

# **Lessons Learned from the World Trade Center Disaster about Critical Utility Systems**

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## **Introduction**

The terrorist attack on the World Trade Center in New York City on September 11, 2001, was unprecedented in terms of damage to and repercussions for civil infrastructure for an event not related to declared military operations. There were 2,830 people killed and 10 major buildings destroyed or subjected to partial collapse. Approximately 2.8 million square meters of commercial office space were removed from service, of which 1.1 million belonged to the World Trade Center complex (Federal Emergency Management Agency, 2002).

The World Trade Center site is located within an intricate complex of infrastructure systems. It is important, therefore, to assess the consequences of such severe damage on the interdependent systems connected to the site.

In this paper, the consequences of the World Trade Center disaster on civil infrastructure systems is explored, and a summary of performance is given for water supply, electrical power, telecommunications, natural gas, and steam energy. The effects of water distribution system damage on fire fighting are addressed. The characteristics of damage and systems performance

resulting from the World Trade Center disaster are compared with those of other major incidents in New York City. Preliminary conclusions are drawn with respect to causes of damage, factors affecting the spread and constraint of damage, and factors that contribute to both the resiliency of urban infrastructure and the attendant services necessary to respond effectively to extreme events.

### **Buildings**

The building performance at the World Trade Center complex has been described in considerable detail (Federal Emergency Management Agency, 2002), and only select features of the building response are described herein. On September 11th, two hijacked aircraft were flown into the World Trade Center towers. At 8:46 a.m. the north face of the north tower (WTC 1) was struck, and at 9:03 a.m. the south face of the south tower (WTC 2) was struck. At 9:59 a.m. and 10:29 a.m., WTC 2 and WTC 1, respectively, collapsed.

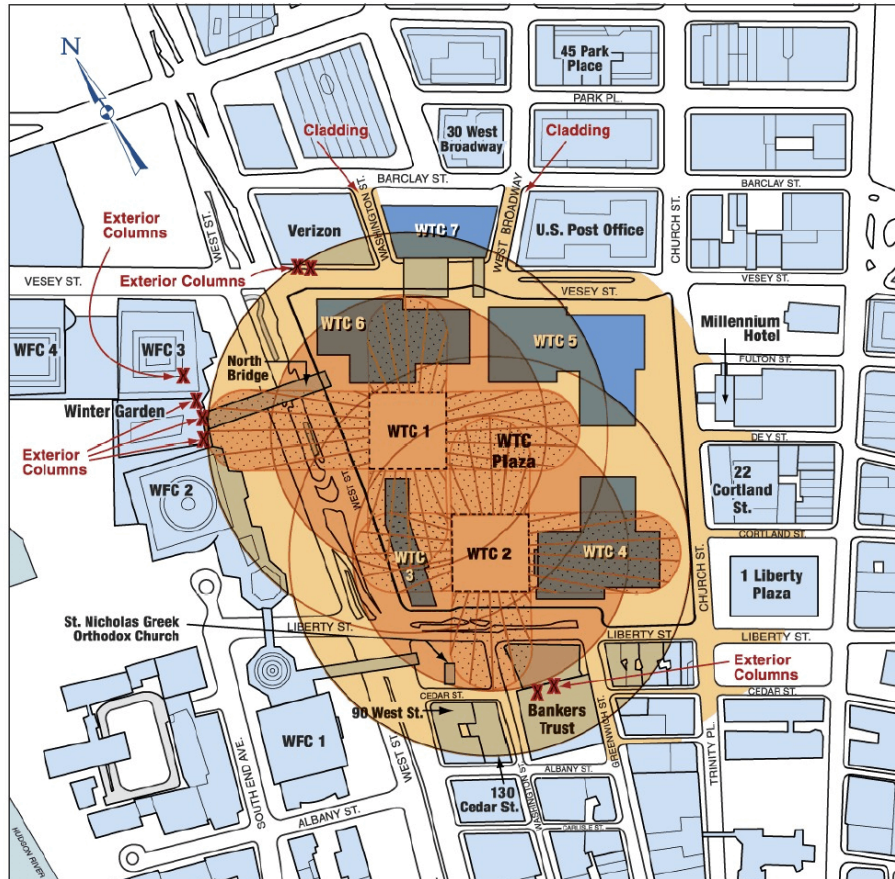
Figure 1 shows the area of the collapse debris impact as depicted by FEMA (2002). Buildings surrounding the towers are also shown, with special emphasis (dark shading) provided for those that were destroyed as a consequence of being struck and/or ignited by debris from the collapsing towers. The inner circles indicate the approximate radius of inner steel column collapse and other heavy debris. The outer circles indicate the approximate radius of fallen aluminum cladding and other relatively light debris. Of special interest for electric power and telecommunications are WTC 7 and the Verizon Building located along Vesey St. immediately north of the World Trade Center complex.

Figure 2 is a map of the buildings surrounding the complex as published by FEMA (2002). The map shows the damage assessment of surrounding structures based on the inspections of 406 buildings on September 14 and 15 by New York City structural engineers. The building inspection procedures and damage classification were adopted from guidelines developed for rapid assessment of buildings after earthquakes (ATC, 1989).

As noted above, the damage to buildings was of unparalleled proportions for a disaster perpetrated independently of official military operations. Of significance also was the damage sustained by other civil infrastructure systems, which are described briefly in the following sections of this paper.

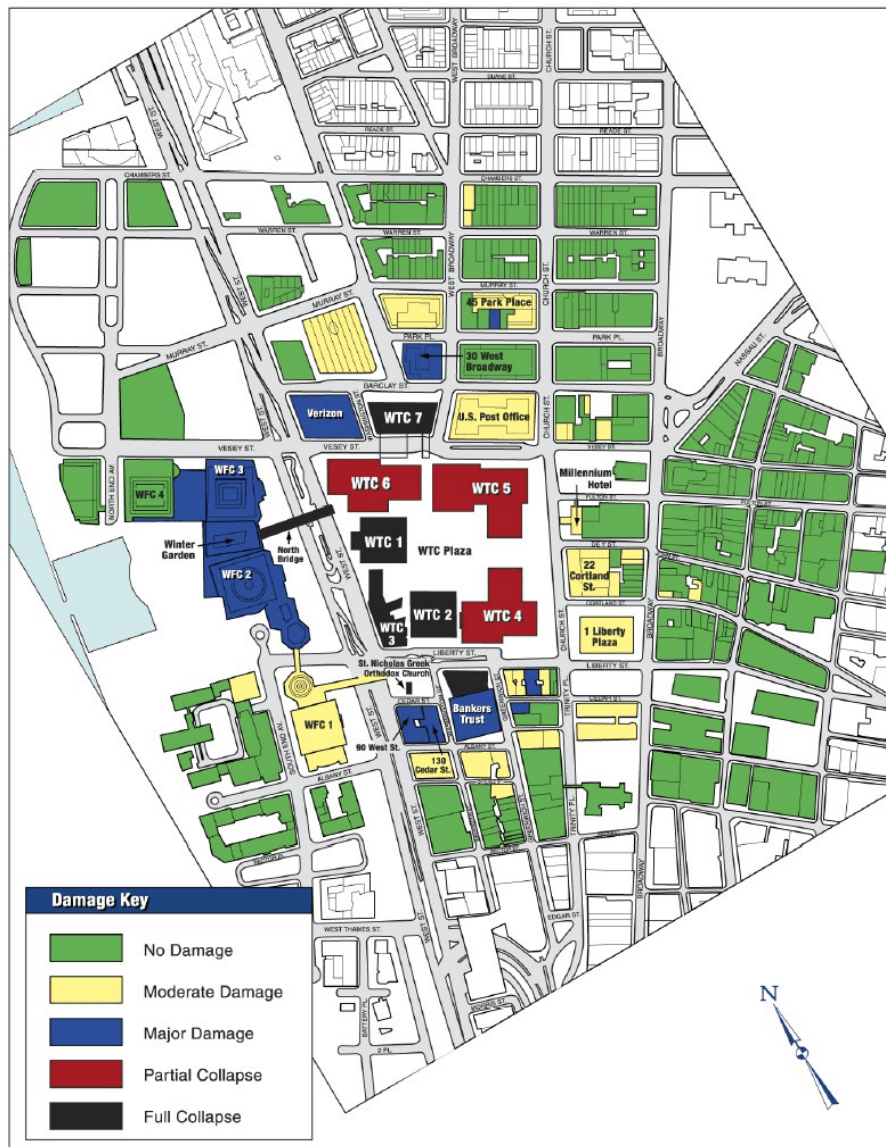
### **Water Supply**

The New York City water supply is maintained and operated by the New York City Department of Environmental Protection (DEP). About 90% of water provided to New York City is conveyed through City Water Tunnels 1 and 2, which were commissioned in 1917 and 1938, respectively. Since



**Figure 1. Schematic depiction of areas of collapse debris impact (after FEMA, 2002).**

commissioning, neither tunnel has been dewatered for inspection, so their state of repair can only be inferred indirectly. City Tunnel 1 is the backbone of supply for Manhattan. It is about 183–213 meters below street surface and transmits water to the distribution pipeline system through riser shafts. Some valves in the tunnel and shafts have not been used in many years, and no attempt is made to operate them because of concerns about malfunctioning and corresponding impact on the system. A third tunnel, City Tunnel 3, is currently under construction, and will supplement supply and allow for dewatering sections of City Tunnels 1 and 2 for maintenance and repair.



**Figure 2. New York City DDC/DoB cooperative building damage assessment map of November 7, 2001 (after FEMA, 2002).**

Four shafts in lower Manhattan provide water for the distribution system that serves the World Trade Center area and nearby neighborhoods. The shafts are equipped with regulators to decrease pressure to a level compatible

with the capacity of the trunk and distribution pipelines. Continuous flow measurements are performed at each shaft. Because the pressure at each shaft is regulated, the resulting flow measurements provide accurate data on rate of flow at constant pressure.

Collapse of the towers and the subsequent collapse of WTC 7 resulted in about 10 locations of ruptured water mains within the disaster area. These locations do not include the loss of a 406-millimeter-diameter water main that was situated beneath the complex. Damage to 508-millimeter- and 305-millimeter-diameter water mains was caused primarily by direct impact from collapsing structures and falling debris.

On September 11th, maximum total water flow recorded at four shafts in lower Manhattan was 7,140 liters per second compared with 5,610 liters per second on September 10. This resulted in an increase of 1,530 liters per second relative to normal usage. Water from the shaft closest to the World Trade Center site accounted for about half the increased flow relative to normal usage. However, the usage was not normal on September 11th. A close inspection of the DEP flow measurements shows water demand from the four shafts declining to about 4,380 liters per second before the collapse of the towers. After collapse, water flow jumped to 6,790 liters per second, and then rose gradually to a peak of 7,140 liters per second. The initial jump of 2,410 liters per second represents water lost through broken water mains beneath and surrounding the complex. The additional 350 liters per second represents the draw from fire hydrants that were used to fight fires in adjacent buildings.

An independent assessment of water drawn from the distribution system was made by interviewing deputy fire chiefs who were in command on the eastern and western sides of the complex. The chiefs were able to identify hydrants, hoses, and fire engines used at the site from which it was estimated that approximately 280 liters per second were being drawn from the water distribution system. Hence, the estimate obtained from fire department commanders and the rate shown by the flow measurements are in reasonably good agreement.

Water pressures at hydrants adjacent to the World Trade Center complex declined throughout the afternoon. Measurements performed by DEP at 6 p.m. show pressure two to three blocks from the site at a level approximately one-third of that under normal conditions. Fire fighting was impaired by the declining pressures. From about 6 p.m. to 2 a.m., DEP personnel shut gate valves in the pipeline network surrounding the site to isolate damaged pipelines from the rest of the system. Isolating the broken mains restored pressure in the intact system outside the perimeter of closed gate valves.

The area initially isolated was relatively large to provide sufficient coverage and confidence that the then-unknown locations of damage would be included within the isolated zone. The area was bounded on the north by

Murray St., and on the east by Broadway (see Figure 2). The isolation area extended to the western side of the World Financial Center and as far south as Morris Street. The isolation zone was eventually reduced to include only the streets immediately adjacent to the World Trade Center complex.

### Fire Fighting

Fires at and adjacent to the World Trade Center complex were fought in essentially two theaters of action. On the eastern side, three tower ladders were deployed to attend to fires at World Trade Center 4, 5, and 7. In the afternoon of September 11th, the decision was made to abandon World Trade Center 7, which collapsed about 5 p.m.

On the western side, fires were fought primarily with water from the Hudson River, which is two to three blocks from the complex. The New York City Fire Department, Marine Division, dispatched four fire boats to the site: *Firefighter* (1,260 liters per second capacity), *John D. McKean* (1,200 liters per second capacity), *Smoke II* (130 liters per second capacity), and *Kevin C. Kane* (410 liters per second capacity). The *McKean* arrived within 15 minutes, just before the second aircraft struck WTC 2. The *Smoke* arrived shortly thereafter. Initially, the *McKean* and *Smoke* were used to ferry wounded and fleeing people to New Jersey City. Between approximately 10 and 11 a.m., the four fire boats took up positions. The *Firefighter* docked on the Hudson River at Vesey Street. The *Smoke* and the *Kane* docked in North Cove, and the *McKean* docked on the Hudson River at Albany Street.

A review of the pumping records, interviews with Marine Division personnel, and inspection of high resolution aerial photographs were used to estimate the amount of water supplied to the World Trade Center complex and surrounding buildings. All fire boats were pumping at high capacity from the Hudson River. However, not all the water was relayed to fire engines. Excess water, unable to flow through hoses and land-based equipment, was discharged into the river without specific measurement. Hence, the fire boat pumping records do not provide a direct measure of water actually used at the site, but an upper-bounds estimate. An alternate estimate was made by obtaining information about the number of hose lines deployed from each boat, and approximating the flow based on hose diameters and distances from boats to fire engines that were relaying the water.

The estimated total flow during September 11th from Marine Division equipment is between 630 and 1,260 liters per second, with the actual value likely to be closer to 630. Hence, fireboats played an important and highly significant role in suppressing fires on and immediately after September 11th. During the critical hours following the collapse of the towers, they provided from two to four times the amount of flow that was pumped from intact water distribution mains near the site.

## Electric Power

Almost all the electric power for New York City is supplied by the Consolidated Edison Company of New York, Inc. (Con Edison). Con Edison serves the densest electrical **load pocket** in the world. It supplies over 3.1 million customers in an area of 1,564 square kilometers served by more than 145,000 kilometers of underground distribution cable and 255,000 manholes and service boxes. Within New York City electric power is transmitted by high voltage cables (typically 138-kilovolt), which are encased in butyl-oil-filled steel pipelines. They connect with electric substations where the power is converted to low voltage (27- or 13.8-kilovolt) feeders. Con Edison uses a **distribution network** concept. The networks are grids supplied by the 13.8-kilovolt feeders that cover anywhere from several city blocks to several square kilometers. The networks are mostly underground, beneath the streets and sidewalks. The Con Edison system includes about 55 distribution networks within the city limits, of which 33 are in Manhattan. Each network is independent of its neighboring networks and is fed from multiple distribution feeders. Con Edison has 50% of all the distribution networks in the world, and its engineers are experts who often act as consultants for other distribution networks.

Because each distribution network is virtually independent, local damage usually will not affect the operation of other networks. Moreover, there is redundancy in the number of 27- or 13.8-kilovolt feeders supplying a given network. Even if multiple feeders are lost, there is reserve capacity to sustain power. The basic design of the network system provides for overall high reliability. According to Con Edison representatives, the annualized power outage per customer is 2.6 minutes in Manhattan compared with a U.S. national average of 111 minutes.

Debris falling from the collapse of WTC 1 damaged and ignited WTC 7, which contained two electric substations. Approximately one hour before the collapse of WTC 7, the New York City Fire Department requested that the substation be de-energized. Con Edison had been preparing for this event and power was immediately shutdown to three networks. The World Trade Center complex had lost power earlier in the morning as a direct result of the fires in the twin towers. The substations were totally destroyed when WTC 7 burned and collapsed. This collapse also resulted in damage to five 138-kilovolt cables. The faults generated by the damaged cables triggered switches that disconnected an additional substation at the lower east side of Manhattan. Thus, five local distribution networks lost power as a result of the events. A sixth network, which services the New York Stock Exchange area, lost six

13.8-kilovolt feeders. It continued to function from the remaining ten feeders, which supplied the local distribution network from a substation located north of the World Trade Center complex. The total power loss throughout all affected portions of the system was approximately 450 megawatts.

Restoration of power to the lower west side of Manhattan involved running 58 kilometers of 13-kilovolt cables above ground from areas that had power to the areas that did not have power. This process was completed in eight days. The first network was restored in three days by this method.

Restoration to the lower east side of Manhattan required that the 138-kilovolt cables into the complex be isolated and repaired. Cable repair involved freezing the butyl-oil-filled pipelines with liquid nitrogen, cutting both the pipeline and three cables contained in each pipe, then capping the cables and pipes, filling and pressurizing each pipe with oil, and soaking the cables. The first damaged 138-kilovolt cable was restored by the morning of September 17.

Con Ed crews worked 24 hours a day to complete the restoration work. Con Ed also set up 82 mobile diesel generators, each with a capacity of 1.2 to 1.8 megawatts, throughout lower Manhattan to supply emergency power to parts of Wall Street, Battery Park City, the Merchantile Exchange, and World Financial Center. The combination of emergency generators and repairs to the area's power system were required to be ready for opening of the New York Stock Exchange on Monday, September 17.

### **Telecommunications**

A major telecommunications central office is located immediately north of the World Trade Center complex at 140 West Street, known as the Verizon Building. The structure was built in 1928 and is 32 stories high. Telecommunications equipment was located on the 1st through 9th floors. A cable vault, transformers, generator, and fuel tanks were housed in the five basement levels of the building.

Verizon claims that the telecommunications capacity of the 140 West Street central office was one of the largest in the world and equivalent to that of Austria, Denmark, and Egypt combined. The building housed four digital switches, 500 optical transport systems, 1,500 channel banks, 17,000 optical fiber lines, 4.4 million data circuits, and 90,000 message trunks.

The building was damaged from the collapse of WTC 1 and WTC 7. Damage from the collapse of WTC 7 was especially severe on the eastern side from about the 9th floor down where most of the telecommunications equipment was located.



The worst physical damage to telecommunication facilities occurred in the cable vault and on the 1st, 4th, 7th, and 9th floors. The emergency 911 system failed instantly, but switched to a back-up node at the Verizon central office at Metrotech, Brooklyn. Due to the 911 design, switching occurred immediately, and the new center never missed a call. There were approximately 38,000 calls on the 911 system on September 11th, which is 71% higher than normal volume.

Three class 5ESS switches were located on the 7th floor, and one was located on the 9th floor. Each switch consists of 40 frames and supports 60,000 customer lines. Remarkably, there was very little direct physical damage to the switches. Telecommunication equipment is designed and operated in compliance with the Network Equipment Building System (NEBS) standards (e.g., Verizon Communications, 2001). These standards have been developed with significant input from experience during natural disasters, including the 1989 Loma Prieta and 1994 Northridge earthquakes. In general, the telecommunication equipment remained intact and continued to function at reliable levels even though severe damage was sustained by the structural and building elements surrounding them. Three of the four switches were scheduled for replacement within two years of the disaster because dust had entered the equipment, clogging the filters and impairing reliable operation. Dust also had a deleterious effect on the turbines and cooling systems within the building.

Steel beams and debris, primarily from the WTC 2 collapse, penetrated the cable vault on West Street, severing 70,000 copper pairs and additional fiber optic lines. Water flooded the cable vault. Nearly 41,600 cubic meters of water had to be pumped from the vault during recovery. There was also water damage on the 7th and 9th floors where fire fighters sprayed water on adjacent buildings.

As a result of the damage, Verizon lost 200,000 voice lines, 100,000 private branch exchange (PBX) lines, 4.4 million data circuits, and 11 cell sites. Over 14,000 business and 20,000 residential customers were affected.

Telecommunications traffic was switched from the Verizon Building to other central offices. Of special importance were the Security Industry Data Network (SIDN) and the Security Industry Automation Corporation (SIAC) circuits that are used to execute and confirm block trades on the stock exchange. These circuits were necessary to resume trading and financial activity. The SIDN and SIAC circuits were rerouted from a central office in mid-town Manhattan to by-pass the Verizon Building. This was accomplished by routing traffic through a facility north of the World Trade Center complex to another large central office in lower Manhattan, from which they were connected with the New York Stock Exchange.

AT&T lost two local transport nodes in WTC 2, which burned and collapsed. Two other network switches located in the vicinity of the

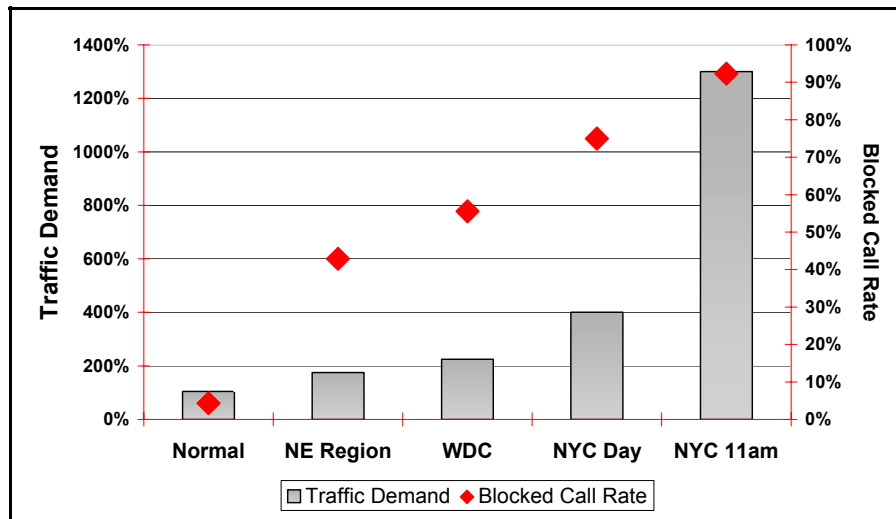
complex were not accessible because of damage, evacuations, and response activities. The equipment was powered down as the offices were evacuated to provide for easier restoration of service later. Telecommunication equipment showed resilience similar to that in the Verizon Building. AT&T Internet Protocol transport and other equipment in a sub-basement level of WTC 2 continued to work even after the building collapsed.

As a result of the disaster, the two largest AT&T local transport nodes in New York City were destroyed. Six other transport nodes in Manhattan were fully functional, and were rapidly configured to reroute traffic. In all, two switches were lost due to building collapse; two others were temporarily out of service because of lost power. Seven other switches in Manhattan remained in operation.

Two switches were restored by the fourth day after the attack, an optical remote module was upgraded to a full switch within six days, and a third local switch was restored within 18 days. Broadband wireless capacity was established whenever possible. Within 24 days of the attack, 24 38-gigahertz radio systems, including antenna and back-up equipment, were deployed throughout the affected area.

A team of telecommunication companies, brokerages, exchanges, and municipal leaders, in combination with federal authorities, developed a plan to restore services so that the New York Stock Exchange could be reopened on September 17. Reliable telecommunications service could have been supplied on Friday, September 14. However, brokerages and financial banking institutions with offices adjacent to the World Trade Center complex could not have been linked to the New York Stock Exchange on that date because of disrupted telecommunication services. These organizations were potentially at a significant competitive disadvantage. Additional routing of cables and fiber optic lines to connect with these organizations was performed over the weekend to prepare for the opening of the stock exchange.

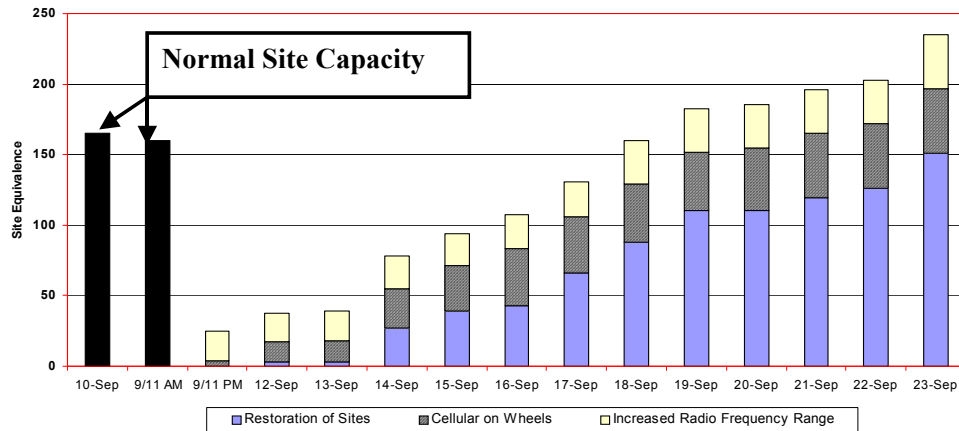
On September 11th the wireless telecommunication industry experienced a 50% increase in call attempts nationally. In contrast, calls increase nationally by about 30% on Mother's Day. Figure 3 shows a bar chart of wireless traffic demand and blocked call percentages for normal conditions in contrast with September 11th conditions for the northeastern United States, Washington, D.C., and New York City areas averaged over the entire day, and New York City at approximately 11 a.m.. In the 9–11 a.m. period on September 11th, there was an approximate 1,300% increase in wireless call attempts experienced by one carrier before the call-count administrative controls were discontinued to support call processing.



**Figure 3. Cellular traffic and blocked call rate on September 11, 2001 (after Condello, 2001).**

At 11 a.m., roughly 92% of wireless calls were blocked in the New York City area. Restoration of wireless service was rapid, as shown by the plot of equivalent site capacity near the World Trade Center complex versus time in Figure 4. Equivalent capacity to restore lost wireless sites was provided by restoring sites; deploying portable wireless cells, known as cellars on wheels; and increasing the radio frequency range allocated to telecommunication providers.

Emergency operations were underway at Verizon, AT&T, and other telecommunication providers immediately after the attack. AT&T, for example, followed a strict and well-rehearsed telephone system protocol in which command-and-control operations were established with multiple technical bridges from upper management to personnel in the field. All telecommunications facilities in the World Trade Center area were secured, and services were restored using the Telecommunications System Priority (TSP) program (National Coordinating Center for Telecommunications, 2002) to assure that critical services received the highest priority. The TSP program is the administrative and operational framework, overseen by the Federal Communications Commission (FCC), for priority restoration and provisioning of telecommunication services in times of crises and events that threaten the U.S. population and national security. Large AT&T trailers containing telecommunications equipment were mobilized and placed in service at a site in New Jersey within 48 hours of the attack.



**Figure 4. Restoration of cellular telecommunications in the vicinity of the World Trade Center (after Condello, 2001).**

Redundant, dispersed facilities and the ability to rapidly by-pass damaged central offices were key aspects of the telecommunications performance. Verizon reports that it was able to process approximately twice the normal daily volume of cell phone calls on September 11th.

### Wireless E-mail

Discussions with representatives of the New York City Mayor's Office, FEMA Region II, and the Port Authority of New York and New Jersey confirm that cell phone and landline voice communications were impaired by delays and busy signals after September 11th. To facilitate emergency communication, the IBM Crisis Response Team assisted both the Red Cross and New York City Mayor's Office after the disaster. The team organized a secure information system for the Mayor's Office with linkages to wireless e-mail. The e-mail system employed BlackBerry handheld units operating on the Cingular Mobitex system. IBM distributed about 70 units to the Mayor's Office and approximately 11 units to the New York State Governor's Office.

Cingular lost connectivity to most of its base stations in lower Manhattan because of failed telecommunication interconnections and interruption of electric power. Service, however, was able to continue because the handheld devices simply roamed to other non-affected base stations in New Jersey and Brooklyn that provided overlapping coverage to lower Manhattan.

The e-mail system is based on the transmission of information packets, each of which may travel by different routes and be separated in time intervals

that exceed those required for voice messages. Because e-mail is asynchronous, message routing is more flexible and able to accommodate heavy traffic more easily than voice communication, which requires synchronous transmissions. Therefore, e-mail communications experienced less disruption than voice communications.

The wireless e-mail system also has queuing capability. If a message is not sent because of congestion, there is an automatic retry algorithm built into the system so that transmissions initially delayed are sent. In a voice network there is no queuing. The e-mail system is also able to save messages so that retrieval can occur at significant lengths of time after initial transmission.

The use of handheld e-mail devices greatly facilitated communications and contributed to substantial improvements in efficiency. Some advantages of wireless e-mail communication that were identified by handset users include reliability and consistency. Communications are not impeded by background noise, which can be troublesome with voice communication in emergency situations. E-mail communications are in text format so no notes have to be taken. Note taking can be difficult when using voice communication devices in the field. Moreover, e-mail messages are automatically logged and can be archived for future record keeping.

### **Natural Gas Distribution**

New York City is served by a natural gas distribution system that involves over 10,000 kilometers of pipelines. Natural gas distribution in Manhattan is provided by Con Edison through approximately 1,000 kilometers of underground piping.

After the towers collapsed, Con Edison crews were dispatched to the disaster area. The gas company personnel could gain access to only a limited number of curb valves to turn off gas flow because debris, vehicles, and equipment were blocking access. To ensure stoppage of gas flow into areas of greatest damage and because of uncertainties regarding the extent of damage, a relatively large section of the distribution network was isolated. Isolation was performed by cutting and capping mains until an area, which was bounded by Chambers Street, Broadway, Rector Street, and the Hudson River, was disengaged from the remainder of the system. The isolation process required approximately 24 hours.

Leakage on September 11th was confirmed in the near vicinity (within one block) of the complex at only four locations at which steel and cast iron mains were situated. Most of these locations coincide with areas of fallen debris and projectile penetration of street cover.

The gas distribution network was restored by returning service successively to nine different sectors. Sectors at the perimeter of the isolated area were restored first, followed by those closer to Ground Zero. The last

sector, which surrounds the complex, was not restored for over a year after the disaster because of ongoing construction and the absence of customers who did not re-occupy their businesses. About 90% of gas service was restored within one week of the disaster. There were about 300 Con Edison personnel engaged in the isolation and restoration efforts, working 24 hours per day.

### **Steam Energy**

New York City is served by a steam energy system consisting of seven steam generating plants and over 160 kilometers of steel transmission and distribution pipelines. The system is operated by Con Edison. The pipelines are typically 254 to 762 millimeters in diameter, and are operated at internal pressures of 1,360 to 2,720 kPa and temperatures of 212 to 246°C. The steam is used for heating, cooling, and processing.

There was damage to several steam pipelines surrounding the World Trade Center complex caused by structural collapse or direct hit by projectiles and falling debris. A 762-millimeter-diameter steam line within the complex was lost. Steam line ruptures in 406- to 610-millimeter-diameter lines were confirmed by video inspection at four locations. On several streets adjacent to the complex, where building damage was especially severe, steam pipelines were cut and capped with no inspection.

Monitoring stations within the distribution network showed a steady drop in steam pressure after the towers collapsed. By 11 a.m. on September 11th, the decision was made to shut down the steam distribution network south of Grand and 7th Avenue in order to preserve service in areas unaffected by damage. The area isolated was chosen conservatively to be sufficiently large to cover locations of damage that were unknown at the time. It was also chosen to expedite the isolation process. In the vicinity of Grand and 7th Avenue, the system configuration was such that only five valves were shut to isolate approximately 30% of the system in lower Manhattan.

It took six days to restore most of the steam service to lower Manhattan. There were several temporary boilers installed and run for several weeks to supply buildings disengaged from the network. Several new mains were installed. The steam system in the immediate vicinity of the complex remained isolated for over a year after the disaster because of construction in damaged buildings and the continued absence of customers who once had occupied the area.

### **Other Incidents**

Two incidents that occurred in New York City before September 11th are used here to show the potential for escalating damage originating from the

failure of a single component. There have been similar incidents in other cities. The incident descriptions are taken directly from O'Rourke (1993).

### **Hellgate Incident**

On December 29, 1989, a 750-millimeter-diameter gas transmission line exploded in the Hellgate area of the Bronx, New York. The explosion killed one person and injured six others, who had been working with a backhoe near the pipeline. The explosion and fire severely damaged a recycling plant, shattered windows, forced the evacuation of several nearby buildings, including a regional bus terminal. If confined to the nearby area, this incident would be regarded as serious by any standard. The accident, however, had much greater repercussions.

Heat and fire from the pipeline caused all electric power to be shut off at the adjacent Hellgate Plant. This cut off electricity to about 135,000 customers, including households and entire buildings, and blacked out an area of 5 square kilometers on the upper east side of Manhattan and 7.5 square kilometers in the Bronx. Traffic lights switched off, forcing substantial traffic jams. The loss of electricity suspended service on eight separate subway lines. Although the trains operate on direct current from the third rail, the station lights and track signaling run on utility-supplied electricity. Evacuation of the bus terminal near the fire left 200 buses stranded. As a result, there was severe disruption of bus service on 12 routes in Manhattan and the Bronx.

The accident occurred on Friday afternoon at about 2:00 p.m., just before the start of weekend rush-hour traffic before New Year's Eve. Hundreds of thousands of commuters were left stranded and a similar number of businesses and buildings incapacitated by the blackout, which lasted from three to five hours over major portions of the city.

### **Garment District Incident**

On August 10, 1983, a 300-millimeter-diameter cast iron water main ruptured near the intersection of 38th Street and 7th Avenue. Water from the burst main flooded an underground electric substation, shorting electric circuits and touching off an immense fire. Loss of the substation blacked out approximately 3 square kilometers, including the Garment District and neighboring areas of the city. This involved over 10,000 customers, including Macy's and Gimbel's Department Stores. The blackout affected the telephone company central office, interrupting telecommunication service to tens of thousands of customers until emergency power was switched on. Phones using electric utility power were lost for a considerably longer time.

The accident occurred during Market Week in the Garment District, when most out-of-town buyers come to New York City to order next year's spring

clothing lines. Direct and indirect business losses during this critical time have been estimated in the tens of millions of dollars.

Fire in the substation caused heat so intense that firefighters could not approach the blaze directly, but had to attack it with more than 2,000 cubic meters of foam. The blaze flared up an air shaft, igniting the roof of a 25-story building. Burning transformers released polychlorinated biphenyls, thereby generating hazardous emissions. The fire took 16 hours to extinguish.

Electric power was not fully restored for over five days. Distribution substations are designed to operate in isolation from the remainder of the system to reduce the chance of one station's failure overloading neighboring substations. This isolation strategy means, however, that bypassing a given station cannot be accomplished easily. Power was diverted from other substations by the time-consuming process of splicing underground lines, all during a period when many electric utility workers were on strike.

It is clear from these incidents that there was sudden and extensive escalation of damage from an otherwise local event. This process of escalating damage was referred to by O'Rourke (1993) as the cascade effect. Figure 5 shows an event tree for the Garment District incident, which illustrates the cascade effect. The pipeline rupture at first caused local disruption through flooding and undermining in its vicinity. When the electric substation was flooded, causing fire, disruption was transferred to a much larger area by electric power outage. Loss of electricity, in turn, affected business, transportation, and telecommunications. The figure shows three principal tiers, or levels, of disruption generated by the pipeline failure. As the damage cascaded from one level to another, losses were sustained in increasingly larger and complex systems.

### **Lessons Learned**

The World Trade Center disaster was an immense and complex event. The lessons learned, as presented here, should be viewed as preliminary. Work is in progress to collect additional information that will lead to refinements in the databases and further clarification of the issues raised by the disaster. Lessons learned are summarized under the five subheadings that follow.

#### **Damage to Underground Facilities**

September 11th damage to underground water, gas, and steam pipelines and telecommunication conduits was caused by direct impact from falling debris or projectile penetration of the ground. There is no direct evidence of damage caused by ground vibrations and secondary effects, such as water hammer. There are records of gas leakage in streets traversed by heavy construction vehicles, but such instances were not exceptional or unanticipated by gas personnel. Virtually all damage of major consequence was the result of direct



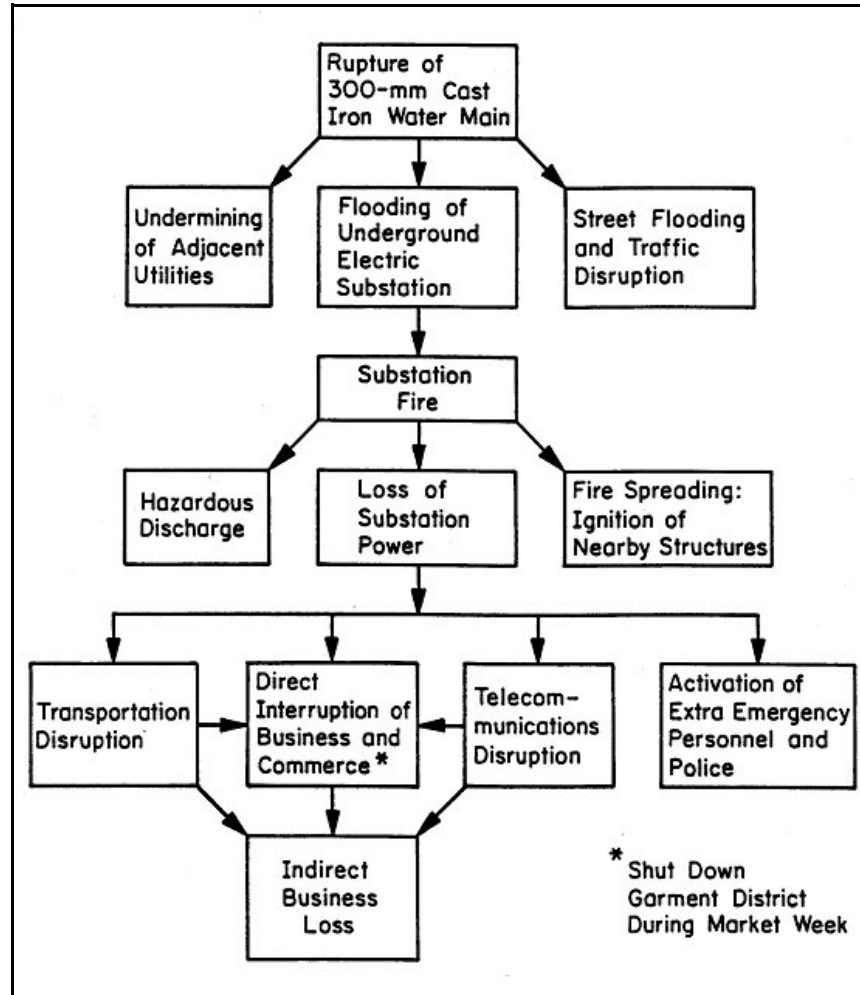


Figure 5. Event tree for Garment District incident (O'Rourke, 1993).

impact. Consequently, the areal extent of damage to critical water, telecommunications, gas, and steam conduits was confined principally to the zones of debris impact (see Figure 1). This lesson is significant for establishing planning and emergency response scenarios. It indicates that underground infrastructure damage from building collapse will likely be confined within the near vicinity of the failed structures.

### **Loss of Infrastructure Systems**

Although physical damage to water, gas, and steam pipelines was confined principally to the area of debris impact around the World Trade Center, the temporary loss of these systems extended far beyond this perimeter. After collapse of the towers, damaged zones of the water and steam systems had to be isolated to preserve pressure and flow in undamaged sections. Gas pipelines had to be shut off to suppress leakage and potential ignition. Because the extent of damage was unknown, conservative decisions were made about the size of the isolation zones. The initially isolated portions of the water, gas, and steam systems covered approximately 0.8 square kilometer, 1.2 square kilometers, and 3.4 kilometers, respectively. One to two weeks were required to restore the isolated zones, with the exception of the damaged conduits immediately adjacent to the World Trade Center site.

In extreme events, conservative decisions under emergency conditions are likely to result in a substantial zone of temporarily lost service. For planning purposes, significant system disruptions should be anticipated.

### **Water Supply**

Damage to water distribution pipelines surrounding the World Trade Center site was sufficiently severe that pressure losses interfered with fire fighting until isolation of damaged water lines could be achieved. Between two and four times the amount of water taken from distribution pipelines was supplied from fireboats during the critical hours after collapse of the towers.

The World Trade Center experience is similar to experience gained during the 1989 Loma Prieta earthquake. Water supplied by fire boat and relayed with a Portable Water Supply System (PWSS), consisting of hose tenders and above-ground hydrants, was responsible for suppressing the fire in the Marina and averting a much more serious conflagration (O'Rourke, 1993). The deployment of fireboats and the strategic use of bay water plays a critical role in emergency earthquake planning for San Francisco, Oakland, and Berkeley, California, as well as Vancouver, British Columbia. The September 11th experience supports a similar strategy for extreme events of non-earthquake origin. Fire boat deployment and implementation of PWSS concepts should be considered for supplying water under extreme emergency conditions. Water supply from fireboats to land-based locations is especially important where significant damage to the distribution pipeline system has occurred or where the capacity of the system to deliver water is limited.

Substantial amounts of water were supplied to World Trade Center sites at significant distances inland. Experience in the San Francisco Bay Area during and after the Loma Prieta earthquake (O'Rourke, 1993) reinforces the World Trade Center experience and demonstrates that water can be conveyed rapidly from marine locations for distances of 1 to 1.5 kilometers, provided

that appropriate planning and equipment acquisition have been undertaken. In a post-September 11th world, it is important to include marine-based fire protection as part of strategic planning for disaster response.

The New York City fire boats with greatest pumping capacity were commissioned in 1938 and 1954. When decisions are made for commissioning new fire boats, it will be advantageous to provide for pumping capacity that is comparable to or exceeds the capability of the current fleet.

### **Telecommunications**

As described above, redundant, dispersed facilities and the ability to rapidly by-pass damaged telecommunication nodes were important contributors to the performance of the telecommunications system. Even so, cell phone and landline traffic were impaired, and substantial repairs to the telecommunication service had to be made before reliable circuits were restored.

There are many central offices in lower and mid-town Manhattan. The proximity of many telecommunication facilities was a distinct asset during response and recovery. Similar configurations may not be present in other urban centers, thereby prompting consideration of additional facilities and dispersion of facilities where loss of business and commercial activity can have severe regional and national consequences. Special consideration should be given to facilities that affect urban, state, and national programs.

In general, the telecommunication equipment performed very well. The successful performance of telecommunication equipment encourages continued testing and evaluation of critical facilities, guided by observations of performance during extreme events.

The emergency procedures enacted by telecommunication companies worked well. The telecommunication industry operates with a formal, well-rehearsed protocol whereby command-and-control operations are rapidly established, with multiple communication pathways between upper management and field personnel. The U.S. telecommunications industry is served by a National Coordinating Center (NCC) that consists of government and industry representatives, who coordinate telecommunication services for national security and emergency preparedness. The NCC uses information sharing and analysis to evaluate the experience of industry participants, including lessons learned during emergency operations. The Network Reliability and Interoperability Council (NRIC) provides recommendations to the telecommunications industry and the FCC for operating telecommunication networks under various conditions, including natural disasters and both cyber (e.g., computer viruses, network intrusion, etc.) and physical attacks. The best practices, compiled by NRIC, have benefitted from lessons learned during previous natural disasters, including the Loma Prieta and Northridge earthquakes (e.g., Network Reliability Council, 2002).

Wireless e-mail proved to be a valuable asset after September 11th. The use of handheld e-mail devices greatly facilitated communications and contributed to substantial improvements in emergency response efficiency.

### **Electric Power Systems**

Perhaps the most important observation from the World Trade Center disaster and other incidents described in this paper is that damage becomes most pervasive when it interferes with the electric power system. Both the Hellgate and Garment District incidents show that power outages were responsible for major escalation of initial damage. The electric power system is, in effect, the gateway for local damage to escalate or cascade into other systems.

The effects of local damage appear to be influenced by the proximity of damage to an electrical substation. When damage affects a New York City substation, its potential for cascading consequences increases dramatically, but nonetheless is capped by the configuration of the electrical network. Because the New York City system is compartmentalized into local distribution networks, substation loss tends to be limited to the one or two local distribution networks that are linked to that substation.

Differently configured systems will not react to damage in the same way. In other systems, for example, damage may trigger switching stations that isolate several substations, thereby resulting in power loss over a substantial area. Other systems do not have the redundancy embodied in the New York City system so that loss of one or two transmission lines or primary distribution feeders may compromise a significant part of the overall network.

The damage on September 11th was so extensive that disruption spread through five distribution networks, with a sixth impaired through the loss of six 13.8-kilovolt feeders. Extensive isolation, repairs, and new feeder installation were required for power restoration to financial centers in lower Manhattan and the resumption of New York Stock Exchange activities. Rehabilitation on such a scale within the short time frame required for the resumption of financial trading activities was only possible through extensive stockpiling of specialized parts and the availability of many trained, highly motivated, and well-equipped staff. System resilience depended on organizational resilience that was embedded in the planning and preparations that had been developed for emergency response.

### **Brave New World**

The events of September 11th have changed not only the way we think about urban infrastructure, but the way we treat infrastructure information. In the “brave new world” after September 11th, knowledge is power both for those who wish to build and those who want destruction. It is therefore logical and responsible for the managers of infrastructure to be cautious about

providing information that involves critical facilities. The notable lack of maps (except those available at the FEMA website) and graphical details in this paper is a testament to this caution. Although detailed information was collected in the preparation of this paper, it is not appropriate for the authors to provide further details until review and clearance of the information can be obtained. Such clearance may take many months or longer.

To benefit from the revolution in information technology, it is necessary to have access to information. It is ironic that the power of information technology may seriously inhibit its beneficial use because we are unable to decide the intentions of those who wish to use it. From an engineering and scientific viewpoint, there has never been a more opportune time for advancing the state-of-the-art and practice for characterizing and modeling complex infrastructure systems. Advanced geographic information systems, remote sensing, condition monitoring, model-based simulation, and systems engineering coupled with the capability of producing precise digital base maps, which can integrate the spatial characteristics of infrastructure, provide unparalleled opportunities. Legitimate concerns about security and attendant restrictions on information are equally important factors that may become barriers, unless we develop suitable procedures for information accessibility and dissemination. It is extremely important to develop a consistent policy regarding the need to know versus the need to secure information and databases about critical infrastructure systems.

In addition to improved protocols for information accessibility, there is the need to integrate and utilize the talent and resources of those working on extreme events. As described in this paper, the rapid inspection procedures for buildings adjacent to the World Trade Center complex and the resiliency of telecommunications equipment can be attributed in part to experience gained from earthquakes. Collectively, the professionals and research specialists, who focus on natural disasters, have expertise in risk assessment for the built environment, design procedures under conditions of uncertainty, strengthening of structures for multiple loadings, simulation of complex infrastructure under various damage states, emergency response, and community recovery. Such expertise is an asset when developing procedures for countering terrorism. An effective approach to homeland security requires that the parties responsible for implementing security have the vision and intelligence to engage those involved in natural hazards. Homeland security should integrate and harmonize the technologies for mitigating natural and terrorist disasters to create communities resilient to all hazards.

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