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1 *Introduction*

1.1 Purpose and Scope of Study

The events in New York City (NYC) on September 11, 2001, were among the worst building disasters and loss of life from any single building event in the United States. Over 3,000 people lost their lives that day at the World Trade Center (WTC) site, including 343 emergency responders. The nation was shocked by the attacks and resulting collapse of office buildings that had been in use every day.

This report presents observations, findings, and recommendations regarding the performance of buildings affected by the September 11 attacks on the WTC towers in New York City. This report also describes the structural and fire protection features of the affected buildings and their performance in response to the terrorist attacks. Due to the unprecedented nature, magnitude, and visibility of the terrorist attacks, this event is among the most well-documented in the media, particularly in terms of photographic images, lives affected, and the immediate responses and ensuing sequence of events. An understanding of these events must include the performance of the buildings under extreme conditions beyond building code requirements. This includes determining the probable causes of collapse and identifying lessons to be learned. Recommendations are presented for more detailed engineering studies, to complete the assessments and to produce improved guidance for building design and performance evaluation tools.

During the September 11 attacks, a large number of buildings were extensively damaged by impact and fire events. To study the response of the affected buildings, a diverse group of experts in tall building design, steel structure behavior, fire protection engineering, blast effects, and structural investigations was empaneled into a Building Performance Study (BPS) Team. The study was sponsored by the Federal Emergency Management Agency (FEMA) and the Structural Engineering Institute of the American Society of Civil Engineers (SEI/ASCE). In conducting the study, the BPS Team received tremendous cooperation from the State of New York, the New York City Department of Design and Construction (DDC), the New York City Office of Emergency Management (OEM), the Port Authority of New York and New Jersey (hereafter referred to as the Port Authority), the National Institute of Standards and Technology (NIST), and the Structural Engineers Association of New York (SEAoNY). In addition, the BPS Team was supported by a coalition of organizations that included the American Concrete Institute (ACI), the American Institute of Steel Construction (AISC), the Council of American Structural Engineers (CASE), the International Code Council (ICC), the Council on Tall Buildings and Urban Habitat (CTBUH), the National Council of Structural Engineers Associations (NCSEA), the National Fire Protection Association (NFPA), the Society of Fire Protection Engineers (SFPE), and the Masonry Society (TMS).

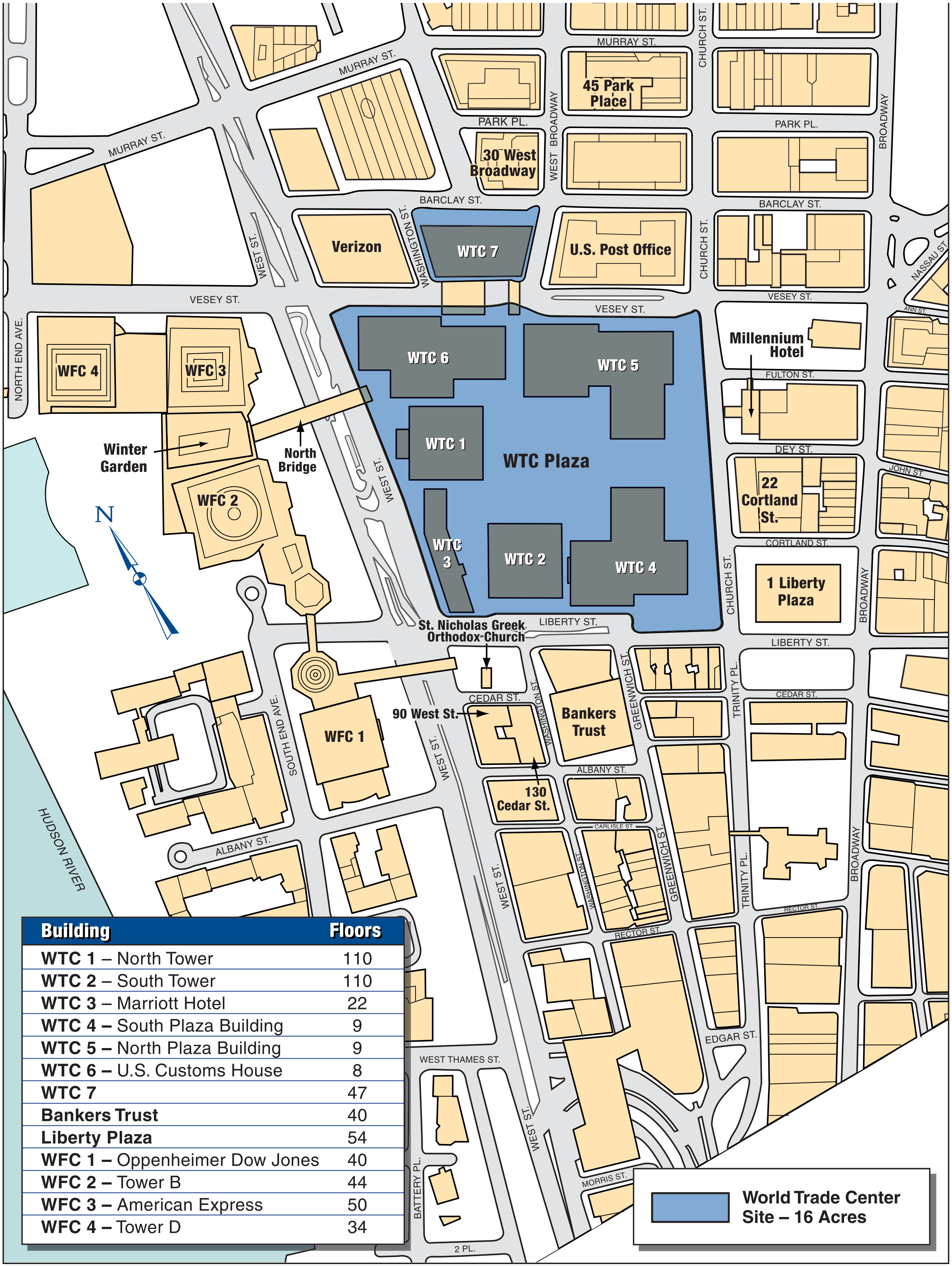
FEMA and ASCE began discussing site studies and teams on September 12, as engineers and emergency management agencies all over the nation rallied to provide support. A number of the team members were at the site immediately after the attacks to assist as needed. As soon as the rescue operations were halted and the FEMA Urban Search and Rescue teams left the site, the BPS Team mobilized to the WTC site and conducted field observations during the week of October 7, 2001. While in New York, the team inspected and photographed the site and individual building conditions, visited the salvage yards receiving steel from the collapsed buildings, attended presentations by design professionals associated with WTC buildings, and reviewed available building drawings. Upon completion of the site visit, the team members continued to collect extensive information and data, including photographs, video footage, and emergency response radio communications; continued surveillance of steel delivered to the recycling yards with the support of SEAoNY volunteers; and conducted additional interviews with direct witnesses of the events as well as participants in the original building design, construction, and maintenance. This information led to the development of a timeline of building loading events and allowed an initial engineering assessment of building performance. The study focus was to determine probable failure mechanisms and to identify areas of future investigation that could lead to practical measures for improving the damage resistance of buildings against such unforeseen events.

1.2 WTC Site

The World Trade Center and adjacent affected buildings were located on New York City's lower west side, adjacent to the Hudson River at the southern tip of Manhattan. As shown in Figure 1-1, the WTC site itself comprises 16 acres with buildings grouped around a 5-acre plaza. It is bounded by Vesey Street to the north, Church Street to the east, Liberty Street to the south, and West Street to the west. The WTC Complex consisted of seven buildings (referred to in this report as WTC 1 through WTC 7), the Port Authority Trans-Hudson (PATH) and Metropolitan Transit Authority (MTA) WTC stations, and associated Concourse areas. The WTC Plaza and its six buildings were originally developed by the Port Authority. Groundbreaking for construction was on August 5, 1966. Steel erection began in August 1968. First tenant occupancy of the 110-story north tower (WTC 1) was in December 1970, and occupancy of the 110-story south tower (WTC 2) began in January 1972. The other WTC buildings were constructed during the 1970s and into the 1980s, with WTC 7 constructed just north of the WTC site in 1985. WTC 3, located immediately west of the south tower, was a 22-story hotel operated by the Marriott Corporation. WTC 4 and 5 were nine-story office buildings, and WTC 6 was an eight-story office building. WTC 7 was a 47-story office building. The seven-building complex provided approximately 12 million square feet of rentable floor space occupied by a variety of government and commercial tenants. Many of the commercial tenants were in the insurance and financial industries. At the time of the September 11 attacks, the entire project had been transferred to a private party under a 99-year capital lease.

The New York Stock Exchange and the Wall Street financial district are located about three blocks southeast of the site. The World Financial Center (WFC) complex was constructed in the early 1980s and is located directly to the west, across West Street. Other prominent buildings immediately surrounding the WTC site include a historic Cass Gilbert designed building at 90 West Street and the Bankers Trust building at 130 Liberty Street, both located immediately to the south; the 1 Liberty Plaza building, located to the east; and the Verizon building, located directly to the north.

A six-story subterranean structure was underneath a large portion of the main WTC Plaza and WTC 1, 2, 3, and 6. Material excavated to construct this site was used to fill a portion of the Hudson River shoreline just across West Street and to create the adjacent World Financial Center (WFC) site. Construction of this deep substructure was a significant challenge, given the proximity of the Hudson River and the presence of a number of tall buildings along the south, east, and north sides of the site. In order to aid the excavation, slurry wall technology was utilized. In this technology, a trench is dug in the eventual location of the perimeter retaining walls. A bentonite slurry is pumped into the trench as it is excavated, and used to keep the trench open against the surrounding earth. Reinforcing steel is lowered into the trench, and concrete is



Building	Floors
WTC 1 – North Tower	110
WTC 2 – South Tower	110
WTC 3 – Marriott Hotel	22
WTC 4 – South Plaza Building	9
WTC 5 – North Plaza Building	9
WTC 6 – U.S. Customs House	8
WTC 7	47
Bankers Trust	40
Liberty Plaza	54
WFC 1 – Oppenheimer Dow Jones	40
WFC 2 – Tower B	44
WFC 3 – American Express	50
WFC 4 – Tower D	34

Figure 1-1 WTC site map.

placed through a tremie to create a reinforced concrete wall around the site perimeter. After the concrete wall is cured, excavation of the substructure begins. As the excavation progresses below surrounding grade, tiebacks are drilled through the exposed concrete wall and through the surrounding soil into the rock below to provide stability for the excavation. At the WTC site, these tiebacks were temporary and were replaced in the final construction by the subterranean floor slabs that provided lateral support to the walls.

A further challenge to the construction of the substructure was the presence of two existing subway lines across the site. The Interboro Rapid Transit System 1 and 9 subway lines, operated by the MTA, ran north to south across the middle of the site adjacent to the east wall of the substructure. A second subway system, PATH, operated by the Port Authority, made a 180-degree terminal bend beneath the western half of the site. This subway tunnel was temporarily supported across the excavation and incorporated into the final construction with a station provided for this line inside the slurry wall, just west of the 1 and 9 subway lines, and below the Plaza area just east of WTC 1 and partially below WTC 6. Although significant damage was sustained by the buildings, subterranean structure, and subway system, only the performances of the above-grade buildings were assessed in this study.

1.3 Timeline and Event Summary

On the morning of September 11, 2001, two hijacked commercial jetliners were deliberately flown into the WTC towers. The first plane, American Airlines Flight 11, originated at Boston's Logan International Airport at 7:59 a.m., Eastern Daylight Time. The plane was flown south, over midtown Manhattan, and crashed into the north face of the north tower (WTC 1) at 8:46 a.m. The second plane, United Airlines Flight 175, departed Boston at 8:14 a.m., and was flown over Staten Island and crashed into the south face of the south tower (WTC 2) at 9:03 a.m.

Both flights, scheduled to arrive in Los Angeles, were Boeing 767-200ER series aircraft loaded with sufficient fuel for the transcontinental flights. These aircraft are described in Appendix E. There were 92 people on board Flight 11 and 65 people on board Flight 175. Figure 1-2 shows the approximate flight paths for the two aircraft.

The north tower was struck between floors 94 and 98, with the impact roughly centered on the north face. The south tower was hit between floors 78 and 84 toward the east side of the south face (Figures 1-3 and 1-4). Each plane banked steeply as it was flown into the building, causing damage across multiple floors. According to Government sources, the speed of impact into the north tower was estimated to be 410 knots, or 470 miles per hour (mph), and the speed of impact into the south tower was estimated to be 510 knots, or 590 mph. As the two aircraft impacted the buildings, fireballs erupted (Figure 1-5) and jet fuel spread across the impact floors and down interior shaftways, igniting fires (Figure 1-6). The term fireball is used to describe deflagration, or ignition, of a fuel vapor cloud. As the resulting fires raged throughout the upper floors of the two WTC towers, thousands attempted to evacuate the buildings. It was estimated by the Port Authority that the population of the WTC complex on September 11, 2001, was 58,000 people. This estimate includes the PATH and MTA stations and the Concourse areas. Almost everyone in WTC 1 and WTC 2 who was below the impact areas was able to safely evacuate the buildings, due to the length of time between the impact and collapse of the individual towers.

At 9:59 a.m., 56 minutes after it was struck, the south tower collapsed. The north tower continued to stand until 10:29 a.m., when it, too, collapsed. The north tower had survived 1 hour and 43 minutes from the time the jetliner crashed into it. Over 3,000 lives were lost in the collapse of the twin towers, counting 2,830 building occupants, 157 airplane crew and passengers, and 343 firefighters, police personnel, and other emergency responders.

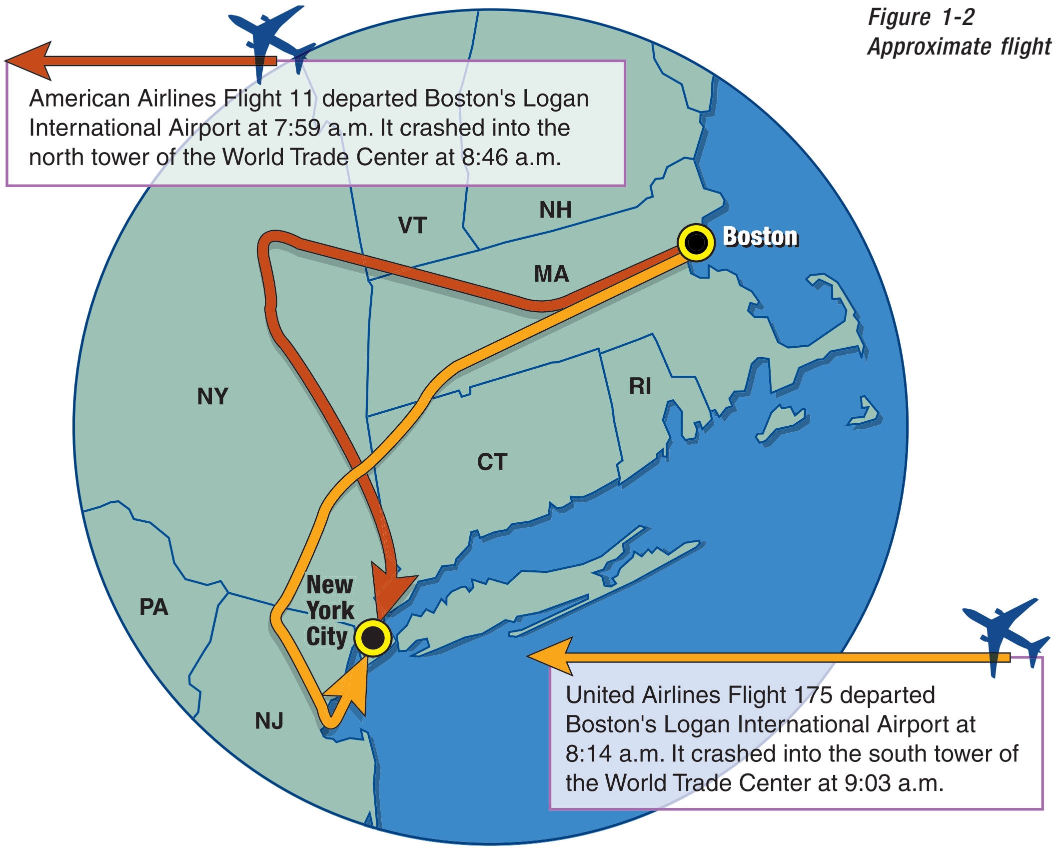


Figure 1-2
Approximate flight paths of aircraft.

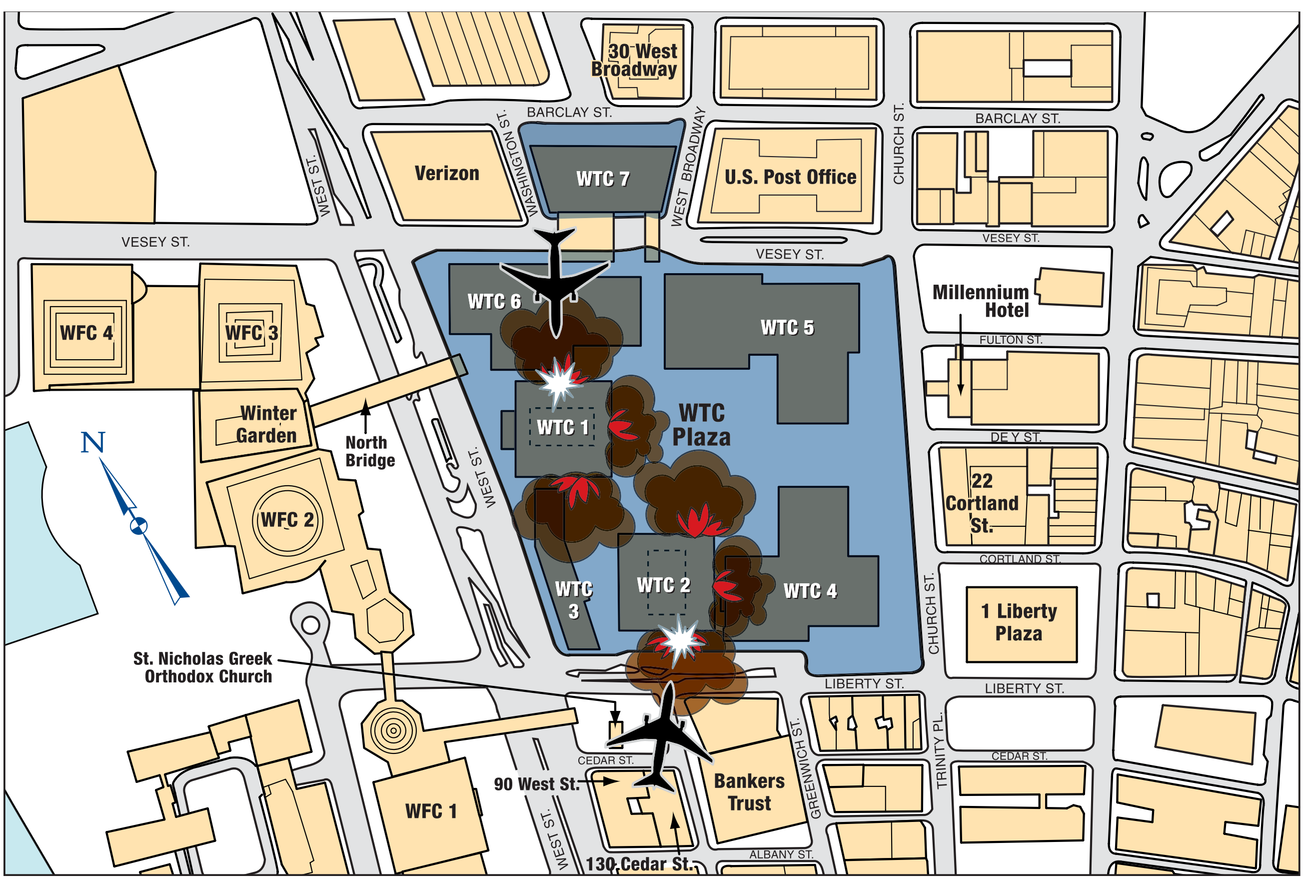


Figure 1-3 WTC impact locations and resulting fireballs.

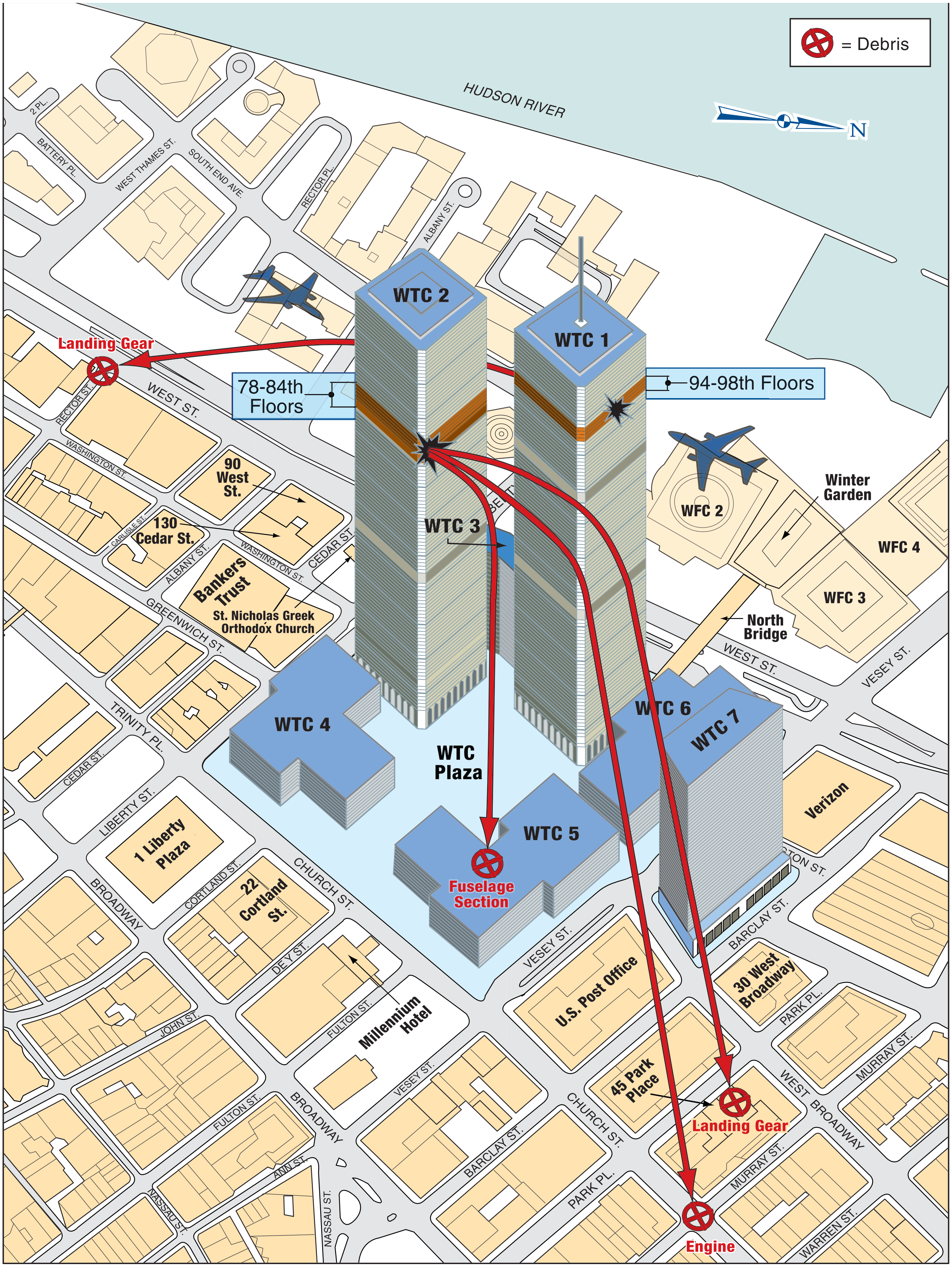


Figure 1-4 Areas of aircraft debris impact.

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Figure 1-5 Fireball erupts on the north face of WTC 2 as United Airlines Flight 175 strikes the building.

OEM

Figure 1-6 View of the north and east faces showing fire and impact damage to both towers.

Debris from the collapsing towers, some of it still on fire, rained down on surrounding buildings, causing structural damage and starting new fires (Figure 1-7). The sudden collapse of each tower sent out air pressure waves that spread dust clouds of building materials in all directions for many blocks. The density and pressure of the dust clouds were strong enough to carry light debris and lift or move small vehicles and break windows in adjacent buildings for several blocks around the WTC site. Most of the fires went unattended as efforts were devoted to rescuing those trapped in the collapsed towers. The 22-story Marriott World Trade Center Hotel (WTC 3) was hit by a substantial amount of debris during both tower collapses. Portions of WTC 3 were severely damaged by debris from each tower collapse, but progressive collapse of the building did not occur. However, little of WTC 3 remained standing after the collapse of WTC 1. WTC 4, 5, and 6 had floor contents and furnishings burn completely and suffered significant partial collapses from debris impacts and from fire damage to their structural frames. WTC 7, a 47-story building that was part of the WTC complex, burned unattended for 7 hours before collapsing at 5:20 p.m. The falling debris also damaged water mains around the WTC site at the following locations:

- 20-inch main on West Street, closed to the slurry wall, about midway between Vesey Street and Liberty Street
- 20-inch main along the Financial Center north of the South Link Bridge
- 20-inch main at the corner of Liberty Street and West Street
- main in front of the West Street entrance to 90 West
- 24-inch main on Vesey Street, near West Street
- main at the corner of Vesey Street and West Broadway, near the subway station
- main at the southwest edge of 30 West Broadway
- 16-inch main inside the slurry wall

Damaged mains were located after the collapses, but access was impeded by the collapse debris.

The timeline of the major events is summarized in Table 1.1. The times and seismic data were recorded at the Lamont-Doherty Earth Observatory (LDEO) of Columbia University. The signal duration and Richter Scale magnitudes were included to indicate the relative magnitudes of energy transmitted through the ground between the events. Figure 1-8 shows the accelograms recorded by the observatory during the events.

Other buildings surrounding the WTC plaza were also damaged by falling debris. A few buildings, such as the Bankers Trust building, suffered significant damage but remained standing. Many buildings had their façades and glazing damaged and their interiors blanketed with debris from the collapse of the WTC towers and WTC 7. Figures 1-9A and 1-9B are satellite images of the WTC site taken before and after the September 11 attacks, respectively.

1.4 Response of the Engineering Community

1.4.1 Local Authorities

Immediately after the attacks, it became apparent to the City of New York that there was an enormous need for structural engineering and construction expertise and support. Within hours, the DDC appealed to several construction companies (Bovis/Lend-Lease, AMEC, Turner-Plaza and Tully) and the engineering firm, LZA Technology/Thornton-Tomasetti (LZA) to assist in the search and rescue effort. Mobilization began immediately. A reconnaissance inspection by DDC and LZA took place in the afternoon of September 11. A first round of building inspections was performed on September 12 by engineers from DDC, the NYC Department of Buildings (DoB), and LZA.

Figure 1-7 Schematic depiction of areas of collapse debris impact, based on aerial photographs and documented damage. Striped areas indicate predominant locations of exterior steel columns. Inner circles indicate approximate radius of exterior steel columns and other heavy debris. Outer circles indicate approximate radius of aluminum cladding and other lighter debris. Heavy Xs show where exterior steel columns were found outside the predominate debris areas.

DDC, the agency that had responsibility to manage all construction and engineering at the site, was joined by engineers and construction managers from the Port Authority on the following days. Beginning on September 13, consulting support was provided by SEAoNY, Mueser Rutledge Consulting Engineers, Leslie E. Robertson Associates, the U.S. Army Corps of Engineers, FEMA Urban Search and Rescue, and various other New York City departments.

The engineering efforts had two objectives – safety of personnel involved in the recovery process and evaluation of the conditions and processes that would allow a return to safe occupancy of the buildings in the area.

Table 1.1 Timeline of Major Events[1]

Start Time[2]	Signal Duration	Magnitude (Richter Scale)	Event
8:46:26 EDT (12:46 UTC)	**12 seconds**	**0.9**	WTC 1 (the north tower) was hit by American Airlines Flight 11, a hijacked 767-200ER commercial jet airliner.
9:02:54 EDT (13:02 UTC)	**6 seconds**	**0.7**	WTC 2 (the south tower) was hit by United Airlines Flight 175, also a hijacked 767-200ER jet.
9:59:04 EDT (13:59 UTC)	**10 seconds**	**2.1**	WTC 2 began collapsing after 56 minutes, 10 seconds. Large debris from the collapse fell on WTC 3 and WTC 4, 130 Cedar Street, 90 West Street, and Bankers Trust. WTC 3 suffered a partial collapse. Fire was initiated in WTC 4 and 90 West Street.
10:28:31 EDT (14:28 UTC)	**8 seconds**	**2.3**	WTC 1 began collapsing after 102 minutes, 5 seconds. Large debris from the collapse fell on WTC 3, 5, 6, and 7; the Winter Garden; and the American Express (World Financial Center 2) building. WTC 3 collapsed to the 3rd floor, and fires were initiated in WTC 5, 6, and 7.
17:20:33 EDT (21:20 UTC)	**18 seconds**	**0.6**	WTC 7 began collapsing.

[1] Based on seismic recordings made by the Lamont-Doherty Earth Observatory of Columbia University, 34 kilometers north of the WTC site.

[2] EDT = Eastern Daylight Time; UTC = Coordinated Universal Time. Times cited in this report are based on these times, rounded to the nearest minute.

1.4.2 SEAoNY Participation

Immediately after the attacks, members of the Board of Directors of SEAoNY initiated contact with DDC, DoB, and OEM. By Wednesday morning, September 12, the Board had established communications with the New York Police Department (NYPD), OEM, and DDC. SEAoNY teams of structural engineers were retained through their firms by LZA and began assisting with the rescue and recovery efforts on Thursday, September 13. They served continuously (24 hours a day, 7 days a week) through January 9, 2002. The SEAoNY teams provided engineering guidance with search and rescue, demolition, and temporary construction, as well as assistance to contractors working to stabilize or remove debris.

Seismic Record at Palisades, NY, 34 km North of the World Trade Center Disaster

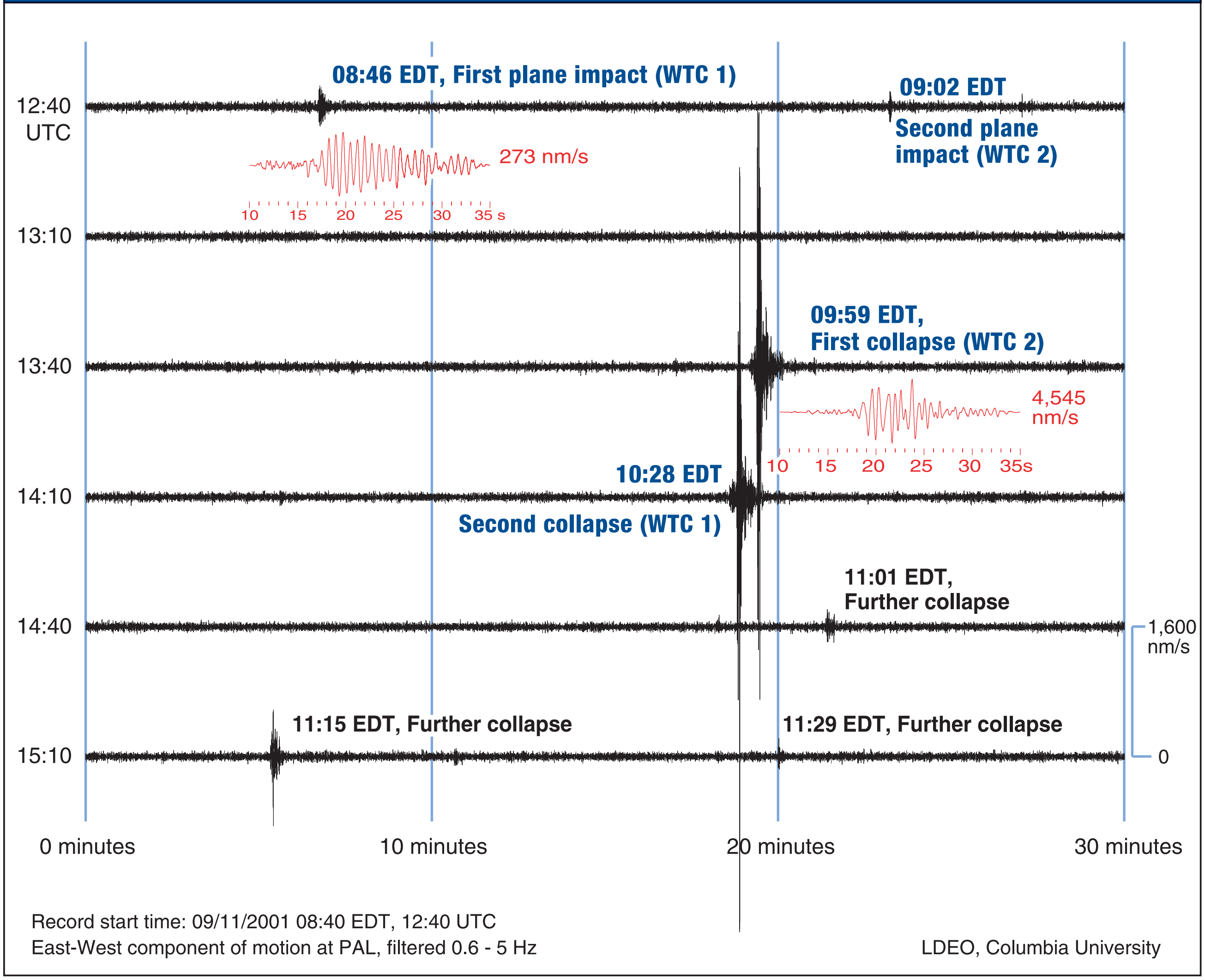

Figure 1-8 Seismic recordings on east-west component at Palisades, NY, for events at WTC on September 11, 2001, distance 34 km. Three hours of continuous data are shown starting at 08:40 EDT (12:40 UTC). The two largest signals were generated by the collapses of towers 1 and 2. Expanded views of first impact and first collapse are shown in red. The amplitude of the seismic signal is in nanometers per second (nm/s), and the peak amplitude of the ground motion at this station reached to 4,545 nm/s for the first collapse. Note the relatively periodic motions for impacts 1 and 2.

Structural engineers acted as guides through the site, providing descriptions of structures and offering judgment on the stability of structures and debris. They provided warnings of potential hazards and assisted with choosing crane and other equipment locations and installations. Assisting the LZA team, structural engineers worked in four teams staffed by SEAoNY members. In the first 30 days after the attack, more than 10,000 engineer hours, or 1-1/2 engineer-years per week, were expended by these teams.

DDC was also asked on September 14 to rapidly assess the condition of the more than 400 buildings in lower Manhattan suspected of being damaged by the collapse of the WTC towers. It appeared that the zone of damage was significant and that many buildings may have received debris or vibration damage. The potentially hazardous conditions would make the area unsafe for rescue and removal personnel. DDC and LZA assigned this task to SEAoNY. These systematic building inspections were organized, coordinated, and performed by members of SEAoNY. Engineering firms representing those members worked as consultants to

Figure 1-9A Satellite photograph of the WTC site taken before the attacks.

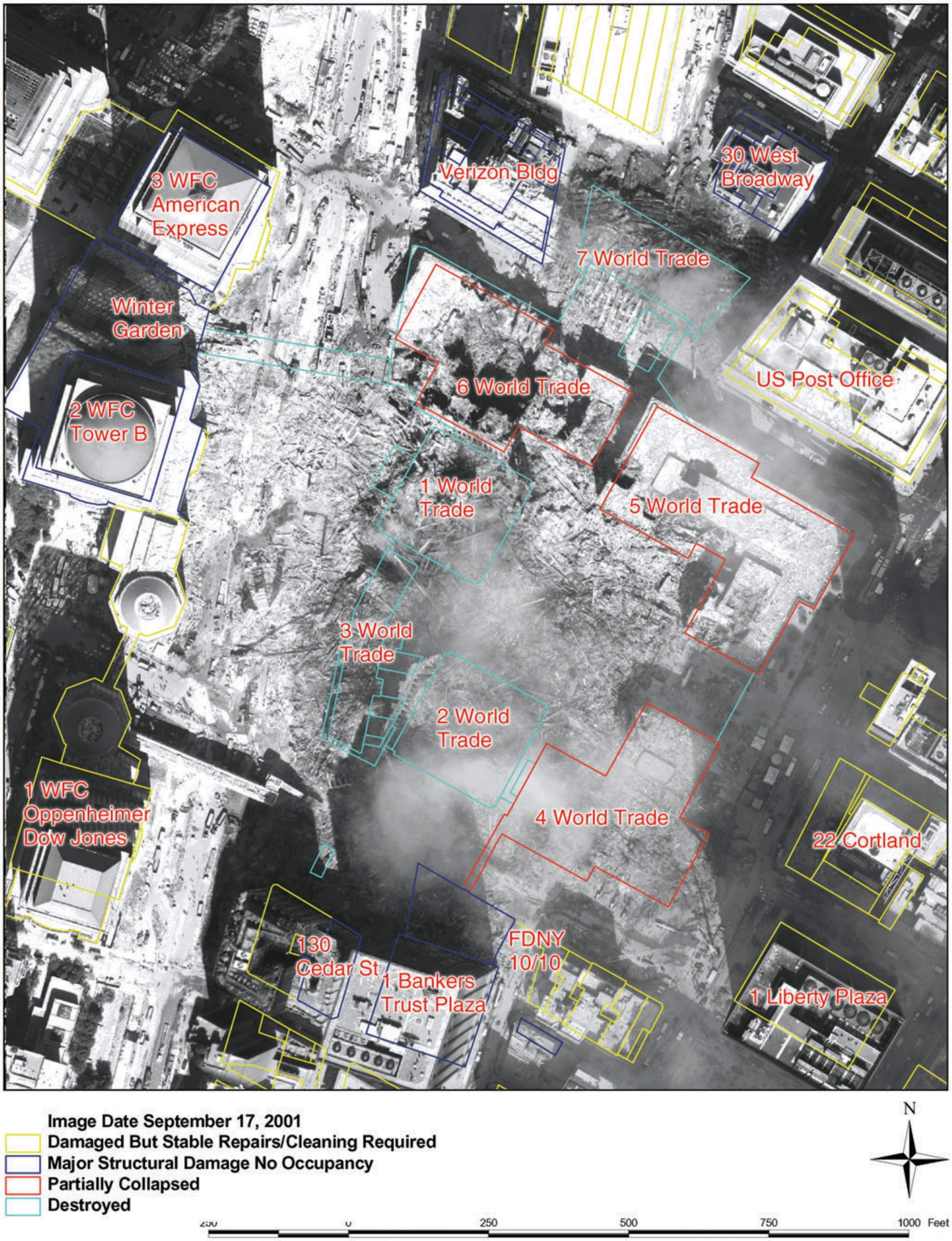

Figure 1-9B Satellite photograph of the WTC site taken after the attacks.

LZA. The purpose of the building assessment was to assist in determining which buildings could be safely reoccupied and to identify structural or falling hazards that might injure site personnel or the public.

Similar efforts had been conducted by Structural Engineers Associations in the western United States following earthquakes; however, no formal mechanisms were in place in New York for this type of effort. The field manual *ATC 20*, *Procedures for Post-earthquake Safety Evaluation of Buildings,* published by the Applied Technology Council (ATC) was used for procedural guidance on performing the inspections. Custom forms for rapid visual assessments were created. Additional teams of structural engineers organized by SEAoNY completed the first round of assessments of approximately 400 buildings on September 17 and 18.

After the initial assessments had been completed, additional inspections were recommended for the buildings that appeared to be the most distressed. These additional inspections were completed within a matter of days after the recommendations were discussed with DDC. As a follow-up, a second round of evaluations for all of the buildings was performed between October 4 and 10, and detailed engineering reports for the most severely damaged buildings (outside of the WTC site) were prepared in conjunction with DDC and LZA. Building evaluation summaries are presented in Chapter 7 (Peripheral Buildings).

In the initial response, most of SEAoNY's members volunteered, as did structural engineers from across the country who coordinated with SEAoNY through NCSEA. SEAoNY members located in New York City also volunteered office space, equipment, and support to other engineers working at the WTC site. To eliminate any potential liability issues and to meet the long-term commitment required by the engineers due to the magnitude of the event, all of these engineers were retained by DDC through LZA.

SEAoNY volunteers provided assistance to the BPS Team by maintaining five teams of structural engineers to monitor steel debris from the WTC site as it arrived at the salvage yards. Their goal was to locate material from the impact zones. SEAoNY engineers also collected hundreds of hours of video and thousands of still photographs from other engineers and the general public in an effort to fully document the collapses and the recovery operations.

As with any first-time event, difficulties were encountered at the beginning of the relationship between the volunteer engineering community and the local government agencies. There were no procedures for either the engineers or the agencies to follow for such an event, leading to a situation in which the organization of the work and the procedures to be followed were developed and revised almost daily in response to the circumstances.

Issues of identification, credentials, responsibility, and liability required considerable attention. Because the site was treated as a crime scene, access at various locations had to be obtained through checkpoints manned by the National Guard, the Fire Department of New York (FDNY), and the NYPD. Also, because there was no identification system in place for the first few days, it took up to 3 hours for SEAoNY volunteers to get to the command center from the outer perimeter of the site, a distance of less than six blocks. In addition, there were issues related to the responsibilities and liabilities of individual volunteers, their firms, and SEAoNY. Currently in New York City, there is no process for deputizing volunteers, nor are there any "Good Samaritan" laws in effect.

Lessons learned in hindsight can be valuable to other engineering and professional organizations throughout the country. SEAoNY has drafted a "Structural Engineering Emergency Response Plan (SEERP)," which will be used in discussions with New York City to develop and formalize relationships and procedures that will improve responses to any future emergency events or disasters. Appendix F presents the draft SEERP, which may be useful to other cities considering such activities.

1.5 Overview of Building Codes and Fire Standards

1.5.1 Building Codes

Building design and occupancy in the United States is governed by building codes that specify the minimum environmental, or external, loads that a building must have the strength to resist. They also prescribe requirements for internal challenges such as fire protection and timely egress for life safety. However, designers must consider project circumstances and owner requirements when determining building design loads. The primary external loads specified are:

- gravity
- wind
- earthquake

Other risks considered include the potential for fire, hazardous material leaks or explosion, and the need to promptly evacuate occupants to safety. These demands establish building code requirements for fire resistive construction, emergency egress, and fire protection systems.

National model building codes do not include requirements to design for loads that might be imposed due to acts of war or terrorism. It is usually considered unnecessary to provide the capacity to resist such loads in most buildings; however, these loads may be included at the discretion of building owners if they desire a higher level of protection (e.g., an embassy, bank, or military facility).

Gravity loads include both the weight of the building and its contents. The weight of the building is calculated based on building construction plans and material densities. The weight of the contents is not specifically known at the time of design because it will depend on the building user and will vary with time. Therefore, the codes specify minimum floor loads on a pounds per square foot basis. For instance, for a standard office occupancy, the codes typically specify a minimum live load of 50 pounds per square foot (psf) of floor area. It is the responsibility of the building owners to see that floors are not overloaded.

Wind loads specified by codes are based on maps of design wind speed for different regions of the country. As wind speed increases, the wind pressure on the building increases proportionally to the square of the wind velocity. The pressure on the building also varies with the height and degree of shielding provided by other buildings and geographic features. Although not usually required by building codes, engineers frequently use wind tunnel studies to more accurately determine wind loads on tall buildings, where standard calculations may not be adequate. WTC 1, 2, 4, 5, and 6 all had extensive wind tunnel studies performed as part of the design process. WTC 1 and WTC 2 were among the first structures that were designed using wind tunnel studies.

The hazard presented by earthquakes is also highly dependent on the geographic region. In all regions of the country, including the most severe seismic areas of California, the effects of earthquakes are relatively small for very tall buildings. The flexibility of a very tall building, say 100 stories, generally allows the building to respond as the ground moves back and forth without developing forces nearly as large as those produced by design wind loads. Therefore, even in a severe seismic area, tall building design is generally controlled by wind loads.

Engineers design buildings for gravity, wind, and earthquake loads. Architects, in concert with fire protection professionals, including fire protection engineers, oversee the selection and application of fire resistive construction elements and fire protection systems such as sprinklers, fire alarms, and special hazard protection.

The building codes also prescribe the minimum requirements for life safety if a fire occurs. The prescribed fire safety features are intended to limit the fire threat and safeguard those in the building. Prime among these features are the egress and emergency notification (alarm) requirements.

Particularly in high-rise buildings, fire safety requirements are prescribed to maintain the integrity of the structure by controlling the intensity of fire and providing adequate structural strength during fires. In modern building codes, this is accomplished through a three-step approach:

- The first line of defense is the automatic sprinkler protection designed to control fires in their early stage of development and either extinguish them or hold the fire in check for the arrival of the fire department. Sprinklers are not normally capable of controlling fires that are of large size before the sprinklers can operate. Such was the case in the twin towers.
- The second line of defense is manual firefighting by the fire department or fire brigades. The building is provided with standpipes, emergency control of elevators, special emergency communication systems, control centers, and other features to enable effective firefighting above the levels that can be attacked from the exterior. It was this line of defense that successfully controlled the 1975 fire. In the September 11 incident, the damage done to the elevators and the height of the fires precluded the fire department from being able to directly attack the fire. Even if they had reached the fire floors, they would have been faced with a fire situation possibly beyond even the excellent capabilities of the FDNY.
- The final line is the fire resistance of the building and its elements, including the building frame, the floors, partitions, shaft enclosures, and other elements that compartmentalize the building and structurally support it. Most important of these are the requirements for the structural frame (including columns, girders, and trusses). See Section 1.5.3 for a discussion of fire resistance ratings.

All three of these lines of defense were present, but were overwhelmed by the magnitude of the events of September 11, 2001.

For life safety and egress, stairways must have minimum widths based on the maximum number of occupants who may be in the building. Stairs must be separated from the remainder of the building by a minimum 1- or 2-hour fire resistant barrier to provide a level of safety while occupants traverse the stairs. At least two stairways must be provided with widely separated entry points. In most jurisdictions, elevators are designed to automatically return to the lobby level during a fire alarm to be controlled by firefighters. In many high-rise buildings, the elevator shafts and exit stairs are pressurized to keep out smoke and heat. The use of elevators is discouraged for emergency egress because of the potential for elevator failure and the likelihood of the elevator shaft acting like a chimney, carrying heat, smoke, and toxic gases throughout the building.

Fire protection systems (sprinklers, fire alarms, and special-hazard protection) are required to provide early notification and fire control until the fire department can arrive and begin manual suppression efforts. Smoke management systems are intended to aid emergency evacuation of building occupants and operations of emergency personnel. Manual suppression efforts by emergency personnel are aided by the presence of standpipe systems.

1.5.2 Unusual Building Loads

In planning a new building, an owner may request enhanced requirements in its design for events that are not anticipated by the building codes. In some cases, where unusual hazards such as explosive or toxic materials exist, the building codes prescribe special life safety and fire protection features. In most non-hazardous occupancies, these are not required. Only a very small percentage of buildings have extraordinary provisions for unusual circumstances and there is a limit to the events that can be handled and the strength capacities that can be provided. Defense facilities, nuclear power plants, and overseas embassies are just a few examples where special strengthening features are requested by building owners in the design and engineering of their facilities.

The WTC towers were the first structures outside of the military and the nuclear industries whose design considered the impact of a jet airliner, the Boeing 707. It was assumed in the 1960s design analysis for the WTC towers that an aircraft, lost in fog and seeking to land at a nearby airport, like the B-25 Mitchell bomber that struck the Empire State Building on July 28, 1945, might strike a WTC tower while low on fuel and at landing speeds. However, in the September 11 events, the Boeing 767-200ER aircraft that hit both towers were considerably larger with significantly higher weight, or mass, and traveling at substantially higher speeds. The Boeing 707 that was considered in the design of the towers was estimated to have a gross weight of 263,000 pounds and a flight speed of 180 mph as it approached an airport; the Boeing 767-200ER aircraft that were used to attack the towers had an estimated gross weight of 274,000 pounds and flight speeds of 470 to 590 mph upon impact.

Including aircraft impact as a design load requires selecting a design aircraft, as well as its speed, weight, fuel, and angle and elevation of impact. Figure 1-10 compares the design characteristics of several large aircraft that were in use or being planned for use during the life of the WTC towers. The maximum takeoff weight, fuel capacity, and cruise speed shown for each class of aircraft are presented for comparison of relative sizes and speeds. The larger square represents the floor plan area of the WTC towers (approximately 207 feet by 207 feet), and the smaller square represents a more typical size for a high-rise building. The likelihood of a building surviving an aircraft impact decreases as aircraft size and speed increase. The Airbus A380 is expected to be flying in 2006. Its weight and fuel capacity are approximately three times those of a 767-200ER. The security of aircraft is critical to the safety of high-rise and all other buildings; aircraft security measures should be commensurate with the size and potential risk posed by the aircraft.

The decision to include aircraft impact as a design parameter for a building would clearly result in a major change in the design, livability, usability, and cost of buildings. In addition, reliably designing a building to survive the impact of the largest aircraft available now or in the future may not be possible. These types of loads and analyses are not suitable for inclusion in minimum loads required for design of all buildings. Just as the possibility of a Boeing 707 impact was a consideration in the original design of WTC 1 and WTC 2, there may be situations where it is desirable to evaluate building survival for impact of an airplane of a specific size traveling at a specific speed. Although there is limited public information available on this topic (Bangash 1993, DOE 1996), interested building owners and design professionals would require further guidance for application to buildings.

1.5.3 Overview of Fire-Structure Interaction

Control of structural behavior under fire conditions has historically been based on highly prescriptive building code requirements. These requirements specify hourly fire resistance ratings. A popular misconception concerning fire resistance ratings for walls, columns, floors, and other building components is that the ratings imply the length of time that a building component will remain in place when exposed to an actual fire. For example, a 2-hour fire-resistant wall is often expected to remain standing for 2 hours if exposed to an actual fire. However, the time to collapse of such a wall in an actual fire may be greater or less than 2 hours. The standard method of test to evaluate fire resistance (ASTM E119) is a comparative test of relative specimen behavior under controlled conditions and is not intended to be predictive of actual behavior. Further, the results of the ASTM E119 test do not consider actual conditions such as member interactions, restraint, connections, or situations where damage to the structural assembly is present prior to initiation of the fire.

1.5.3.1 ASTM E119 Standard Fire Test

Building code requirements for structural fire protection are based on laboratory tests conducted in accordance with the Standard Test Methods for Fire Tests of Building Construction and Materials, ASTM E119 (also designated NFPA 251 and UL 263). Since its inception in 1918, the ASTM E119 Standard Fire Test has required that test specimens be representative of actual building construction. Achieving this requirement in actual practice has been difficult because available laboratory facilities can only accommodate floor specimens on the order of a 14-foot x 17-foot (4.3-meter x 5.2-meter) plan area in a fire test furnace. The specimens do not account for impact damage to fire protection coatings. For typical steel and concrete structural systems, the behavior of specimens in an ASTM E119 fire test does not reflect the behavior of floor and roof constructions that are exposed to uncontrolled fire in real buildings. The ASTM E119 fire endurance test exposes the test specimen to the time-temperature relationship shown in Appendix A, Figure A-9.

In contrast with the structural characteristics of ASTM E119 test specimens, floor slabs in real buildings are continuous over interior beams and girders, connections range from simple shear to full moment connections, and framing member size and geometry vary significantly, depending on structural system and building size and layout. Even for relatively simple structural systems, realistically simulating the restraint, continuity, and redundancy present in actual buildings is extremely difficult to achieve in a laboratory fire test assembly. In addition, the size and intensity of a real uncontrolled fire and the loads superimposed on a floor system during that exposure are variables not investigated during an ASTM E119 fire test. Many factors influence the intensity and duration of an uncontrolled fire and the likelihood of full design loads occurring simultaneously with peak fire temperatures is minimal.

The ASTM E119 Standard Fire Test was developed as a comparative test, not a predictive one. In effect, the Standard Fire Test is used to evaluate the relative performance (fire endurance) of different construction assemblies under controlled laboratory conditions, not to predict performance in real, uncontrolled fires.

1.5.3.2 Performance in Actual Building Fires

Extensive fire research in the United States and the international community established that the temperatures generated during an actual fire, represented by a time-temperature curve, is not only a function of the fire load, but also the following:

- ventilation (air access through the windows, doors, and heating, ventilation, and air conditioning [HVAC] system)
- compartment geometry (floor area, ceiling height, length to width to height ratios)
- thermal properties of the walls, floor, and ceiling construction
- combustion characteristics of the fuel (rate and duration of heat release)

International research in the past 30 years has substantiated the importance of ventilation rates. It is now recognized that two entirely different types of fires can occur within buildings or compartments. The first is a “fuel surface controlled fire” that will develop when compartment openings are sufficiently large to provide adequate combustion air for unrestricted burning. Such fires will generally be of short duration and the intensity will be controlled by the fire load and its arrangement.

The second type of fire is “ventilation controlled” and will develop when the compartment openings are not large enough to allow unrestricted burning. Such fires will burn longer than fires controlled by the amount of surface fuel. Fires in large spaces often burn in ventilation controlled and fuel surface controlled regimes, at different times during the fire and at different locations within the enclosure.

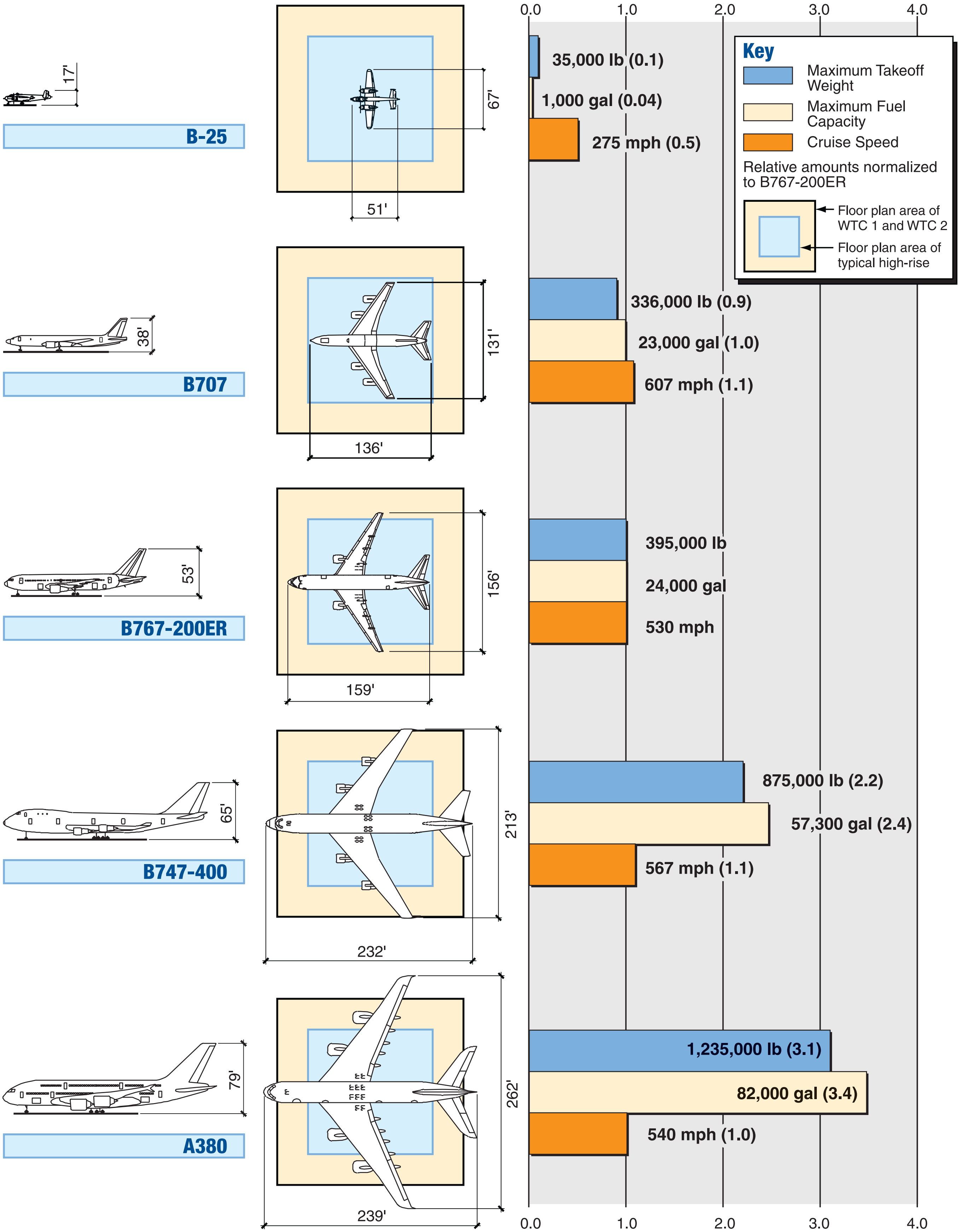

Figure 1-10 Comparison of high-rise building and aircraft sizes.

These real fires contrast with building code requirements for fire resistant design, which are based on a presumed duration of a standard fire as a function of fire load and building occupancy, height, and area. The severity of actual fires is determined by additional factors, which are not typically considered in building codes except as an alternate material method or equivalency when accepted by the enforcing official (the authority having jurisdiction). Although there have been a number of severe fires in protected steel buildings, including the three described in Appendix A, Section A.3.1.3, the team is unaware of any protected steel structures that have collapsed in a fire prior to September 11. However, none of the other fire events had impact damage to structural and fire protection systems. Recent fire research provides a basis for designing more reliable fire protection for structural members by analytical methods that are becoming more acceptable to the building code community. Such methods were not available when the WTC buildings were designed in the 1960s.

1.6 Report Organization

All seven WTC buildings, the Bankers Trust building, and other buildings that sustained major impact and/or fire damage from the attacks on the WTC towers are discussed in detail in this report. Information is presented about building performance documented during this study, as well as findings and recommendations for each building, as appropriate.

In order to simultaneously conduct multiple investigations into each building, a Chapter Leader was assigned as a lead coordinator and author for each chapter or appendix. This approach allowed a high level of productivity and resulted in a different writing style for each chapter. Additionally, the scope and level of detail varies considerably between chapters. The two major factors that define chapter content are the type and level of damage a building suffered and the availability of building information during this study, including damage documentation, structural and architectural plans, fire protection systems, building contents, and modifications made during occupancy.

This report opens with an executive summary, followed by the Introduction (Chapter 1), which documents the purpose and scope of this report; the events and actions that occurred on September 11, 2001, at the WTC site; and background information on the building design and codes.

The WTC buildings are presented in Chapters 2 through 5, and are grouped by types of construction and damage. Chapter 2 presents observations, data, and the results of preliminary analyses conducted on each tower (WTC 1 and WTC 2). Chapter 3 briefly discusses the hotel (WTC 3) performance for two severe debris impact events from the collapsing towers. Chapter 4 includes WTC 4, 5, and 6, because all three buildings are of similar construction and experienced fire damage from debris. Chapter 5 presents observations, data, and preliminary analyses of WTC 7, which also suffered a complete collapse. Chapter 6 describes how the Bankers Trust building arrested a local collapse on the north side that was initiated by debris impact from the collapse of WTC 2. Buildings adjacent to the WTC site that sustained major damage are presented in Chapter 7 (Peripheral Buildings). Chapter 8 presents observations, findings, and recommendations for each building, as well as overall recommendations based on the collective assessment of individual building performance and related issues.

The following appendixes are included to allow development of pertinent issues and topics without interrupting the flow of the report:

A – Overview of Fire Protection in Buildings

B – Structural Steel and Steel Connections

C – Limited Metallurgical Examination

D – WTC Steel Data Collection

E – Aircraft Information

F – Structural Engineers Emergency Response Plan

G – Acknowledgments

H – Acronyms and Abbreviations

I – Metric Conversions

The reader should be aware that English units are the primary system of measurement in this report, except where temperature information is presented, such as in the discussion of fire protection systems. Temperatures are presented in degrees Celsius, followed by degrees Fahrenheit. This approach allows for ease of reading by general audiences while retaining the measurement system preferred by fire protection engineers.

1.7 References

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