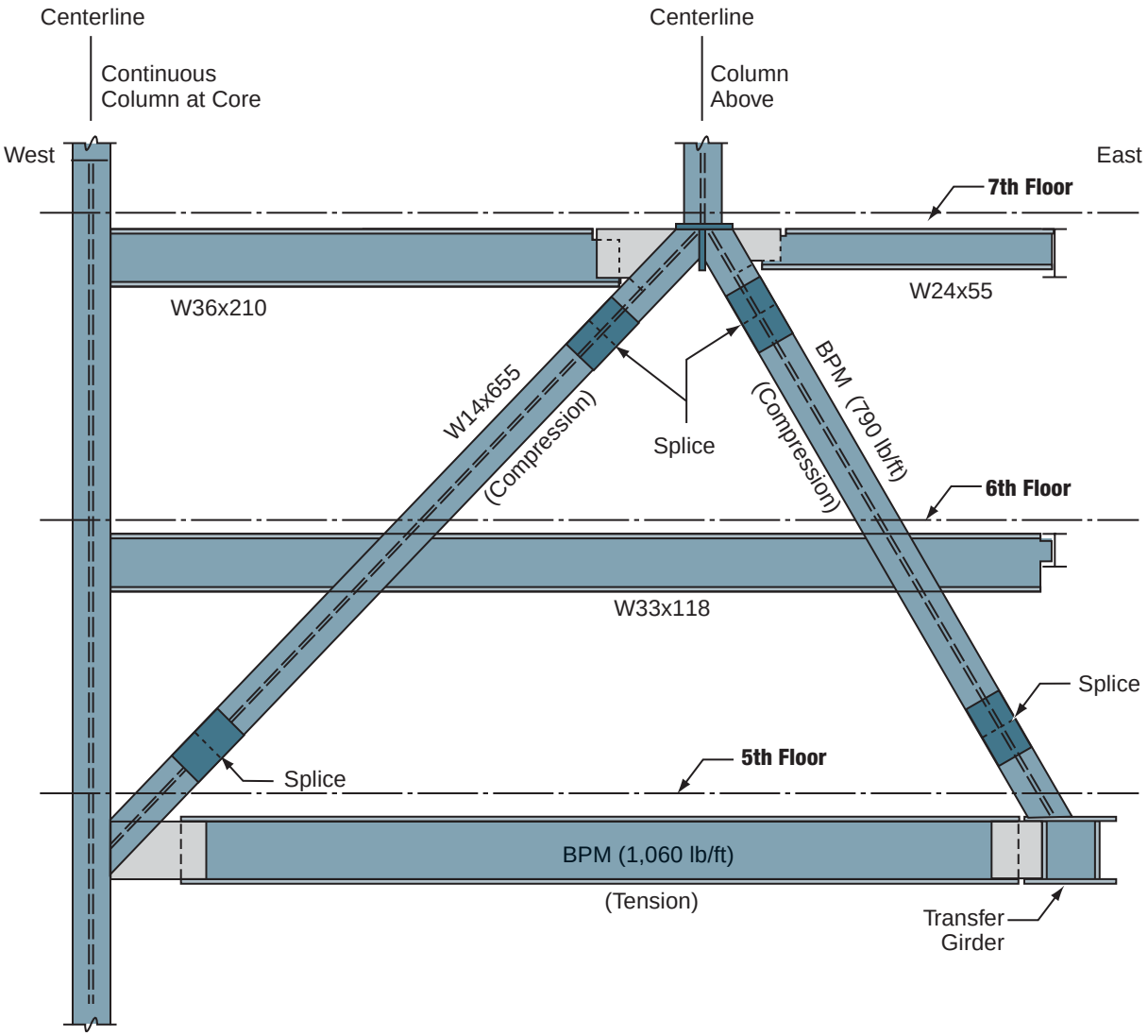


Figure 5-7 Truss 1 detail. (BPM = built-up plate member.)

5.2.4 Connections

A variety of framing connections were used. Seated beam connections were used between the exterior columns and the floor beams. Single-plate shear connections were generally used at beam-to-beam connections. Double-angle connections were provided between some beam and end-plate connections at beam-to-interior columns. Floor-framing connections used 7/8-inch-diameter ASTM A325 bolts; connections for bracing, moment frames, and column splices used 1-inch diameter ASTM A490 bolts.

Along the east and west elevations, center-to-center column spacing was typically less than 10 feet. Column trees were used at these locations. A column tree is a shop-fabricated column assembly with beam stubs shop-welded to the column flanges. The field connections were made at the end of the stubs at the center of the span between columns. One-sided lap plates were used for both flange and web connections.

Along the north and south elevations, and within the core up to the 7th floor, the spans were approximately 28 feet. At these locations, traditional moment frame construction was used. Top and bottom flange plates, as well as one-sided web shear plates, were shop-welded to column flanges. The beams were then field-bolted into the connection.

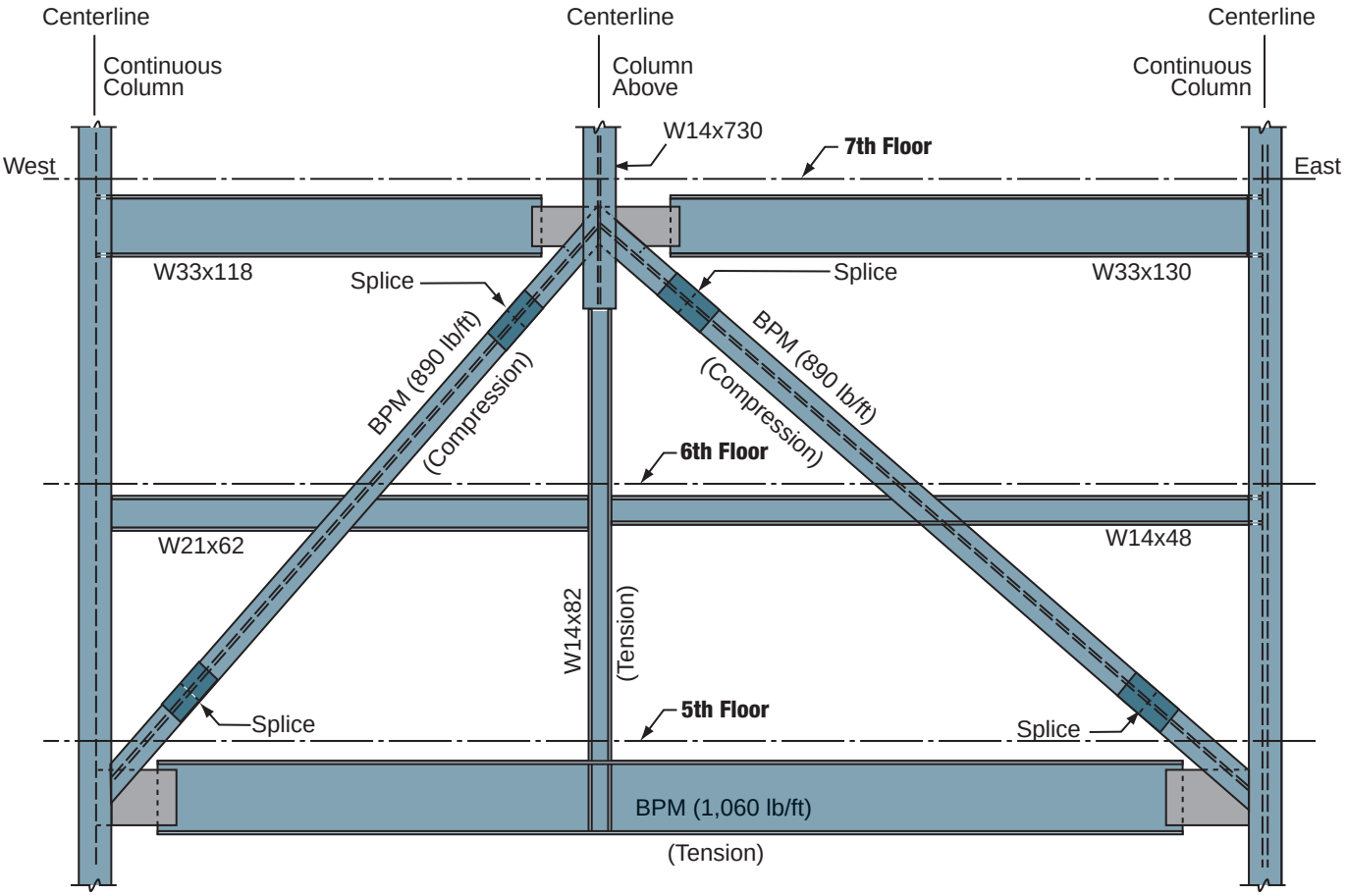


Figure 5-8 Truss 2 detail. (BPM = built-up plate member.)

The majority of column splices were bolted according to American Institute of Steel Construction (AISC) details. They were located 3 feet 6 inches above the floor and were not designed to accommodate tensile forces. Columns below the 7th floor were often "jumbo" shapes (W14x455 to W14x730) or built-up jumbo box shapes with plates up to 10 inches thick welded from flange to flange, parallel to the web, to provide the necessary section properties. For these massive columns, either the upper shaft was beveled to be field-welded or side plates were shop-welded to the lower shaft and field-welded to the upper shaft once the column was erected and plumb.

The majority of the bracing members were two channels or two T-sections connected to the structure by a welded gusset plate. A single wide flange cross-section was also used. These members were connected with web and flange plates, similar to those used in the moment frames. Some of the bracing members on the east and west sides of the building were as large as the jumbo column sections. Large connection plates were sandwiched to each side of these large braces, beams, and columns at their junctions. Bolts attached all the components to each other at these joints.

The granite façade panels were manufactured off site and were supported by individual trusses. Each panel had a single vertical/gravity connection and top and bottom lateral/wind connections to transmit these forces back to the base building. Horizontal panel adjustments could be accommodated within the panel itself. The building columns had welded angles and channels that provided horizontal and lateral support. The top of the panel was connected to the angle, and the bottom of the panel was connected to the channel. These steel-panel connections had vertically slotted holes for vertical adjustment.

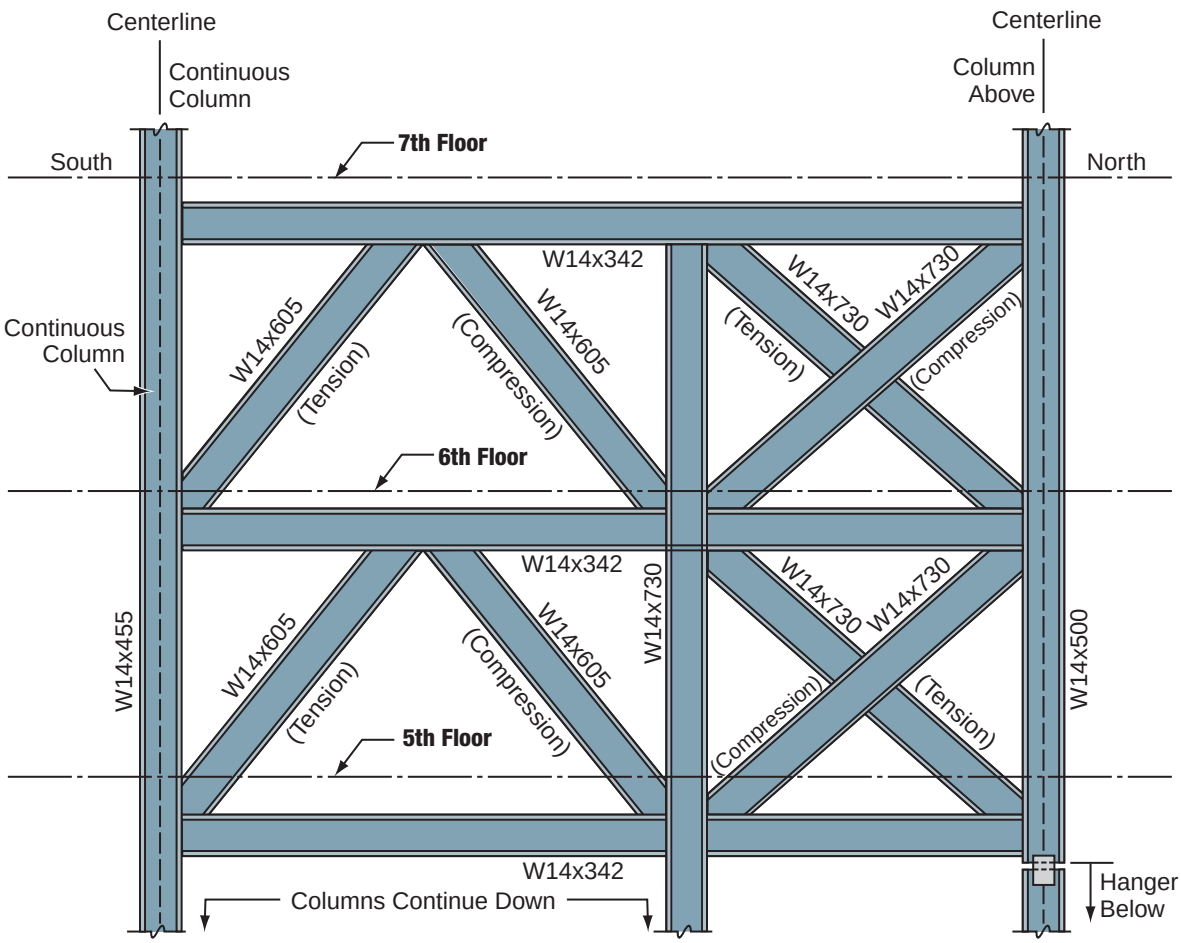


Figure 5-9 Truss 3 detail.

5.3 Fire Protection Systems

5.3.1 Egress Systems

There were two main exit stairways in WTC 7. Stairway 1 was located on the west side, and Stairway 2 was located on the east side within the central core. Both exit stairways discharged directly to the exterior at ground level and were approximately 4 feet 10 inches wide. The stairways were built of fire-rated construction using gypsum wallboard. Subsequent to the 1993 bombing incident at the WTC, battery-operated emergency lighting was provided in the stairways and photoluminescent paint was placed on the edge of the stair treads to facilitate emergency egress. In addition to the battery-powered lighting, the stairs also had emergency system lighting powered by the generators.

Twenty-eight passenger elevators and three service elevators served the various levels of WTC 7. Occupants using the elevators would typically discharge at the third level and either exit through the Lobby to bridges bringing them over to the WTC Plaza, or proceed down the escalators to grade level.

5.3.2 Detection and Alarm

Smoke detectors were located in telecommunications, electrical, and communications closets, as well as inside the HVAC system ducts, in the mechanical rooms, and in all elevator lobbies. Manual pull stations were provided at the entrances to stairways and at each of the exits. Speakers for voice evacuation

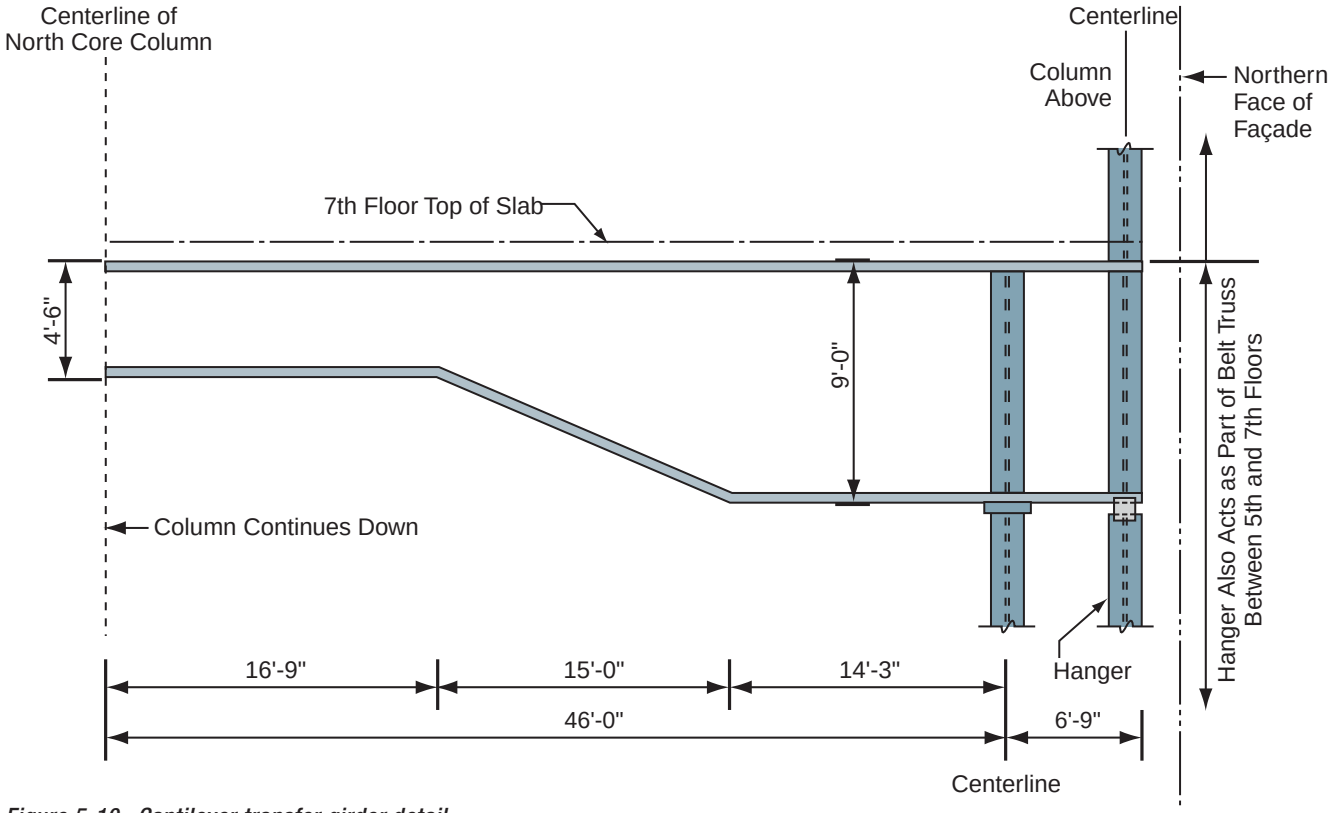


Figure 5-10 Cantilever transfer girder detail.

announcements were located throughout the building and were activated manually at the Fire Control Center (FCC). Strobes were provided and were activated automatically upon detection of smoke, water flow, or initiation of a manual pull station. Monitoring of the fire-alarm control panel for WTC 7 was provided independently at a central station. In addition to the emergency generators, the existing uninterruptible power supply (UPS) provided 4 hours of full operation for the fire-alarm system and 12 hours of standby operation. The floor contained a combination of area smoke and heat detectors.

5.3.3 Compartmentalization

Concrete floor slabs provided vertical compartmentalization to limit fire and smoke spread between floors (see Figure 5-11). Architectural drawings indicate that the space between the edge of the concrete floor slab and curtain wall, which ranged from 2 to 10 inches, was to be filled with firestopping material.

A zoned smoke control system was present in WTC 7. This system was designed to pressurize the floors above and below the floor of alarm, and exhaust the floor of alarm to limit smoke and heat spread.

The fireproofing material used to protect the structural members has been identified by Silverstein Properties as "Monokote." The Port Authority informed the BPS Team that New York City Building Code Construction Classification 1B (2-hour rating for beams, girders, trusses, and 3-hour rating for columns) was specified for WTC 7 in accordance with the architectural specifications on the construction notes drawing PA-O. According to the Port Authority, the construction notes on drawing PA-O also specified the following:

- Exterior wall columns (columns engaged in masonry walls) shall be fireproofed on the exterior side with 2-inch solid gypsum, 3-inch hollow gypsum, 2-inch concrete or spray-on fireproofing.
- Interior columns shall be fireproofed with materials and have rating conforming with Section C26-313.3 (27-269 current section).

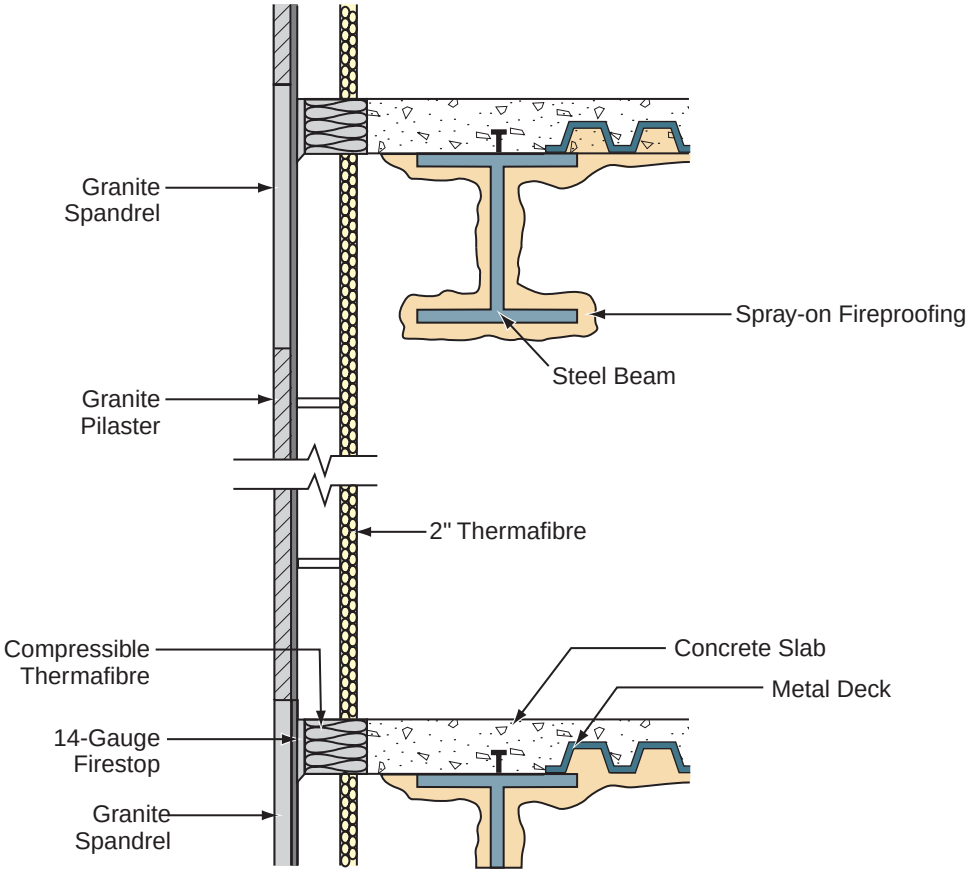


Figure 5-11 Compartmentalization provided by concrete floor slabs.

- Beams and girders shall be fireproofed with 2-inch grade Portland cement concrete, Gritcrete, or srpay-on fireproofing or other materials rendering a 2-hour fire rating.

The Port Authority stated that it believed the thickness of the spray-on fireproofing was determined by the fireproofing trade for the specific structural sections used, based on the Underwriters Laboratories formula for modifications, which were reviewed by the Architect/Engineer of Record during the shop drawing submittal. Spray-on fireproofing, as required by the code, was also listed on the drawing as an item subject to controlled inspections, in accordance with Section C26-106.3 (27-132 current section). The Architect/Engineer of Record was responsible for ensuring that the proper thickness was applied. The Port Authority had extended its fireproofing inspection program to this building.

5.3.4 Suppression Systems

The primary water supply appears to have been provided by a dedicated fire yard main that looped around most of the complex. This yard main was supplied directly from the municipal water supply. Fire department connections were located on the south and west sides.

WTC 7 was a sprinklered building. However, only the core spaces on the 5th floor were sprinkler protected, and none of the electrical equipment rooms in the building were sprinkler protected. The sprinkler protection was of "light hazard" design. The sprinkler system on most floors was a looped system fed by a riser located in Stairway 2. The loading dock was protected with a dry-pipe sprinkler system. The area of the fuel tank for OEM had a special fire detection and suppression system.

The Fire Pump Room was located on the ground floor in the southwest corner of the building and contained an automatic (as well as a manual) fire pump. There were two Fire Department of New York connections in the southwest quadrant - one on the south façade and one on the west façade.

Each stairway had standpipes in it. At each floor in each stairway, there was a 2-1/2-inch outlet with a 1-1/2-inch hose (with a 3/4-inch nozzle). In addition, the east side of each floor also had a supplemental fire hose cabinet. Primary water supply to the standpipe system came from a yard main, which was fed from the municipal water supply.

5.3.5 Power

Power to WTC 7 entered at 13,800 volts (V), was stepped down to 480/277 V by silicone oil-filled transformers in individual masonry vaults on the 5th floor, and was distributed throughout the building. On each floor, one of the 277 legs was tapped and stepped down to supply single-phase 120-V branch circuits. The main system had ground fault protection. Emergency power generators were located on various levels and provided a secondary power supply to tenants. This equipment supplied backup power for communications equipment, elevators, emergency lighting in corridors and stairwells, and fire pumps. Emergency lighting units in the exit stairways, elevator lobbies, and elevator cabs were equipped with individual backup batteries.

The tanks that provided fuel for the emergency generators were located in the building. The Silverstein and Salomon Smith Barney (SSB) fuel tanks were underground below the loading dock. The OEM tank was on the ground floor on a fire-rated steel platform within a 4-hour fire-rated enclosure. SSB had supply and return piping to the emergency generators made from a 2-1/2-inch double-wall steel pipe with a 4-inch outside diameter. The SSB fuel oil riser was single-wall pipe with a masonry shaft. Only the horizontal piping on the 5th floor was a double-wall pipe within a pipe. The pumps located at the ground floor could supply 75 gallons per minute (gpm). A 3-gpm fuel supply rate was needed for each of the nine 1,725-kilowatt (kW) generators located on the 5th floor. One gallon would be consumed and the other 2 gallons would continue to circulate through the system. The SSB fuel oil pumps were provided with UPS power supported by both base building emergency power and SSB standby power. The volume between the inner and outer pipes was designed to contain a leak from the inner pressurized pipe and direct that fuel oil to a containment vessel. Upon detection of fuel oil in the containment vessel, the fuel oil pumps automatically de-energized. The SSB fuel oil pumps and distribution piping were dedicated to the SSB generator plant. The base building life safety generators and OEM generators had their own dedicated fuel oil pumps and piping. The Silverstein generators consisted of two 900-kW units, which were also located on the 5th floor, and supplied by a 275-gallon day tank. Other characteristics of the design or controls for the fuel system for the generators are unknown.

5.4 Building Loads

The degree of impact damage to the south façade could not be documented. However, damage was evident from review of photographs and video records. The number of fires observed after the collapse of WTC 1 also makes it likely that debris impact damage occurred in a number of locations.

An array of fuels typically associated with offices was distributed throughout much of the building. In addition, WTC 7 contained 10 transformers at street level, 12 transformers on the 5th floor, and 2 dry transformers on the 7th floor. The Con Ed substation contained (outside the building footprint) eight 30-foot-wide transformers that supplied 13-kilovoltampere (kVA) power to the 6th floor of the building. Fuel oil (ranging from diesel to #4) was provided for the generators serving OEM, SSB, Silverstein Properties, and the U.S. Secret Service. Table 5.2 shows where the generators, fuel tanks, pumps, and risers were located for the various occupants. There was also a Con Ed 4-inch-diameter gas line with 0.25 pounds per square inch (psi) (low) pressure going into WTC 7 for cooking purposes. Early news reports had indicated that a high-pressure, 24-inch gas main was located in the vicinity of the building; however, this proved not to be true.

Table 5.2 WTC 7 Fuel Distribution Systems

	Storage Tanks	Pumps	Riser	Day Tank	Generators
OEM	Used Silverstein tank to fill day tanks	Ground floor; 33.3 gpm	Located in shaft in west elevator bank	275-gallon tank on 7th floor; one 6,000-gallon tank located between low-rise elevators in east elevator shaft between 2nd and 3rd floors	Three 500-kW on 7th floor on south side
Salomon Smith Barney	Two 6,000-gallon tanks under loading dock on ground level	In Fire Pump Room, west side of ground floor; 75 gpm	Located in shaft in mechanical rooms on southwest corner of building	None; pressurized recirculating loop with 2.5-inch-inside-diameter double-wall supply and return steel pipe on 5th floor	Nine 1,725-kW on 5th floor, six on north side, three in southwest corner
Silverstein Properties	Two 12,000-gallon tanks under loading dock on ground level	Between elevator shafts on west side of ground floor; 4.4 gpm	Located in shaft in west elevator bank	275-gallon tank on 5th floor	Two 900-kW on 5th floor in southwest corner
U.S. Secret Service	Used Silverstein tank	Used Silverstein pumps	Located in shaft in west elevator bank	Approximately 50- to 100-gallon tank under generator on 9th floor	9th floor
American Express	Day tank only	None	None	275-gallon tank on 8th floor on west side next to exterior wall	8th floor

As described in Section 5.6.2, the sequence of the WTC 7 collapse is consistent with an initial failure that occurred internally in the lower floors on the east side of the building. The interest in fuel oil is therefore directed at the parts of the fuel oil distribution system having the potential of supporting a fire in the lower floors on the east side of the building. The risers for the fuel distribution system were in one of the two utility shafts in the west end of the building. One exception was the American Express Corporation, which had a generator with a 275-gallon tank on the west end of the 8th floor. This tank was the sole supply for the American Express generator and was not connected to any other fuel oil source. The 275-gallon tank was filled by bringing containers of fuel oil to the tank and transferring the oil into the tank. Except for the part of the diesel oil distribution system serving the SSB generators, all of the generators were located at the west end, with relatively short horizontal distribution piping.

The SSB system involved three separate generator locations on the 5th floor: three generator sets in the southwest corner of the building, two in the northwest section, and four in the northeast section. The distribution pipe was double-wall welded black iron with leak detection between the pipes. The outer pipe was at least 4 inches in diameter and the inner pipe at least 2-1/2 inches. The pipe traversed most of the length of the 5th floor immediately north of a concrete masonry wall running most of the length of the

floor in an east-west direction. At the east end of the 5th floor and to the south of the wall was a 1- to 2-story mechanical equipment room. Transfer Trusses 1 and 2 were located in this room. The east end of Truss 1 was supported by a truss element that ran perpendicular (i.e., north-south) to the main east-west portions of the truss. There was a set of double doors opening from the mechanical room to the area containing the four generator sets previously mentioned. The fuel oil distribution pipe ran above this door several feet to the north of the masonry wall. The type, quality, and hardware on the door set are unknown. The position of the door (i.e., open or closed) at the time of the incident is also unknown. Also, no information was available in regard to the size of the undercut on the door.

The fuel oil pumps were powered from the generator sets. Fuel oil would have been pumped from the tanks when the emergency power system sensed a power interruption. The pump then operated in response to the pressure difference between the supply and return, and the pump would circulate oil as long as such a difference existed. Upon sensing a power interruption, the system would automatically switch to emergency mode. This would have been done with a transfer switch that monitored the building power supply and transferred to the emergency power system if the power from the Con Ed source was interrupted. It was also possible for the transfer to be made manually. Relative to continuity of power to the building, Con Ed reported that "the feeders supplying power to WTC 7 were de-energized at 9:59 a.m." It is believed that the emergency generators came on line immediately. It is also believed that some of them may have stopped operating because of the contamination of the intake air flowing into the carburetors and radiators. Except for the SSB system, where it is understood that a UPS system provided backup power to the 75-gpm pump, the flow of oil would stop and, as soon as the day tanks were empty, the involved generator set would stop running.

The SSB generators did not use day tanks. Instead there was a pressurized loop system that served all nine generators. As long as the 75-gpm pump continued to operate, a break in the line could, under some conditions, have a full or partial break that would not cause the system to shut down and could discharge up to the 75-gpm capacity of this positive displacement pump. It is understood that the SSB pump was supplied power from both the SSB generators and from the UPS.

Engineers from the New York State Department of Environmental Conservation investigated oil contamination in the debris of WTC 7. Their principal interest was directed to the various oils involved in the Con Ed equipment. However, they reported the following findings on fuel oil: "In addition to Con Ed's oil, there was a maximum loss of 12,000 gallons of diesel from two underground storage tanks registered as 7WTC." To date, the NY State Environmental Protection Agency (EPA) and DEC have recovered approximately 20,000 gallons from the other two intact 11,600-gallon underground fuel oil storage tanks at WTC 7.

Based on the listings in Table 5.2, it is probable that the 20,000 gallons that were recovered were from the Silverstein Properties' emergency power system. The data obtained from Silverstein indicate that the pumping rate from their tanks was 4.4 gpm. If the Silverstein pump had started pumping at 10 a.m., when Con Ed shut down power to the building immediately following the collapse of WTC 2, and continued pumping until the collapse of WTC 7 at 5:20 p.m., less than 2,000 gallons would have been used. The residual 20,000 gallons found in the two 12,000-gallon tanks, therefore, can not be used as an indicator of whether or not the Silverstein generator sets were on line and running.

Similarly, the SSB pump, which had a pumping rate of 75 gpm, would have drained the two 6,000-gallon tanks serving that system in less than 3 hours. This could have accounted for the lost 12,000 gallons reported by EPA or the tanks could have been ruptured and the oil spilled into the debris pile. Again, this is not a valid indicator of whether or not the SSB generator sets came on line. The NY State EPA indicates that the SSB tanks will be pulled from the debris in the near future. This may or may

not give some indication of the amount of oil still in the tanks when they were crushed. If there is evidence that the majority of diesel fuel was still in the tanks, it can be concluded that the SSB system did not discharge diesel oil as hypothesized in Section 5.6.1. Conversely, evidence that indicates that the tanks were low on oil at the time of rupture, and that they were full at the start of the September 11 incident, would lend support to the hypothesis that the SSB system was operating and pumping oil from these tanks.

Currently, there are no data available on the post-collapse condition of the OEM 6,000-gallon tank located between the 2nd and 3rd floors. The OEM system also included a 275-gallon day tank located on the 7th floor. The OEM system had a fuel supply system with the capability of transferring fuel from the Silverstein tanks to the 6,000-gallon OEM tank. The OEM generator sets were located in the southwest portion of the 7th floor. OEM also had an 11,000-gallon potable water tank on the south side of the 7th floor.

The Secret Service diesel distribution system, like the OEM system, was designed to refurbish its supply from the Silverstein tanks. This appears to have been pumped directly to a day tank having an estimated capacity of 50 to 100 gallons located near the northwest corner of the 9th floor. The generator set was also in the same location.

The 275-gallon tank associated with the American Express generator was located at the west end of the 8th floor. If full, the 275 gallons represent a potential of about 600 MegaJoules, which would be enough to cause a serious fire that could spread to other fuels, but not felt to be enough to threaten the stability of the building's structural elements.

5.5 Timeline of Events Affecting WTC 7 on September 11, 2001

The effects of the collapse of WTC 1 and WTC 2, the ensuing fires in WTC 7, and the collapse of WTC 7 are discussed below. Figure 5-12 shows the vantage points of the photographs taken illustrating these effects, as well as the extent of the debris generated by each of the collapses.

5.5.1 Collapse of WTC 2

At 9:59 a.m., WTC 2 (the south tower) collapsed. The approximate extent of its debris is shown in Figure 5-12(A). It appears that the collapse of WTC 2 did not significantly affect the roof, or the east, west, and north elevations of WTC 7. It is unknown if there was any damage to the south elevation after WTC 2 collapsed, but both the covered, tubular pedestrian bridge (see Figure 5-13) and the Plaza bridge were still standing after the collapse of WTC 2.

5.5.2 Collapse of WTC 1

At 10:29 a.m., WTC 1 (the north tower) collapsed, sending its debris into the streets below. The extent and severity of the resulting damage to WTC 7 are currently unknown. However, from photographic evidence and eyewitness accounts discussed below, it was assumed that the south side of the building was damaged to some degree and that fires in WTC 7 started at approximately this time.

Figure 5-14 is an aerial photograph that shows the debris clouds spreading around WTC 7 just after the collapse of WTC 1. Figure 5-15 is a photograph of WTC 1 debris between the west elevation of WTC 7 and the Verizon building. Figure 5-12(B) shows a plan-view diagram approximating the extent of this debris just after the collapse of WTC 1.

It does not appear that the collapse of WTC 1 affected the roof, or the east, west, and north elevations of WTC 7 in any significant way. However, there was damage to the southwest corner of WTC 7 at approximately floors 8 to 20, 24, 25, and 39 to 46, as shown in Figure 5-16, a photograph taken from West Street.

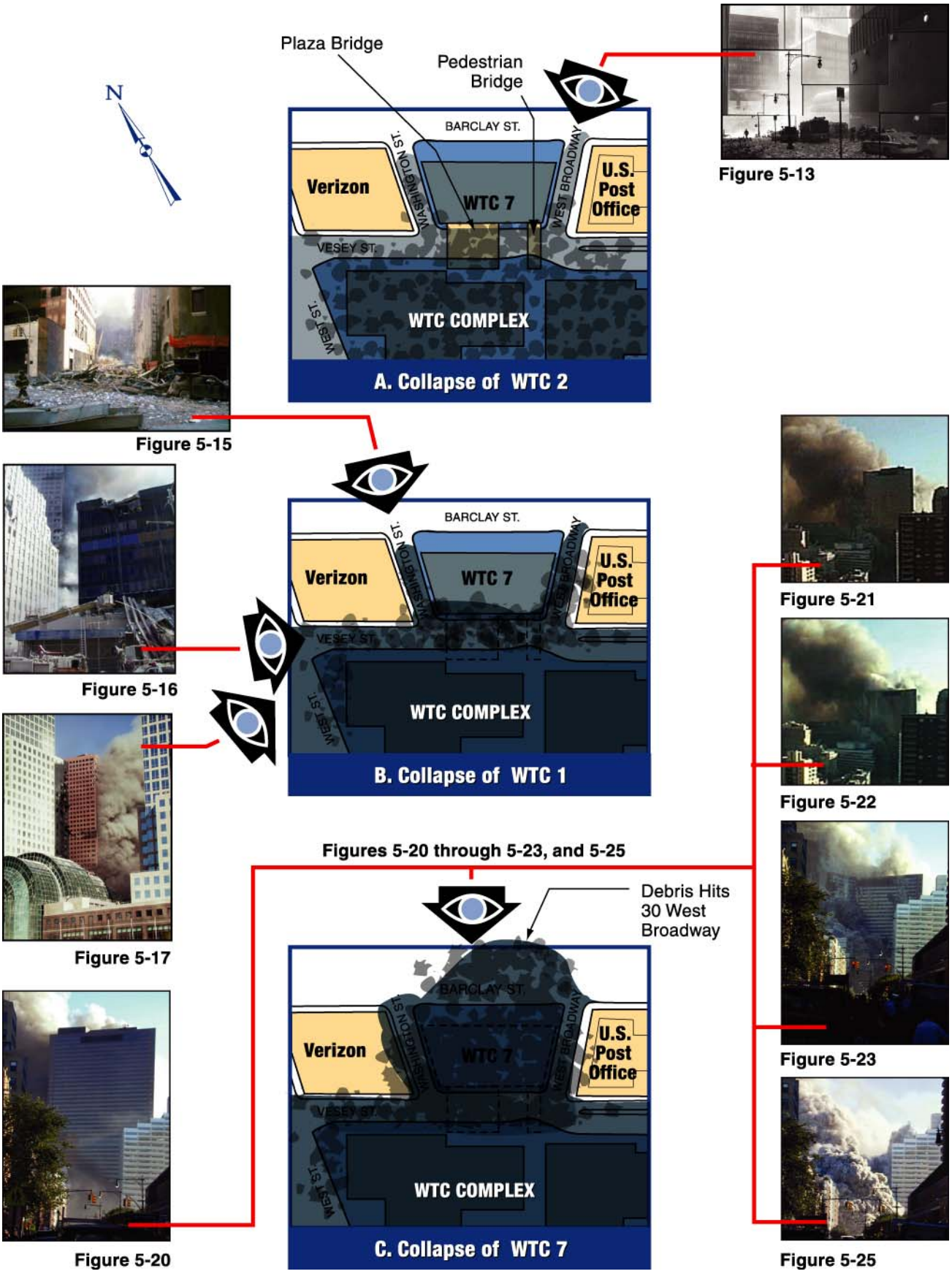


Figure 5-12 Sequence of debris generated by collapses of WTC 2, 1, and 7.

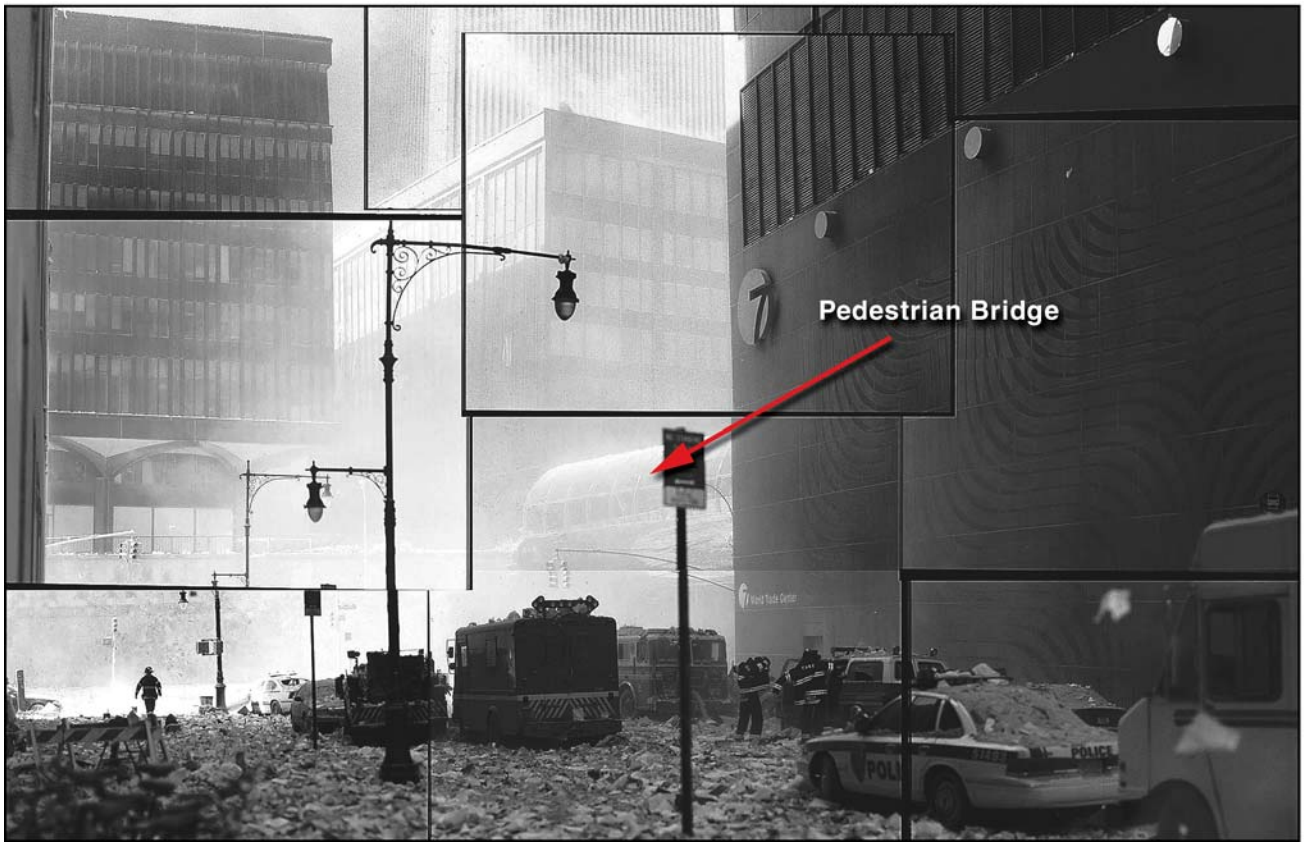


Figure 5-13 Pedestrian bridge (bottom center) still standing after WTC 2 has collapsed, sending substantial dust and debris onto the street, but before WTC 1 (top center) has collapsed.

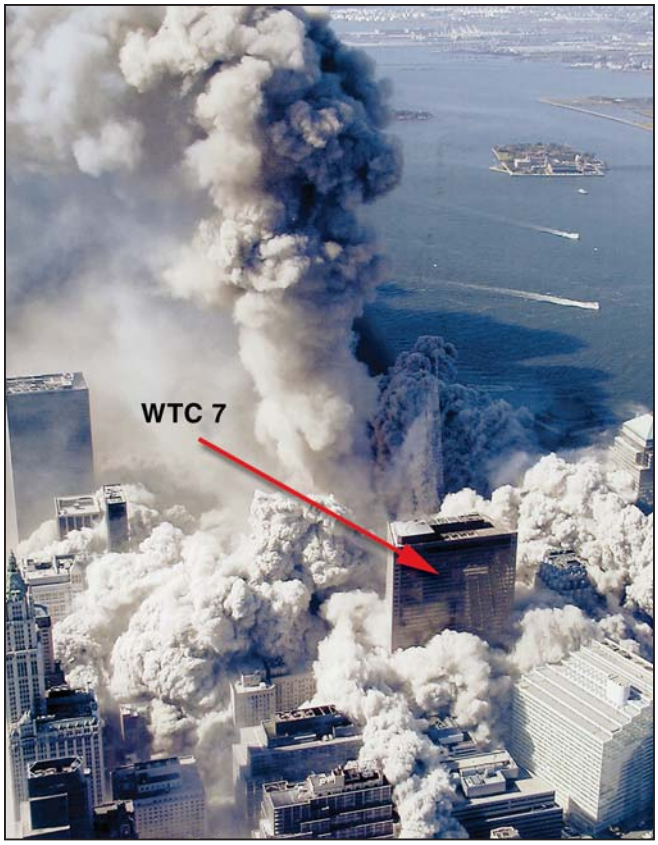


Figure 5-14
View from the north of the WTC 1 collapse and the spread of debris around WTC 7. Note the two mechanical penthouses of WTC 7 are intact.

GEORGE MILLER / NYCTA

Figure 5-15 Debris from the collapse of WTC 1 located between WTC 7 (left) and the Verizon building (right).

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Figure 5-16
Damage to southwest corner of WTC 7 (see box), looking from West Street.

Figure 5-17, a photograph taken across from the World Financial Center (WFC), shows the west elevation and indicates damage at the southwest corner of WTC 7 at the 24th, 25th, and 39th through 46th floors.

According to the account of a firefighter who walked the 9th floor along the south side following the collapse of WTC 1, the only damage to the 9th floor façade occurred at the southwest corner. According to firefighters' eyewitness accounts from outside of the building, approximately floors 8-18 were damaged to some degree. Other eyewitness accounts relate that there was additional damage to the south elevation.

5.5.3 Fires at WTC 7

Currently, there is limited information about the ignition and development of fires at WTC 7, as well as about the specific fuels that may have been involved during the course of the fire. It is likely that fires started as a result of debris from the collapse of WTC 1.

According to fire service personnel, fires were initially seen to be present on non-contiguous floors on the south side of WTC 7 at approximately floors 6, 7, 8, 10, 11, and 19. The presence of fire and smoke on

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Figure 5-17
Building damage to the southwest corner and smoke plume from south face of WTC 7, looking from the World Financial Plaza. Note damage to WFC 3 in the foreground.

lower floors is also confirmed by the early television news coverage of WTC 7, which indicated light-colored smoke rising from the lower floors of WTC 7.

Video footage indicated that the majority of the smoke appeared to be coming from the south side of the building at that time as opposed to the other sides of the building. This is corroborated by Figure 5-17, a photograph taken at 3:36 p.m. that shows the south face of WTC 7 covered with a thick cloud of smoke, and only small amounts of smoke emanating from the 27th and 28th floors of the west face of WTC 7.

News coverage after 1:30 p.m. showed light-colored smoke flowing out of openings on the upper floors of the south side of the building. Another photograph (Figure 5-18) of the skyline at 3:25 p.m., taken from the southwest, shows a large volume of dark smoke coming from all but the lowest levels of WTC 7, where white smoke is emanating. The mode of fire and smoke spread was unclear; however, it may have been propagated through interior shafts, between floors along the south façade that may have been damaged, or other internal openings, as well as the floor slab/exterior façade connections.

It appeared that water on site was limited due to a 20-inch broken water main in Vesey Street. Although WTC 7 was sprinklered, it did not appear that there would have been a sufficient quantity of water to control the growth and spread of the fires on multiple floors. In addition, the firefighters made the decision fairly early on not to attempt to fight the fires, due in part to the damage to WTC 7 from the collapsing towers. Hence, the fire progressed throughout the day fairly unimpeded by automatic or manual suppression activities.

A review of photos and videos indicates that there were limited fires on the north, east, and west faces of the building. One eyewitness who saw the building from a 30th floor apartment approximately 4 blocks

Figure 5-18 WTC 7, with a large volume of dark smoke rising from it, just visible behind WFC 1 (left). A much smaller volume of white smoke is seen rising from the base of WTC 7. Note that the lower, lighter-colored smoke (to right) is thought to be from the two collapsed towers

away to the northwest noted that fires in the building were not visible from that perspective. On some of the lower floors, where the firefighters saw fires for extended periods of time from the south side, there appeared to be walls running in an east to west direction, at least on floors 5 and 6, that would have compartmentalized the north side from the south side. There were also air plenums along the east and west walls and partially along the north walls of these floors instead of windows that may have further limited fires from extending out of these floors and, therefore, were not visible from sides other than the south.

As the day progressed, fires were observed on the east face of the 11th, 12th, and 28th floors (see Figure 5-19). The Securities and Exchange Commission occupied floors 11 through 13. Prior to collapse, fire was seen to have broken out windows on at least the north and east faces of WTC 7 on some of the lower levels.

On the north face, photographs and videos show that the fires were located on approximately the 7th, 8th, 11th, 12th, and 13th floors. American Express Bank International occupied the 7th and 8th floors. The 7th floor also held the OEM generators and day tank. Photographs of the west face show fire and smoke on the 29th and 30th floors.

Figure 5-19
Fires on the 11th and 12th floors of the east face of WTC 7.

It is important to note that floors 5 through 7 contained structural elements that were important to supporting the structure of the overall building. The 5th and 7th floors were diaphragm floors that contained transfer girders and trusses. These floors transferred loads from the upper floors to the structural members and foundation system that was built prior to the WTC 7 office tower. Fire damage in the 5th to 7th floors of the building could, therefore, have damaged essential structural elements.

With the limited information currently available, fire development in this building needs additional study. Fires were observed to be located on the lower levels for the majority of the time from the collapse of WTC 1 to the collapse of WTC 7. It appears that the sprinklers may not have been effective due to the limited water on site, and that the development of the fires was not significantly impeded by the firefighters because manual firefighting efforts were stopped fairly early in the day.

Available information indicates that fires spread horizontally and vertically throughout the building during the course of the day. The mode of spread was most likely either along the south façade that was damaged, or internally through shafts or the gap between the floor slab and the exterior wall. It is currently unclear what fuel may have been present to permit the fires to burn on these lower floors for approximately 7 hours. The change in the color and buoyancy of the smoke as the day progressed may indicate a change in the behavior of the fires. The darker color may be indicative of different fuels becoming involved, such as fuel oil, or the fire becoming ventilation limited. The increased buoyancy of the fires suggests that the heat release rate (or "fire size") may have also increased.

The mechanisms behind these apparent changes in behavior are currently unknown and therefore various scenarios need to be investigated further. These include gathering additional information regarding storage of materials on various levels, the quantity and combustibility of materials, and the presence of dense storage, including file rooms, tape vaults, etc. In addition, further analysis is needed on the specific locations of the fuel tanks, supply lines, fuel pumps, and generators to determine whether it may have been possible for a fuel line to be severed by the falling debris, allowing the pumps to run and pump fuel out of the broken pipes.

5.5.4 Sequence of WTC 7 Collapse

Approximately 7 hours after fires initiated in WTC 7, the building collapsed. The start of a timed collapse sequence was based on 17:20:33, the time registered by seismic recordings described in Table 1.1 (in Chapter 1). The time difference between each of the figures was approximated from time given on the videotape. Figures 5-20 to 5-25 illustrate the observed sequence of events related to the collapse.

~5:20:33 p.m. WTC 7 begins to collapse. Note the two mechanical penthouses at the roof on the east and west sides in Figure 5-20.

~5:21:03 p.m. Approximately 30 seconds later, Figure 5-21 shows the east mechanical penthouse disappearing into the building. It takes a few seconds for the east penthouse to "disappear" completely.

~5:21:08 p.m. Approximately 5 seconds later, the west mechanical penthouse disappears (Figure 5-22) or sinks into WTC 7.

~5:21:09 p.m. Approximately 1 or 2 seconds after the west penthouse sinks into WTC 7, the whole building starts to collapse. A north-south "kink" or fault line develops along the eastern side as the building begins to come down at what appears to be the location of the collapse initiation (see Figures 5-23 and 5-24).

~5:21:10 p.m. WTC 7 collapses completely after burning for approximately 7 hours (Figure 5-25). The collapse appeared to initiate at the lower floors, allowing the upper portion of the structure to fall.

Figure 5-20
View from the north of WTC 7 with both mechanical penthouses intact.

The debris generated by the collapse of WTC 7 spread mainly westward toward the Verizon building, and to the south. The debris significantly damaged 30 West Broadway to the north, but did not appear to have structurally damaged the Irving Trust building at 101 Barclay Street to the north or the Post Office at 90 Church Street to the east. The average debris field radius was approximately 70 feet. Figures 5-12(C) and 5-26 show an approximation of the extent of the debris after the collapse of WTC 7.

5.6 Potential Collapse Mechanism

5.6.1 Probable Collapse Initiation Events

WTC 7 collapsed approximately 7 hours after the collapse of WTC 1. Preliminary indications were that, due to lack of water, no manual firefighting actions were taken by FDNY.

Section 5.5.4 describes the sequence of the WTC 7 collapse. The described sequence is consistent with building collapse resulting from an initial (triggering) failure that occurred internally in the east portion of a lower floor in the building. There is no clear evidence of exactly where or on which floor the initiating failure occurred. Possibilities can be divided into three potential scenarios based on floor. In each

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Figure 5-21
East mechanical penthouse collapsed. (From video.)

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Figure 5-22
East and now west mechanical penthouses gone. (From video.)

Figure 5-23
View from the north of the "kink" or fault developing in WTC 7.

case, the concern is the failure of either a truss or one or more columns in the lower floors of the east portion of the building. Each of the scenarios is a hypothesis based on the facts known and the unknown conditions that would be required for the hypothesis to be valid. The cases are presented not as conclusions, but as a basis for further investigation.

4th Floor Scenarios. The bottom cords of the transfer trusses were part of the support of the 5th floor slab and, as such, were located below the slab and above the ceiling of the 4th floor in a position exposed to fire from below. The bottom cord members were massive members weighing slightly over 1,000 pounds per foot. Such members are slow to heat up in a fire. It was reported that these bottom cords were fireproofed. The space below was the cafeteria dining room. The best information available indicates that the dining room was furnished with tables and chairs. The intensity and duration of a fire involving these furnishings would not be expected to sufficiently weaken either the trusses or the columns supporting the trusses. Member collapse as a result of a fire on the 4th floor would require either that there was significant additional fuel or that the fireproofing on the trusses or columns was defective. Fuel oil leakage from the 5th floor is also a possibility; however, no evidence of leakage paths in the east end of the second floor was reported.

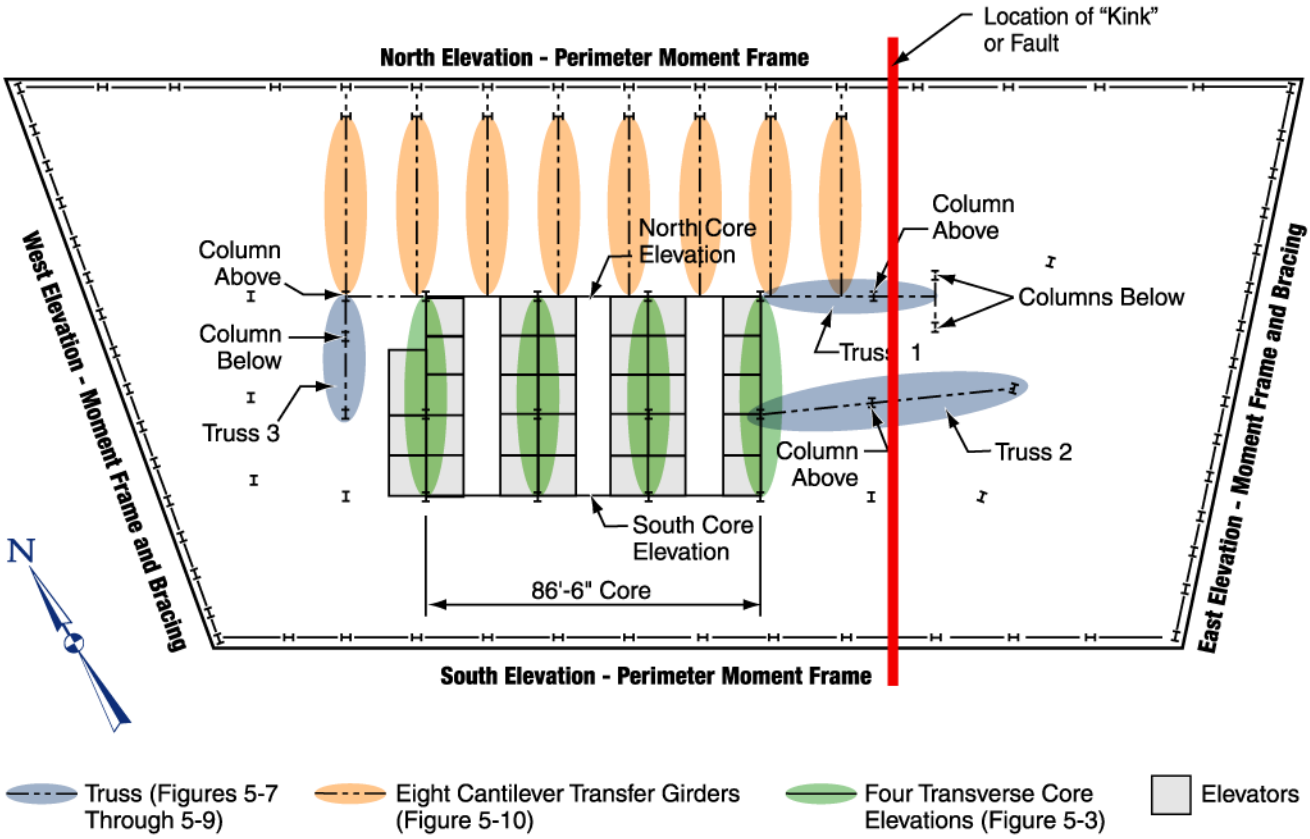

Figure 5-24 Areas of potential transfer truss failure.

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Figure 5-25 Debris cloud from collapse of WTC 7.

Figure 5-26 Debris generated after collapse of WTC 7.

5th Floor Scenarios. From a structural standpoint, the most likely event would have been the collapse of Truss 1 and/or Truss 2 located in the east end of the 5th and 6th floors. These floors are believed to have contained little if any fuel other than the diesel fuel for the emergency generators, making diesel oil a potential source of fire. As noted in Section 5.4, the fuel distribution system for the emergency generators pumped oil from tanks on the lower floors to the generators through a pipe distribution system. The SSB fuel oil system was a more likely source of fire around the transfer trusses. The SSB pump is reported as a positive displacement pump having a capacity of 75 gpm at 50 psi. Fuel oil was distributed through the 5th floor in a double-wall iron pipe. A portion of the piping ran in close proximity to Truss 1. However, there is no physical, photographic, or other evidence to substantiate or refute the discharge of fuel oil from the piping system.

The following is, therefore, a hypothesis based on potential rather than demonstrated fact. Assume that the distribution piping was severed and discharged up to 75 gpm onto the 5th floor in the vicinity of Truss 1. Seventy-five gpm of diesel fuel have the potential of approximately 160 megawatts (MW) of energy. If this burning diesel fuel formed pools around Truss 1, it could have subjected members of that truss to temperatures significantly in excess of those experienced in standard fire resistance test furnaces (see Appendix A). If the supply tanks were full at the start of the discharge, there was enough fuel to sustain this flow for approximately 3 hours. If the assumed pipe rupture were incomplete and the flow less, the potential burning rate of the discharged oil would be less, but the duration would be longer. At even a 30-gpm flow

rate (about 60 MW potential), the exposed members in the truss could still be subjected to high temperatures that would progressively weaken the steel. For the above reasons, it is felt that burning of discharged diesel fuel oil in a pool encompassing Truss 1 and/or Truss 2 needs to be further evaluated as a possible cause of the building collapse.

In evaluating the potential that a fire fed by fuel oil caused the collapse, it is necessary to determine whether the following events occurred:

1. The SSB generators called for fuel. This would occur once the generators came on line.

2. The pumps came on, sending fuel through the distribution piping.

3. There was a breach in the fuel distribution piping and fuel oil was discharged from the distribution system.

   Although there is no physical evidence available, this hypothesis assumes that it is possible that both the inner and outer pipes were severed, presumably by debris from the collapse of WTC 1. Depending on ventilation sources for air, this is sufficient to flashover the space along the north wall of this floor. The temperature of the fire gases would be governed to a large extent by the availability of air for combustion. The hot gases generated would be blocked from impacting Trusses 1 and 2 by the masonry wall separating the generation area from the mechanical equipment room, assuming that this wall was still intact after collapse of the tower and there were no other significant penetrations of walls.

4. The discharged fuel must be ignited.

   For diesel oil to be ignited, there must be both an ignition source and the oil must be raised to its flash point temperature of about 60 ℃ (140 ℉). Because there were fires on other floors of WTC 7, an assumption of ignition at this level in the building is reasonable, but without proof.

5. There is sufficient air for combustion of the discharged fuel oil.

   The air required for combustion of 75-gpm (160 MW potential) diesel fuel is approximately 100,000 cubic feet per minute (cfm). If less air is available for combustion, the burning rate will decrease proportionally. As the engine generator sets come on line, automatic louvers open and 80,000 cfm are provided for each of the nine SSB engines. A portion is used as combustion air for the drive engines; the rest is for cooling, but could supply air to an accidental fire. Given open louvers and other sources for entry of air, it is, therefore, probable that a fuel oil spill fire would have found sufficient air for combustion.

6. The hot fire gases reach and heat the critical member(s).

   For this to happen, the fire must have propagated either fuel or hot gases to the members in the truss in the mechanical equipment room. If the double door to the mechanical equipment room was either open or fell from its frame at some point, or if the door was undercut, the spilled fuel oil might have flowed into the mechanical equipment room, enveloping truss members in the main (hottest) portion of the flame. Such a situation could produce an exposure possibly exceeding that in the standard furnace test producing localized heat fluxes approaching the 200 kW/m^2 used by Underwriters Laboratories to simulate a hydrocarbon pool fire, with exposure temperatures in the range of 1,200 ℃ (2,200 ℉). If such intense exposure existed, the steel would be weakened more rapidly than normally expected. If the door was of superior construction (as with a fire door), it is unlikely that the fire would have reached the trusses in the mechanical equipment room until such time that the door failed.

A further hypothesis that would help explain the long time lapse between the collapse of WTC 1 and the collapse of WTC 7 would be that the masonry wall and door resisted the fire for a number of hours, but eventually failed. The new opening then allowed the fire (still supplied with a continuous discharge of fuel oil) to flow into the mechanical equipment room, envelope elements of the fireproofed trusses, and eventually cause a buckling collapse of one or both of them. For the fire to last long enough for this to occur, the flow rate would have to be around 30 gpm. At a rate of 30 gpm, the fuel would last for about 7 hours and would produce a fire of about 60 MW. The possibility that such a scenario could occur would be dependent on the specific construction details of the wall, the door, and the fireproofing on the truss.

Another hypothesis that has been advanced is that the pipe was penetrated by debris at a point near the southwest corner where there was more damage caused by debris from the collapse of the towers. This would have resulted in fuel oil spilling onto the 5th floor, but not being immediately ignited. However, a major portion of the 12,000 gallons in the SSB tanks would pump out onto the 5th floor, forming a large pool. At some point, this would have ignited and produced the required fire. This hypothesis has the advantage of assuming a pipe break in the area most severely impacted by the tower debris and accounts for the long delay from the initial incident to the collapse of WTC 7. The principal challenge is that such a fire would have more severely exposed Truss 3. If Truss 3 had been the point of collapse initiation, it is not expected that the first apparent sign of collapse would be the subsidence of the east penthouse.

Evaluation of fires on the 3rd to 6th floors is complicated by the fact that these floors were windowless with louvers, generally in a plenum space separating any direct line of sight between the open floor space and the louvers. None of the photographic records found so far show fires on these floors.

Further investigation is required to determine whether the preceding scenarios did or could have actually occurred.

Other Involved Floors Scenarios. Fire was known to have occurred on other floors. If a fire on one of these floors involved a large concentration of combustible material encasing several columns in the east portion of the floor, it might have been of sufficient severity to cause the structural members to weaken. Such fuel concentrations might have been computer media vaults, archives and records storage, stock or storage rooms, or other collections. It is possible that the failure of at least two or possibly more columns on the same floor would have been enough to cause collapse.

5.6.2 Probable Collapse Sequence

The collapse of WTC 7 appears to have initiated on the east side of the building on the interior, as indicated by the disappearance of the east penthouse into the building. This was followed by the disappearance of the west penthouse, and the development of a fault or "kink" on the east half of WTC 7 (see Figures 5-23 and 5-24). The collapse then began at the lower floor levels, and the building completely collapsed to the ground. From this sequence, it appears that the collapse initiated at the lower levels on the inside and progressed up, as seen by the extension of the fault from the lower levels to the top.

During the course of the day, fires may have exposed various structural elements to high temperatures for a sufficient period of time to reduce their strength to the point of causing collapse. The structural elements most likely to have initiated the observed collapse are the transfer trusses between floors 5 to 7, located on lower floors under the east mechanical penthouse close to the fault/kink location.

If the collapse initiated at these transfer trusses, this would explain why the building imploded, producing a limited debris field as the exterior walls were pulled downward. The collapse may have then spread to the west. The building at this point may have had extensive interior structural failures that then led to the collapse of the overall building. The cantilever transfer girders along the north elevation, the strong

diaphragms at the 5th and 7th floors, and the seat connections between the beams and columns at the building perimeter may have become overloaded after the collapse of the transfer trusses and caused the interior collapse to propagate to the whole floor and to the exterior frame. The structural system between floors 5 and 7 appears to be critical to the structural performance of the entire building.

An alternative scenario was considered in which the collapse started at horizontal or inclined members. The horizontal members include truss tension ties and the transfer girder of the T-1 truss at the east side of the 5th floor. Inclined members spanned between the 5th and 7th floors and were located in a two-story open mechanical room. The horizontal haunched back span of the eastern cantilever transfer girders, located roughly along the kink, rested on a horizontal girder at the 7th floor supported by the T-1 transfer truss. Even if the cantilever transfer girder had initiated the collapse sequence, the back span failure would most likely have not caused the observed submergence of the east mechanical penthouse.

The collapse of WTC 7 was different from that of WTC 1 and WTC 2, which showered debris in a wide radius as their frames essentially "peeled" outward. The collapse of WTC 7 had a small debris field as the façade was pulled downward, suggesting an internal failure and implosion.

To confirm proposed failure mechanisms, structural analysis and fire modeling of fuels and anticipated temperatures and durations will need to be performed. Further study of the interaction of the fire and steel, particularly on the lower levels (i.e., 1st–12th floors) should be undertaken to determine specific fuel loads, location, potential for impact from falling debris, etc. Further research is needed into location of storage and file room combustible materials and fuel lines, and the probability of pumps feeding fuel to severed lines.

5.7 Observations and Findings

This office building was built over an electrical substation and a power plant, comparable in size to that operated by a small commercial utility. It also stored a significant amount of diesel oil and had a structural system with numerous horizontal transfers for gravity and lateral loads.

The loss of the east penthouse on the videotape suggests that the collapse event was initiated by the loss of structural integrity in one of the transfer systems. Loss of structural integrity was likely a result of weakening caused by fires on the 5th to 7th floors. The specifics of the fires in WTC 7 and how they caused the building to collapse remain unknown at this time. Although the total diesel fuel on the premises contained massive potential energy, the best hypothesis has only a low probability of occurrence. Further research, investigation, and analyses are needed to resolve this issue.

The collapse of WTC 7 was different from that of WTC 1 and WTC 2. The towers showered debris in a wide radius as their external frames essentially "peeled" outward and fell from the top to the bottom. In contrast, the collapse of WTC 7 had a relatively small debris field because the façade came straight down, suggesting an internal collapse. Review of video footage indicates that the collapse began at the lower floors on the east side. Studies of WTC 7 indicate that the collapse began in the lower stories, either through failure of major load transfer members located above an electrical substation structure or in columns in the stories above the transfer structure. Loss of strength due to the transfer trusses could explain why the building imploded, with collapse initiating at an interior location. The collapse may have then spread to the west, causing interior members to continue collapsing. The building at this point may have had extensive interior structural failures that then led to the collapse of the overall building, including the cantilever transfer girders along the north elevation, the strong diaphragms at the 5th and 7th floors, and the seat connections between the interior beams and columns at the building perimeter.

5.8 Recommendations

Certain issues should be explored before final conclusions are reached and additional studies of the performance of WTC 7, and related building performance issues should be conducted. These include the following:

- Additional data should be collected to confirm the extent of the damage to the south face of the building caused by falling debris.
- Determination of the specific fuel loads, especially at the lower levels, is important to identify possible fuel supplied to sustain the fires for a substantial duration. Areas of interest include storage rooms, file rooms, spaces with high-density combustible materials, and locations of fuel lines. The control and operation of the emergency power system, including generators and storage tanks, needs to be thoroughly understood. Specifically, the ability of the diesel fuel pumps to continue to operate and send fuel to the upper floors after a fuel line is severed should be confirmed.
- Modeling and analysis of the interaction between the fires and structural members are important. Specifically, the anticipated temperatures and duration of the fires and the effects of the fires on the structure need to be examined, with an emphasis on the behavior of transfer systems and their connections.
- Suggested mechanisms for a progressive collapse should be studied and confirmed. How the collapse of an unknown number of gravity columns brought down the whole building must be explained.
- The role of the axial capacity between the beam-column connection and the relatively strong structural diaphragms may have had in the progressive collapse should be explained.
- The level of fire resistance and the ratio of capacity-to-demand required for structural members and connections deemed to be critical to the performance of the building should be studied. The collapse of some structural members and connections may be more detrimental to the overall performance of the building than other structural members. The adequacy of current design provisions for members whose failure could result in large-scale collapse should also be studied.

5.9 References

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