The 1906 San Francisco Earthquake and Fire—Enduring Lessons for Fire Protection and Water Supply

C. Scawthorn,[a)] M.EERI, **T. D. O'Rourke,**[b)] M.EERI, **and F. T. Blackburn**[c)]

Prior to 18 April 1906 the San Francisco Fire Department and knowledgeable persons in the insurance industry regarded a conflagration in San Francisco as inevitable. The 1906 San Francisco earthquake and ensuing fire is the greatest single fire loss in U.S. history, with 492 city blocks destroyed and life loss now estimated at more than 3,000. This paper describes fire protection practices in the United States prior to 1906; the conditions in San Francisco on the eve of the disaster; ignitions, spread, and convergence of fires that generated the 1906 conflagration; and damage to the water supply system in 1906 that gave impetus to construction of the largest high-pressure water distribution network ever built—San Francisco's Auxiliary Water Supply System (AWSS). In the 1980s hydraulic network and fire simulation modeling identified weaknesses in the fire protection of San Francisco—problems mitigated by an innovative Portable Water Supply System (PWSS), which transports water long distances and helped extinguish the Marina fire during the 1989 Loma Prieta earthquake. The AWSS and PWSS concepts have been extended to other communities and provide many lessons, paramount of which is that communities need to develop an integrated disaster preparedness and response capability and be constantly vigilant in maintaining that capability. This lesson is especially relevant to highly seismic regions with large wood building inventories such as the western United States and Japan, which are at great risk of conflagration following an earthquake.
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INTRODUCTION

The fire in San Francisco following the 1906 earthquake was the largest urban fire in history up to that time, only being exceeded since, in peacetime, by the fire following the 1923 Tokyo earthquake. The earthquake and resulting fires caused an estimated 3,000 deaths and $524 million (in 1906 dollars) in property loss (http://www.sfmuseum.net/hist10/06timeline.html). Fires that ignited in San Francisco soon after the onset of the earthquake burned for three days because of the lack of water to control them. Damage in San Francisco was devastating, with 28,000 buildings destroyed, 80 percent of which were due to the fire rather than the shaking. Fires also intensified the loss at Fort Bragg and Santa Rosa, California.

[a)] Professor, Department of Urban Management, Kyoto University, Kyoto 606-8501 Japan
[b)] Professor, School of Civil & Environmental Engineering, Cornell University, Ithaca, NY 14853
[c)] San Francisco Fire Department (ret.), current residence: Bad Wildbad 75323 Germany

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For decades following the earthquake and fire, civic leaders and the public spoke of the event as "the Fire," attributing relatively little significance to the earthquake, even though it was one of the most important seismic events in history. To some extent, this focus on fire was driven by fear of losing investor confidence (Branner 1913). Nonetheless, most San Francisco damage in toto had been caused by the fire. One expert estimate, for example, ascribed as little as 5 percent of the city damage to direct earthquake effects (Dillman, quoted in Freeman, 1932) Studies of the earthquake and fire with respect to structures and structural materials (USGS 1907) focused as much on the fire as on the earthquake, finding that a number of engineered buildings had not been badly damaged by the earthquake and even, if well fireproofed, had survived the fire in reasonable shape. As a result, for many years the event was more popularly known as "the Fire," and earthquake provisions were not especially emphasized in building codes in California until after the 1925 Santa Barbara and 1933 Long Beach events.

This attitude was justified in many ways—fire was a major issue, not only in San Francisco before and after the earthquake, but in the United States in general. America in the nineteenth and early twentieth centuries in fact was burning, and the San Francisco fire and the response to that fire needs to be understood in that context. Toward that goal, this paper examines the fire-related aspects of the 1906 earthquake, not only in light of its time but also with regard to its implications for our cities today.

BEFORE THE EARTHQUAKE

Nineteenth-century urban America was highly flammable. Starting with the disastrous 1835 New York City fire, the United States was subjected to a series of urban conflagrations for the next 100 years—nine events from 1835 to 1905, for example, each involved the destruction of at least 1,000 buildings (Scawthorn et al. 2005). The largest of these events was the 1871 Chicago fire, which at 17,000 buildings lost was the biggest urban fire in history to that time; but Jacksonville, Florida, lost 1,700 buildings in 1901; Patterson, New Jersey, 525 buildings in 1902; Baltimore, Maryland, 80 city blocks in 1904; Chelsea, Massachusetts, 3,500 buildings in 1908; and Salem, Massachusetts, 1,600 buildings in 1914, to name a few.

These conflagrations were the result of a number of contributing factors, including the following:

- Highly flammable construction. New York following its 1835 "Great Fire" had defined and enforced a downtown zone in which no wood buildings were permitted. Most other cities, however, tolerated wood buildings in their "congested districts," resulting in "conflagration breeder" neighborhoods. Even larger commercial buildings had flammable wooden wainscoting, open stairwells, lack of compartmentation, and other features that made it only a matter of time.
- Inadequate fire protection. The fire service in the early twentieth century was still developing a professional capability. San Francisco was among the most progressive of U.S. cities when it created a paid department in 1866 (Postel 1992). Fire behavior was poorly understood, many firefighters lacked training, communications were poor and equipment was cumbersome. Still, with horses trained to

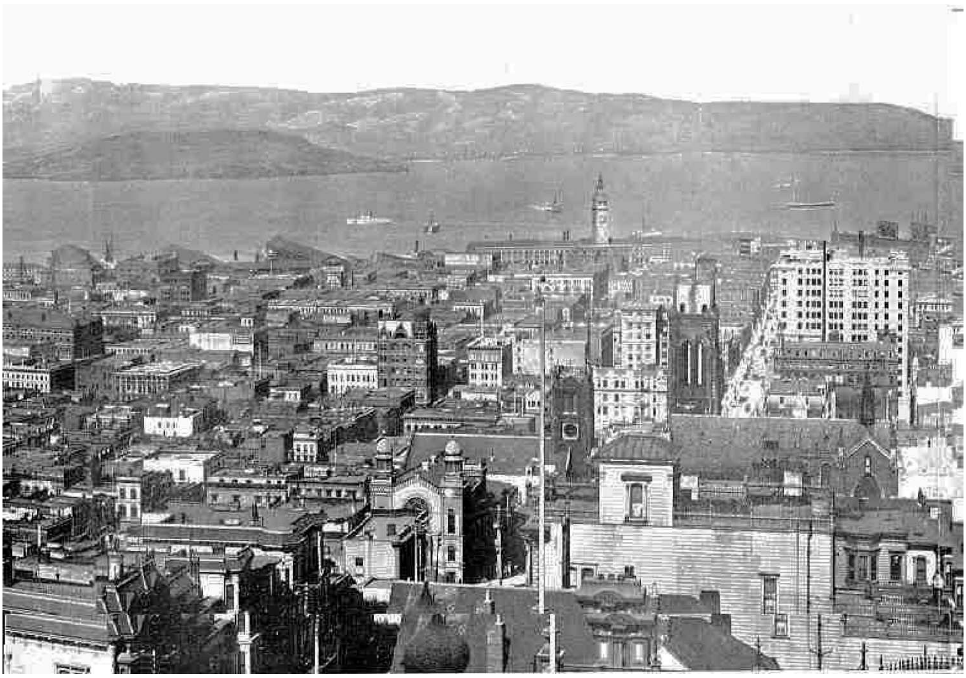

Figure 1. San Francisco in 1905.

walk into harness, and with telegraph alarms and steam pumpers, fire departments could protect cities under normal circumstances.

- Inadequate water supply. Most cities had not yet developed the reliable (distant) high-volume supplies we enjoy today—their supplies were local, highly variable, and carried through small-diameter weak pipes, which often failed when high demands were placed on them in emergency situations.

Studies by major fire departments, such as the New York City Fire Department (FDNY), drew attention to the danger: “The rapid development in all cities of modern technical industries has proven…a source of great danger…In all large cities, especially those of comparatively modern construction, the danger of fires is always greater….” (FDNY 1900). This was perhaps nowhere as true as San Francisco in 1905. As shown in Figure 1, there was a dense concentration of buildings on the eve of the earthquake, many of wood construction, with gas lighting and flammable contents.

Although little could be done about the flammable construction in the near term, high-value central business districts could be protected by a high-pressure water system, which both provided a reliable high-volume water supply and increased the effectiveness of the fire department. New York City was the first to adopt this measure, with the construction from 1903 to 1908 of a high-pressure hydrant system to protect the tall buildings and dry goods districts in Manhattan, tall buildings of downtown Brooklyn, and the amusement park and hotels of Coney Island; Boston, Philadelphia, and Baltimore followed suit.

San Francisco needed—and wanted—a high-pressure system. Its

> *Water supply is ample…but decided probability of local failure in emergency…the City is at present contemplating the installation of an independent system for fire protection, and $150,000 has been appropriated…The entire scheme is at present almost entirely prospective….* (*NBFU 1905*).

In lieu of a high-pressure system, the city had 23 cisterns varying in capacity from 16,000 to 100,000 gallons, maintained by the fire department.

For a disaster, the one in San Francisco is very well documented, including a detailed fire underwriting survey completed nine months before the earthquake. The survey (NBFU 1905) provides a detailed snapshot of the city, its construction and conflagration potential, water supply, and fire department. The San Francisco Fire Department in 1905 protected approximately 400,000 persons occupying an urbanized area of approximately 21 square miles. The department consisted of a total of 585 full-paid fire force personnel (resident within the city and on duty at all times), commanded by Chief Dennis T. Sullivan and deployed in 57 companies (38 engine, one hose, ten ladder, one hose tower, and seven chemical) (NBFU 1905). The distribution of these companies was well conceived, being centered about the congested high-value district (i.e., the central business district or CBD, known in San Francisco as the Financial District), with 24 engine, eight ladder, one water tower, and seven chemical companies within 2 miles of the center of the CBD. All but two of the 38 steam engine companies dated from 1890 or later, and were rated at an average of 680 gallons per minute (gpm), although the eight engines tested in 1905 averaged only about 70 percent of their rated capacity, and the "ability of the men handling the engines was in general below a proper standard." The rated pumping capacity of the 38 first line and 15 relief and reserve engines totaled 35,100 gpm. In summary, the department was rated by the National Board of Fire Underwriters (NBFU 1905) as efficient, well organized and, in general, adequate. For the factors noted above, however, the NBFU concluded that

> *…In fact, San Francisco has violated all underwriting traditions and precedent by not burning up. That it has not done so is largely due to the vigilance of the fire department, which cannot be relied upon indefinitely to stave off the inevitable.*

THE FIRE

The earthquake is well documented elsewhere in this volume and will not be discussed here, except to note that it occurred at 5:12 a.m. on 18 April 1906 and was approximately M_w 7.9. Within moments after the earthquake, Chief Dennis T. Sullivan was fatally injured in connection with a neighboring building collapsing onto the fire station where he was sleeping; he lingered for four days. Ten fire stations sustained major damage (S. Tobriner, pers. comm.), although the earthquake did not seriously damage any engines, which all went into service (Reed 1906). Street passage was in general not a problem, and a number of fires were quickly suppressed, although many more could not be responded to. The NBFU (Reed 1906) reported that

> *…fires in all parts of the city, some caused directly by earthquake, some indirectly, prevented an early mobilization of fire engines and apparatus in the valuable business district, where other original fires had started and were gaining headway.*

The NBFU concluded that even under normal conditions the multiple simultaneous fires would probably have overwhelmed a much larger department, such as New York's, which had three times the apparatus (NBFU 1905). Nevertheless, Bowlen (see Scawthorn and O'Rourke, 1989) concluded that by 1 p.m. (i.e., about eight hours after the earthquake)

> *…the fire department, except that it was without its leader, was in fairly good shape, that is the men and horses were in good trim for firefighting, the apparatus was in shape and could be worked where there was water. There is not one report of an engine or man going out of commission during the early hours of the fire, and the department was hard at work all the time, even though there was little to show for its effort.*

The number of fires and/or explosions after the earthquake has been estimated as between 50 (Reed 1906) and 52 (Scawthorn and O'Rourke 1989); locations can be seen in Figure 2. Fire growth is shown in Figure 3. The conflagration following the 1906 earthquake was a complex fire, actually consisting of several separate major fires that grew together until there was one large burned area, comprising the northeast quadrant of the city and destroying more than 28,000 buildings. The identification and location of fires involved in the 1906 conflagration was aided substantially by an undated manuscript prepared by F. J. Bowlen, a battalion chief at the time of the earthquake (Bowlen, n.d.; Scawthorn and O'Rourke 1989). The progress of these fires generally has been divided into four periods (Reed 1906; Bowlen, n.d.), although actual times for these periods differ among sources. Generally, the four periods comprise the following times: (1) from the earthquake until midday or late in Day 1, when most of the South of Market area had been destroyed, but the higher-value area north of Market still remained largely intact; (2) the night of Day 1 and the early hours of Day 2, when the area north of Market was invaded by the fire, progressing from the west; (3) continued progress of the fire to the north, and a bit to the south, during the remainder of Day 2; and (4) during Day 3, fire progression northward around Telegraph Hill to the bay, while contemporaneously spreading into the Mission Creek area. The fire mostly was spent or extinguished by the morning of April 21st, approximately four full days after the main shock of the earthquake.

With regard to fighting the fire, in 1906 SFFD engine companies consisted of a steam pumper plus a hose wagon with 700 feet of 2.75-inch or 3-inch hose (70 or 75 mm), and an officer plus 9 to 11 men, which allowed for rapid deployment of hose lines while the steam pumper was hooking up to a water supply. Typical fire department hose of the time was 2.5 inches (65 mm). SFFD's larger hose allowed higher flows with

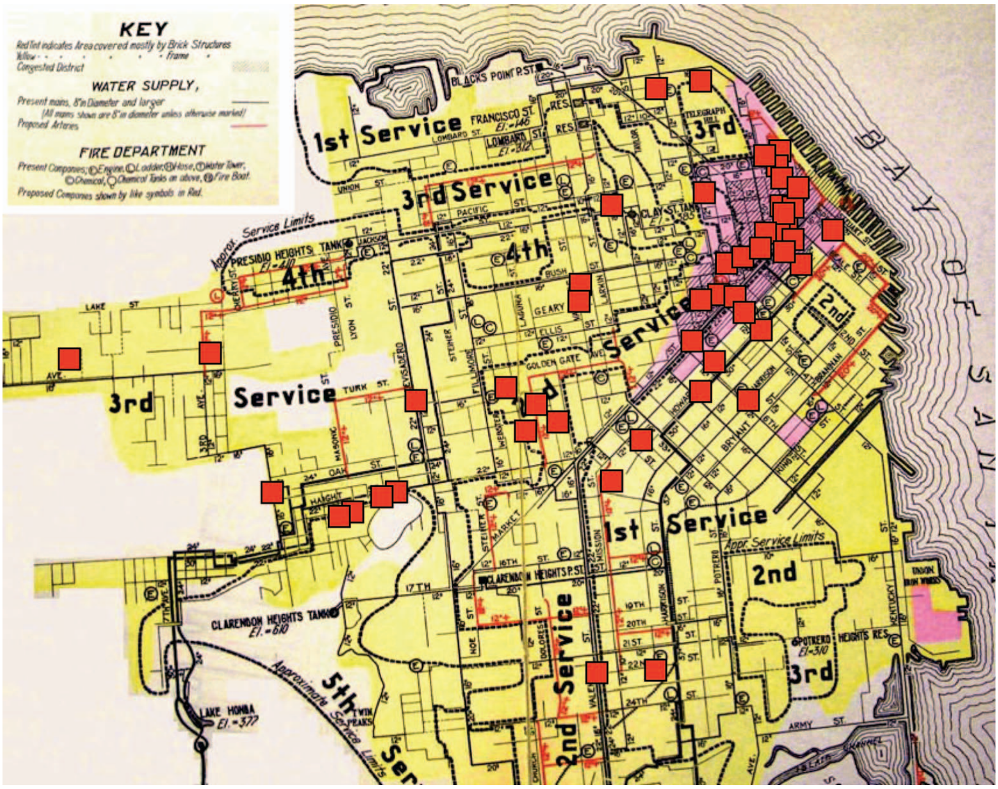

Figure 2. San Francisco in 1906: Black lines are 8-inch and larger water mains (thicker the line, larger the diameter). Yellow area is primarily wood-frame construction, while pink is primarily masonry; crosshatched pink area downtown is the "congested area," that is, the central business district. Ignitions following the 1906 earthquake are shown as red squares. (Adapted from NBFU, 1905) In color: see plates following p. S68.

much less friction loss, thus allowing higher efficiency in fighting fires. During the 1906 fire, engine companies were redeployed from area to area as the water supply gave out; with the large crew the company could rapidly pick up their hose and move to a new location. A major deficiency in 1906 was the lack of a fireboat for pumping large volumes from San Francisco Bay. Chief Sullivan in 1905 had proposed that the city purchase a fireboat, but the request was denied. In 1906 the SFFD had 23 underground cisterns in service, with capacities from 16,000 to 100,000 gallons, which proved invaluable during the 1906 fire, enabling the Montgomery Block building in the Financial District to be saved.

PERFORMANCE OF THE WATER SUPPLY

At the time of the earthquake, there was a combined volume of 88.7 billion liters in San Francisco's reservoirs on the San Francisco Peninsula. Within the city limits, there

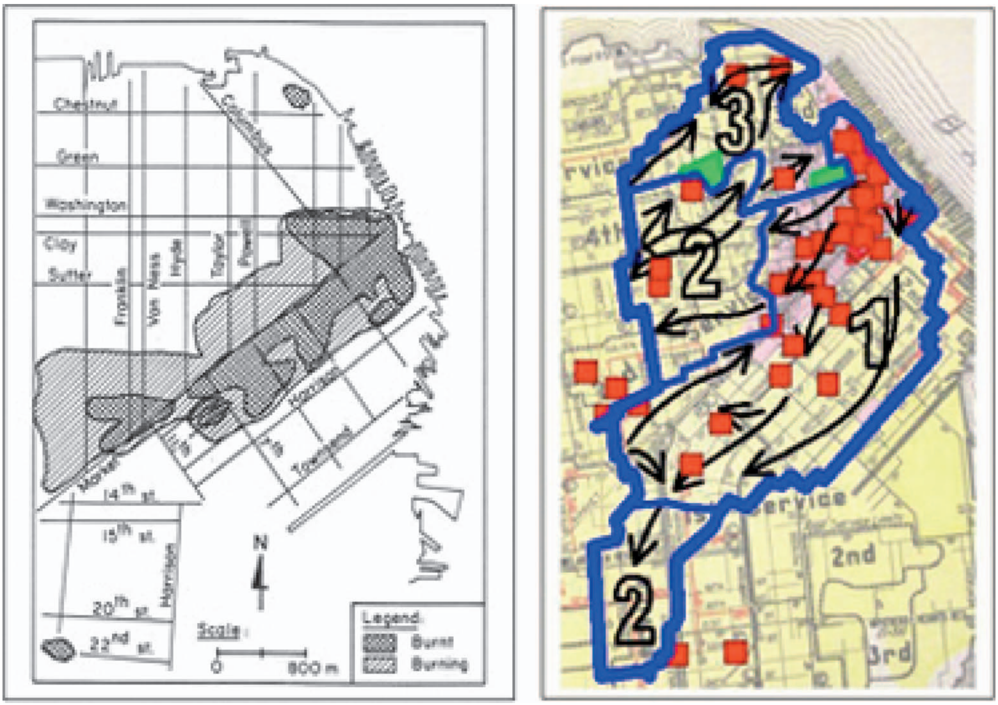

Figure 3. (left) Fires at about midnight April 18 (Source: Scawthorn and O'Rourke 1989); (right) Final burned area outlined in heavy line—arrows show fire path of fire spread, with general areas burned in Days 1, 2, and 3/4 indicated by numerals and divided by thinner lines. Green areas were not burned. In color: see plates following p. S68.

were approximately 711 km of distribution piping at the time of the earthquake, of which roughly 18.5 and 66.5 km were wrought- and cast-iron trunk lines, respectively, mostly constructed during the years of 1870 to 1906. Figure 4 shows the 1906 water supply within the San Francisco city limits, where nine reservoirs and storage tanks provided a total capacity of 354 million liters. All trunk lines 400 mm or larger in diameter are also plotted, as well as zones of lateral spread caused by soil liquefaction.

It can be seen that multiple ruptures of the pipeline trunk systems from the College Hill and University Mound reservoirs occurred in the zones of large ground deformation, thereby cutting off supply of over 56 percent of the total stored water to the Mission and downtown districts of San Francisco. Liquefaction-induced lateral spread and settlement ruptured two pipelines, 400 and 500 mm in diameter, across Valencia Street north of the College Hill reservoir, which emptied the reservoir of 53 million liters, thereby depriving fire fighters of water for the burning Mission District. With the College Hill and University Mound reservoirs cut off, only the Clay Street Tank and the Lombard and Francisco Street reservoirs were within the zone of most intense fire and were therefore capable of providing water directly to fight the blaze. The combined capacity of these

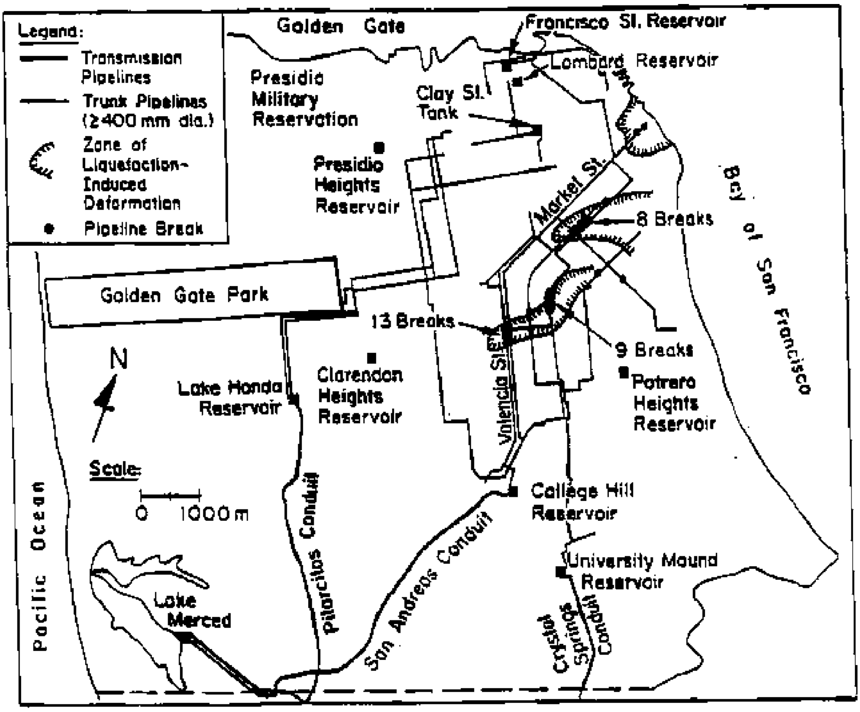

Figure 4. San Francisco Water Supply and effects of permanent ground deformation. (Source: Scawthorn and O'Rourke 1989)

reservoirs was only 21 million liters, or 6 percent of the system capacity (Figure 5). The usefulness of such limited supply was further diminished by breaks in service connections, caused by burning and collapsing buildings. Schussler identifies service line breaks as a major source of lost pressure and water. There were roughly 23,200 breaks in service lines that were between 15 and 100 mm in diameter. Fallen rubble and collapsed structures often prevented firemen from closing valves on distribution mains to diminish water and pressure losses in areas of broken mains and services.

Figure 6 shows the final burned area, relative to the water system and compared to the 1871 Chicago and 1904 Baltimore burned areas. The spatial relationship between unburned districts in San Francisco and availability of water implies that pipeline system integrity played a key role in limiting the spread of fire, and that areas suffering from ruptured pipelines fared poorly. This inference must be made with caution, however, since the development of the fire south of Market by mid-afternoon had resulted in a burning perimeter or flame front on the order of 7.5 km. Effective defense along this flame front would require on the order of 100 to 200 handheld lines, or virtually the entire steam engine force of the fire department. Even if effective, this ignores branding (i.e., fire spread by burning debris, flying over defense lines and causing fires behind the fire line) and does not consider whether the water supply system, if intact, could have

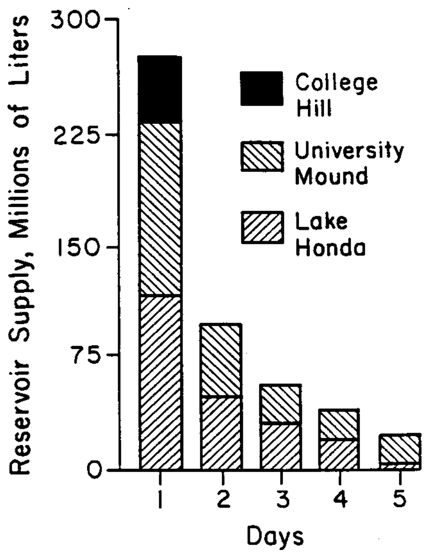

Figure 5. Reservoir storage in San Francisco as a function of time after the earthquake (after O'Rourke et al., 1992a)

furnished the required water (95,000 to 190,000 1/min.). Even if this defense had held, the firefighters, fully occupied south of Market, would have been outflanked by the "Ham and Egg fire,"[1] which did indeed sweep down from the west during the second period, outflanking the defending line along Market. Figure 7 shows a portion of the central business district following the fire—the "damnedest finest ruins."

The bar graph in Figure 5 shows the reservoir storage in San Francisco as a function of time after the earthquake. The amount of water corresponding to Day 1 represents the quantities available roughly two hours after the earthquake struck. After four days, less than one-tenth of the initial capacity of the College Hill, University Mound, and Lake Honda reservoirs still was available. Two factors were critically important in preserving flow. Sixteen hours after the earthquake, water was pumped from Lake Merced into the Pilarcitos pipeline to supply Lake Honda. This action provided an additional 25 million liters/day, thereby maintaining capacity in Lake Honda for distribution to the western parts of the city. After repairs of the San Andreas pipeline over three days, approximately 30 million liters/day were conveyed to the College Hill reservoir for distribution in the South Mission area of the city. By Day 5, approximately 55 million liters of water were flowing into the city, in addition to the 25 million liters still available in the reservoirs.

[1] Following the earthquake, someone "started a fire in a stove to cook breakfast, about 9 o'clock. The chimney had been rendered defective by the earthquake, and fire broke out. This fire [may] have burned over more territory than any other single fire." (http://www.sfmuseum.org/1906/kennedy.html)

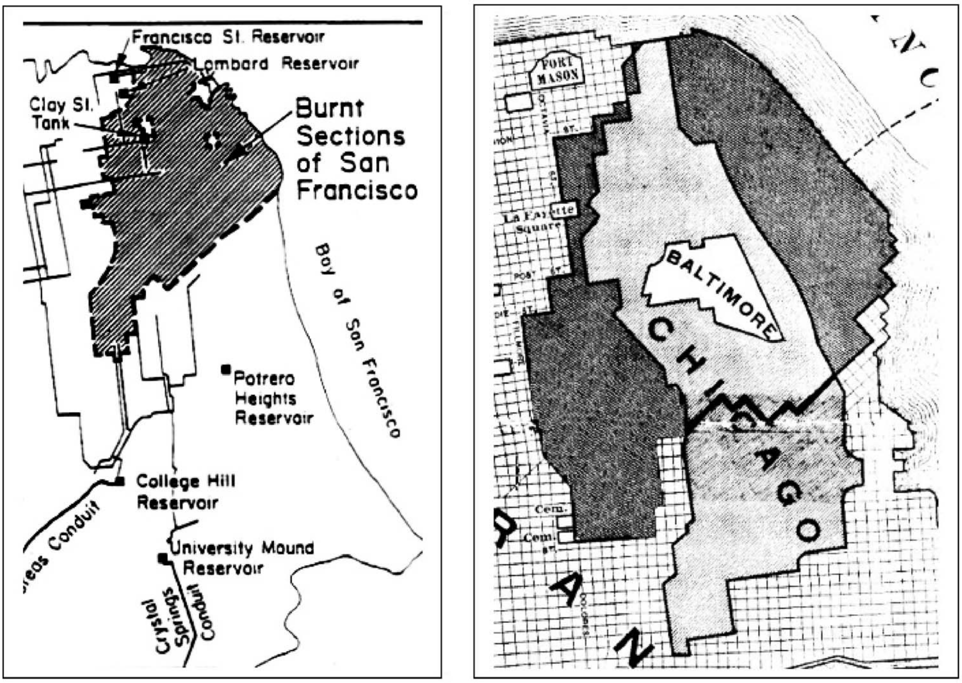

Figure 6. Final burned area: (a) overlaid on water system, and (b) compared with 1871 Chicago and 1904 Baltimore.

Figure 7. Portion of burned central business district (CBD), San Francisco

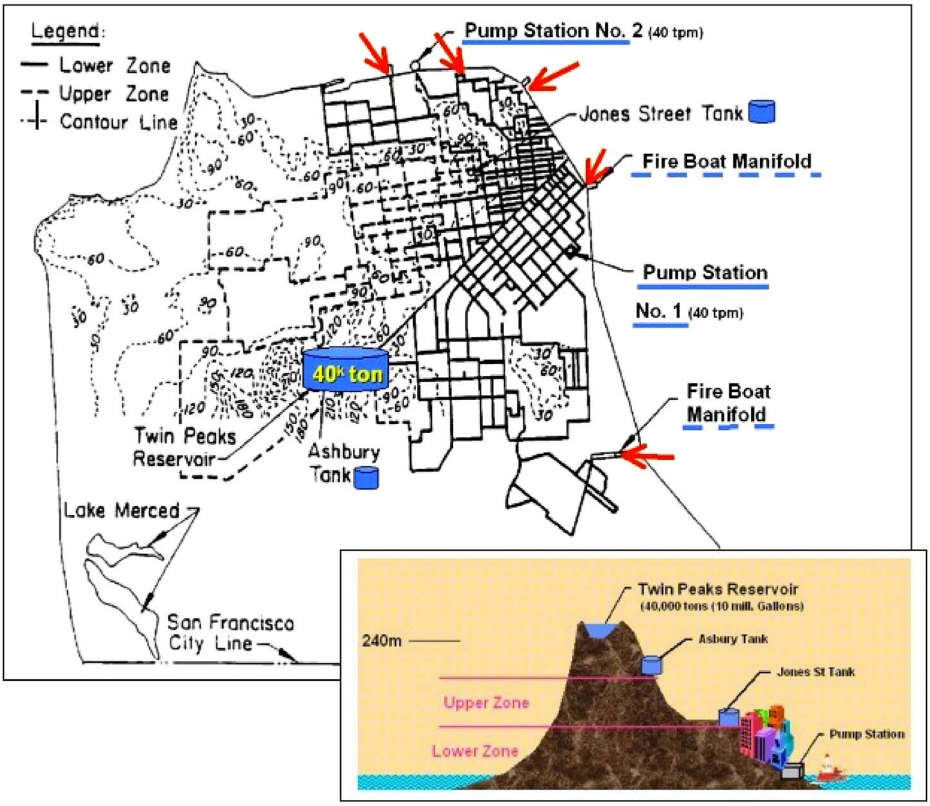

Figure 8. San Francisco Auxiliary Water Supply System (AWSS).

THE AFTERMATH AND THE AWSS

The size of the loss was a shock, of course, perhaps even more to insurers than to the citizens. The insurance industry reacted quickly, setting up a system for adjusting claims before the fires were out (Whitney 1906) and, in general, covering most of the losses, though many issues such as paying off claims for "burnt rubble" had to be dealt with. Being once burned, the insurance industry now demanded the construction of the high-pressure system Dennis Sullivan had called for, that is, if San Francisco ever wished to have an insurance policy written again. As a result, Marsden Manson (San Francisco city engineer) in 1908 proposed the Auxiliary Water Supply System (AWSS), which was developed with a $5.2 million bond issue and was largely completed by 1912. Space does not permit a detailed description of the AWSS here (see Scawthorn et al., 2005, and Markov et al., 1994, for a detailed description). In summary, the AWSS consists of several major components (see Figure 8):

- Static Supplies. The main source of water under ordinary conditions is a 10-million-gallon (40-million-liter) reservoir centrally located on Twin Peaks, the highest point within San Francisco (approximately 227 m or 750 ft. elevation).

- Pump Stations. Because the Twin Peaks supply may not be adequate under emergency conditions, two pump stations exist to supply salt water from San Francisco Bay; each has 10,000 gpm (667 l/s) at 300 psi (20.7 bar) capacity. Both pumps were originally steam powered but were converted to diesel power in the 1970s.
- Pipe Network. The AWSS supplies water to dedicated street hydrants by a special pipe network that by the end of the 1980s had a total length of approximately 120 miles (200 km). The pipe is bell and spigot, originally extra heavy cast iron (e.g., 1 in. or 25 mm wall thickness for 12 in. or 300 mm diameter), and more recent extensions are heavy ductile iron (e.g., .625-in. or 15-mm wall thickness for 12-in. or 300-mm diameter). Restraining rods connect pipe lengths across joints at all turns, tee joints, hills, and other points of likely stress.
- Fireboats. A major deficiency in 1906 was the lack of a fireboat to be able to pump large volumes from San Francisco Bay. Chief Sullivan's request in 1905 that the city purchase a fireboat had been denied. With the construction of the AWSS in 1912, two powerful steam fireboats were provided, each capable of pumping 10,000 gpm (40,000 l/s) into the AWSS system in addition to the two pump stations. The pipe network has manifold connections located at several points along the city's waterfront in order to permit the city's two fireboats to act as additional "pump stations," drafting from San Francisco Bay.
- Cisterns. SFFD in 1906 was finally able to establish a water supply along Van Ness Avenue, a natural east-west fire break as it is 150 feet wide. Water supply was from U.S. Navy ships and tugboats at the foot of Van Ness Avenue. The successful experience of cisterns in 1906 led to the construction between 1912 and 1940 of 128 75,000-gallon-capacity cisterns (200,000 liters, about one hour supply for a typical fire department pumper), every three blocks from SF Bay to Market Street and at other locations. Van Ness Avenue remains today as the major fire break in the northeast section of the city. Today San Francisco has 172 underground cisterns, largely in the northeast quadrant of the city but with newer cisterns in outer residential areas.

Having the Van Ness Avenue fire break is significant, since the building stock west of Van Ness, to and including Pacific Heights, is mainly wood frame and is virtually intact, as it was in 1906—large wood-frame buildings of three to four stories in height, a conflagration hazard. The area east of Van Ness Avenue, to Stockton Street, including Telegraph Hill, was completely burned off in 1906. In the rush to rebuild, it was reconstructed virtually as it was, recreating the conflagration hazard that previously existed. With occasional high winds, narrow streets and densely built wood-frame building of three to four stories in height, this section of San Francisco today is as significant a conflagration hazard as it was in 1906.

The AWSS is a remarkably well-designed system for reliably furnishing large amounts of water for firefighting purposes under normal conditions, with many special features to increase reliability in the event of an earthquake. A key aspect of San Francisco's ability to maintain and even extend this unique system is the fact that it is, by city charter, owned and operated by the fire department. The AWSS is intended as an auxiliary system, to supplement the use of the municipal water supply system for fighting large fires, under non-earthquake as well as earthquake conditions. This is an important point: it does not sit around for decades, waiting for an earthquake. Rather, the department uses it at most greater alarm incidents, thereby gaining valuable experience, confirming its continued functionality and reliability, and justifying the system's existence. Another point is that the underground piping system was designed from the beginning to be highly earthquake resistant—the piping is extra heavy walled and has restrained joints to resist pullout at numerous locations.

San Francisco has several areas of highly liquefiable soils; these were observed to fail in 1906 and to correlate with damage to underground piping. These locations were mapped with other areas of concentrated damage as "infirm ground" zones, and the system was designed so that, while AWSS pipe passes through these zones, the system can be quickly isolated should pipelines in those zones fail. Elsewhere in this volume, O'Rourke et al. describe liquefaction hazards in San Francisco and provide a map of the infirm zones that influenced the design and operation of the AWSS. In modern times, the gate valves isolating the infirm zones have been motorized and can be remotely controlled via radio. As a result of the elevation of the Twin Peaks reservoir, and the capacity of the pumping stations and the fireboats, very high pressures, in excess of 300 psi, can be sustained in the AWSS. This pressure assures a high volume supply, but is too high for many applications and can be reduced via Gleeson valves—a patented pressure reduction valve invented in the San Francisco Fire Department shops. The Gleeson valve permits a firefighter to attach one or several hand lines to an AWSS hydrant, and apply fire streams as if from a fire engine. Thus the AWSS reduces the need for fire engines and permits a continuous water curtain to be sprayed from a line of hydrants along a defensive line.

Designed almost a century ago with great foresight and skill, the San Francisco AWSS was intended to be a seismically reliable water supply system for fire protection. Most of the original pipeline was extra heavy cast-iron pipe with more recent installations using thick-walled ductile iron pipe with restrained joints at high thrust locations. It has been maintained for almost a century, and it embodies the key attributes of redundancy in supply and layout, reliability via layout and seismic design of components, flexibility in application, economy via reducing the need for fire engines and apparatus, and integration in the fire department's day-to-day operations. Even so, the 1989 Loma Prieta earthquake damaged a few components of the AWSS, which, coupled with human inaction, prevented the system from supplying water to the Marina fires, thus demonstrating that there is room for improvement.

FAST FORWARD—THE 1980S

By the early 1980s it was recognized that improvements in the AWSS were needed. Whole sections of the city had been developed since 1912, but the AWSS had not been extended to these new areas. The "infirm" zones still relied on manual response for isolation—the system might drain before a gateman could get to and isolate a break in the system. Portions of the system were in need of replacement. Pump Stations 1 and 2 had been built in 1912, and their seismic adequacy was not clear. More suction connections were needed around the city's waterfront. The city had been reduced to one fireboat—the Phoenix. Additionally, many of the city's firehouses dated from the 1920s to the 1950s, and their seismic adequacy was also not clear.

In response to these needs, several key actions occurred that mutually reinforced each other:

1. for the first time, computer-based simulation models of the entire fire following earthquake problem were developed, and applied to San Francisco (Scawthorn 1982)
2. a hydraulic model of the San Francisco AWSS was developed, taking into account earthquake damage (O'Rourke et al. 1992b)
3. SFFD developed a new system—the Portable Water Supply System (PWSS).

The simulation modeling of fires in San Francisco showed that the city, still composed largely of wood houses, was a major conflagration hazard. Modeling of the AWSS exposed major vulnerabilities in the water delivery system, which could seriously impair fire fighting after a future earthquake. The PWSS provided the means of addressing these problems. Both the fire simulation and the hydraulic network models had been developed in research supported by the National Science Foundation.

In 1985 these facts were presented to Mayor Diane Feinstein at a dramatic meeting in City Hall headed by Chief of Department Emmet Condon together with Chief Frank Blackburn and Charles Scawthorn (San Francisco 2005). The presentation included the simulation modeling of large conflagrations, the hydraulic network simulation results developed by Professors Tom O'Rourke and Mircea Grigoriu at Cornell University, and emphasized life safety, the impacts on the city's revenue base, and renewed concerns of the insurance industry (Scawthorn 1987). The mayor immediately grasped the situation and as a result, a new bond measure, Proposition A for $46 million, was placed on the ballot in 1987, was widely supported during the run-up to the election (see Figure 9), and passed with 89 percent voter approval, providing funding for rehabilitation and extension of the AWSS, construction of new cisterns, and seismic upgrade of the city's firehouses and other fire-related infrastructure.

An important provision of the 1987 bond measure was the installation of 42 motorized gate valves to allow any damaged sections of the AWSS, particularly in the "nine infirm areas," to be closed off. These gate valves are operated by battery power set in an underground vault. They can be operated via radio, the city's dedicated telephone line or by local control. Note that it was the break of one pipe in the infirm area South of Market that drained the Lower Zone in the 1989 Loma Prieta earthquake, leaving much of the city without fire water supply for several hours. It was only when the break could be isolated by manually closing valves, and the Lower Zone re-pressurized, that water supply was restored (Scawthorn and Blackburn 1990). Figure 10 shows the numerous

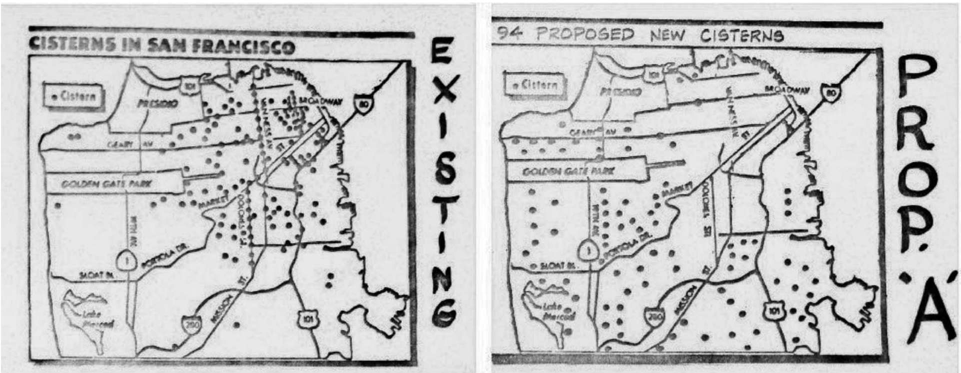

Figure 9. Excerpt from Public Information Sheet re 1987 Proposition A, showing (a) existing cisterns, and (b) 94 proposed new cisterns. To date, 31 new cisterns have been constructed.

breaks that occurred in the municipal water supply system in the Marina District (where the AWSS did not sustain any breaks), indicating how vulnerable ordinary piping is in such "infirm areas."

Another important provision of the 1987 bond measure was an additional 31 cisterns—San Francisco now has 172 underground cisterns strategically located

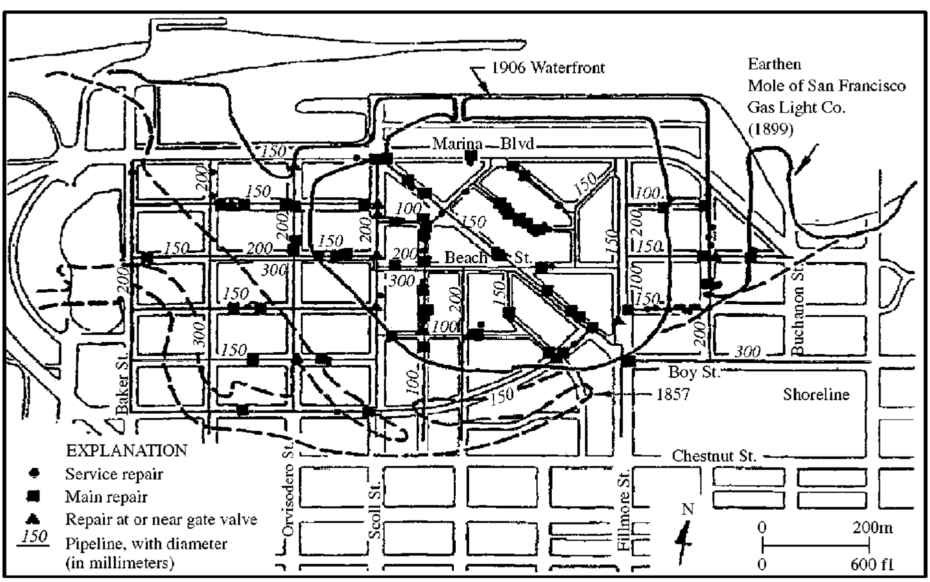

Figure 10. MWSS pipe breaks, Marina District, 1989 Loma Prieta earthquake. (Source: O'Rourke 1992)

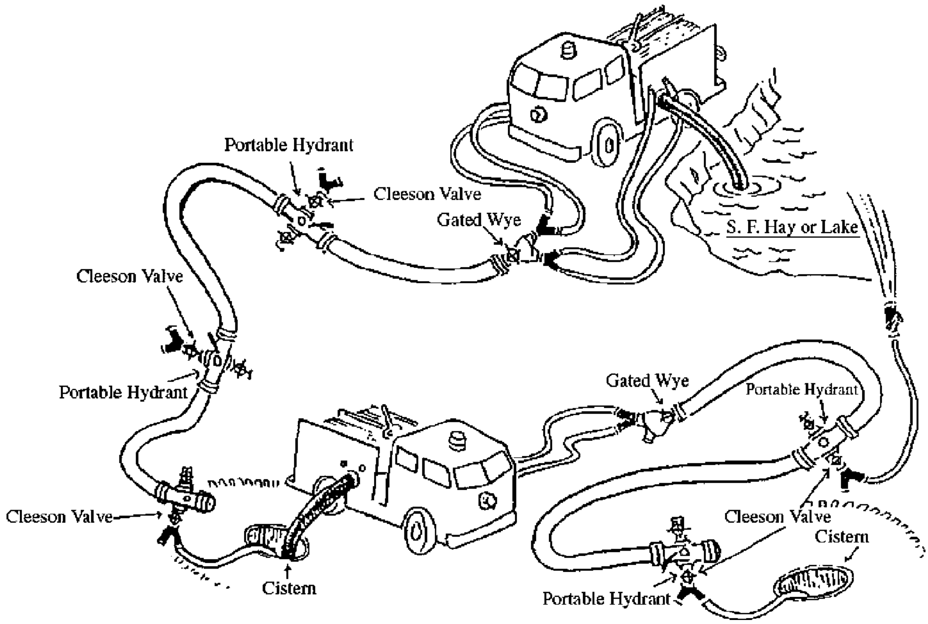

Figure 11. Portable Water Supply System (PWSS).

throughout the city. A former SF Water Department facility at 43rd and Santiago streets in the outer Sunset District has been converted to a 500,000-gallon (2-million liter) cistern in this highly congested outer residential district, and a 243,000 gallon (1-million liter) cistern is located at Grove and Polk streets, near City Hall. This cistern network allows the PWSS system to link up between cisterns to provide an above-ground Emergency Water Network following an earthquake. This is a critical asset for the city of San Francisco to keep fires from becoming conflagrations.

Although the PWSS was conceived of early in the twentieth century by SSFD Chief Dennis Sullivan (Postel 1992), it was not until the early 1980s that it was fully implemented under the leadership of SFFD Chief Frank Blackburn. The PWSS consists of a hose tender typically carrying approximately one mile (1.5 km) of large-diameter hose (LDH) (typically 5-in or 125-mm hose), portable hydrants, pressure reducing valves, wyes and other fittings, and hose ramps to permit vehicle passage over the LDH. Figure 11 shows a PWSS hose tender, with trailer-mounted HydroSub, a portable pump, capable of drafting or pumping water from ponds or other bodies of water. It is not well understood that water can only be practicably drafted a vertical distance of about 26 ft (8 m). If a bridge, seawall, pier or other access point is more than 26 ft (8 m) above the water, then a fire engine cannot draft the water—it must get closer, which is often difficult. To overcome this problem, several systems, such as the Dutch-manufactured HydroSub, are designed to lower a powered pump head to the water and push rather than draft the water through the hose. The HydroSub has a capacity of 1,200 gpm and con-

Figure 12. (a) SFFD Phoenix, top, and Guardian, bottom; (b) hose lines off of the Phoenix in the Marina, supplying PWSS, 1989 Loma Prieta earthquake.

sists of a diesel-driven hydraulic pump that, via long hoses, powers a hydraulically driven centrifugal pump in a separate portable pump head that can be manually carried up to several hundred feet across a flat topography from the unit. LDH is connected to the portable pump head and can then convey the water up to a mile away. In this manner the HydroSub, for example, can access water more than 100 ft (33 m) vertically below its location, or several hundred feet laterally, and from that source supply a location up to a mile away.

San Francisco Fire Department PWSS units responded to the Marina fire following the 1989 Loma Prieta earthquake and to the 1991 East Bay Hills fire, as well as many other urban and wildland incidents. The fire in the Marina was a particularly difficult situation—the municipal water supply system had failed due to numerous breaks caused by liquefaction (O'Rourke 1992), and a major fire had developed in a densely built area of wood houses. The fireboat Phoenix, however, was able to respond and supply the PWSS, which quickly contained the fire (Scawthorn et al. 1992) (Figure 12). These and other incidents revealed that an essential element of a PWSS system is special procedures and techniques, which should be regularly reinforced via training and exercises. Systems similar to the PWSS have since been adopted by a number of other fire departments (e.g., Oakland, Berkeley, Vallejo—all in California—and Vancouver, British Columbia (see Figure 13) as well as selected water departments.

In the 1989 event, the fireboat Phoenix was critical in supplying water to the PWSS system at the Marina fire. The success of the Phoenix led to the purchase in 1989 of the fireboat Guardian, formerly of Vancouver, British Columbia. The Phoenix can pump 9,600 gpm (640 l/s, equivalent to one of the land pump stations), while the Guardian can pump 24,000 gpm (1,600 l/s, somewhat greater than the two land pump stations combined).These two powerful boats can supply the PWSS system from various points

Figure 13. (a) PWSS and trailer-mounted HydroSub, ready to go; (b) rear view, showing rig in Vallejo FD livery, hose tender on left with deck-mounted monitor, 1,000 ft of 5-inch hose in tubs, and portable hydrants on rear and side. Note hose ramps carried underneath. To right is HydroSub, showing hose reel for hydraulic supply to pump head. (Photos: C. Scawthorn, courtesy Vallejo Fire Department)

along the SF waterfront, giving the SFFD a valuable asset in setting up Emergency Water Supply as needed if the municipal system fails in an earthquake.

PLANNING AND POLICY IMPLICATIONS

Following the 1989 Loma Prieta earthquake, a number of cities took an interest in San Francisco's AWSS and PWSS. Vancouver, British Columbia, is a city much like San Francisco: a beautiful, densely built-up city of wood buildings surrounded by water but with a major potential for earthquake damage to its buildings, and a highly vulnerable water supply. As a consequence, Vancouver chose in the 1990s to build a Dedicated Fire Protection System (DFPS) modeled after San Francisco's. The DFPS has two pump sta-

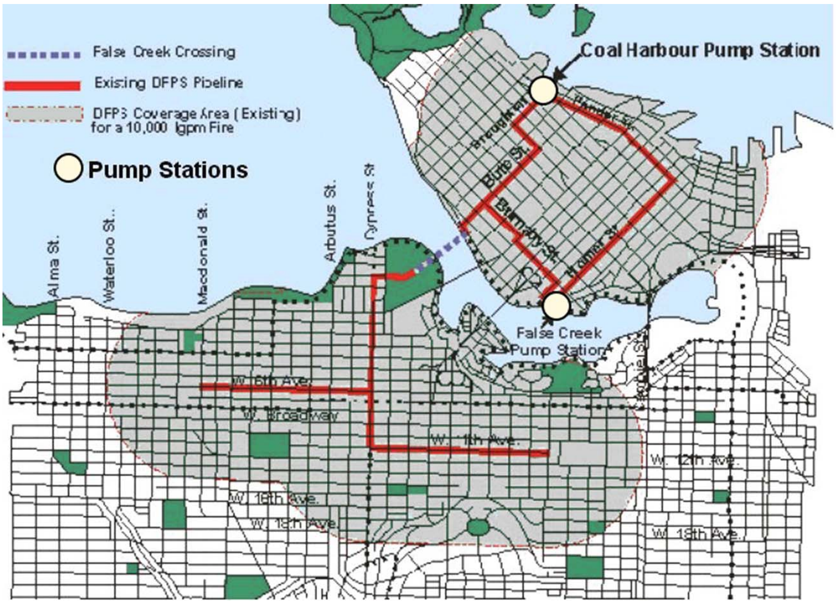

Figure 14. Vancouver, B.C., Dedicated Fire Protection System (DFPS). The two pump stations supply a downtown loop and a submarine crossing to the Kitsilano district. The shaded area shows the area that is protected by the combination of high pressure from the DFPS and Vancouver's PWSS.

tions, each capable of pumping 10,000 Igpm (imperial gallons per minute), and a system of underground welded steel mains protecting the CBD, with a submarine crossing to the vulnerable Kitsilano District, Figure 14. The DFPS is a significant investment, however, which not all cities can afford to make (it was justified in Vancouver by not having to increase the capacity of the ordinary water supply system). Several cities in the San Francisco Bay Area, including Oakland, Berkeley, and Vallejo have chosen to acquire PWSS systems, which provide them with significant emergency water supply capability.

While today's fire departments are much better trained and equipped than their counterparts of 100 years ago, they offer a relatively thin defense against conflagration. In 1906 SFFD engine companies consisted of a steam pumper plus a hose wagon with 700 feet of 2.75-inch or 3-inch hose. This size hose allowed high flows with much less friction loss, thus allowing higher efficiency in fighting fires than use of 2.5-inch hose. Each engine company had an officer plus 9 to 11 men, thus allowing rapid deployment of hose lines while the steam pumper was hooking up to a water supply. During the 1906 fire, engine companies were redeployed from area to area as the water supply gave out—with its large crew a company could rapidly pick up its hose and move to a new location. This is a critical difference with the fire department of today; engine companies have an on-duty crew of one officer plus three firefighters. One firefighter is needed to operate

Table 1. SFFD on-duty staffing

Year	Engines	Ladders	Div. Chiefs	Batt. Chiefs	Total Fire Personnel	Total On-Duty Fire Personnel
1906	38	16	2	10	585	585
1957	47	18	3	11	1,856	515
1990	42	18	2	10	Approx. 1,500	315
2005	42	18	2	9	Approx. 1,500	268

the pumper, thus leaving only the officer and two firefighters to deploy the hose lines. The SFFD of 2006 carries 1,000 feet of 3-inch hose. Once an engine is deployed today, with hose laid out and charged, the available crew is not able to pick up the hose and re-deploy without a significant time delay. The general public in 1906 helped the firefighters leading hose lines and this also occurred in the 1989 Loma Prieta event. Use of the general public to assist during a major event is part of SFFD's Emergency Planning (see www.sfgov.org/site/sfnert), and should be part of the emergency planning of all fire departments (Scawthorn et al. 2005).

Good communications permit departments to rapidly respond and marshal forces to focus on a major fire. Budget pressures, however, are constantly pressuring cities to reduce fire department staffing—a false economy that saves a bit in the short run, but can be brutally expensive when disaster strikes. SFFD on duty staffing is a major issue—while total staffing is much larger than in 1906, today most firefighters live far removed from San Francisco, and budget pressures have substantially reduced on duty staffing. Most recently, SFFD, while "officially" having 42 engine companies, actually employs "rolling" station closures, in which four companies are alternately not manned for a day (i.e., there are only 38 on-duty companies). In a major event such as the 1906 event, the department would have to prioritize use of available units until mutual aid or the off-duty shifts can arrive. Current on-duty staffing is at a level that severely impacts the ability of the department to fight multiple major fires with substantial loss of the municipal water supply, Table 1. This decline is paralleled in most other fire departments in the United States, all of whom rely more and more on mutual aid, which, however, will not be readily available following a large earthquake.

San Francisco has an assessed property value of $106 billion (City Controller 2004). This building stock is protected by the SFFD and is the revenue base to operate city departments. Political leadership has to consider the ramifications of reducing on-duty staffing of the fire department to levels that may hamper the ability of SFFD to prevent conflagrations from getting out of control following a major earthquake. This was clearly demonstrated in the East Bay Hills fire, a non-earthquake event that destroyed 3,500 houses in Oakland and Berkeley in a few hours on the hot, dry, windy Sunday morning of 19 October 1991. The East Bay Hills fire was not the result of an earthquake—it was only one ignition under adverse meteorological conditions where, even though California's Office of Emergency Services was able to marshal hundreds of fire engines by late that afternoon, in many locations they lacked water and were forced to stand by.

Of particular note is the often-overlooked role the insurance industry plays in natural hazards mitigation. It was the insurance industry that identified the conflagration risk in 1905 and recommended construction of an AWSS (NBFU 1905). The AWSS was built at the behest of the industry following the disaster. It was also the insurance industry that again reviewed conflagration potential in major U.S. cities in the 1980s (Scawthorn 1987), which played a role in San Francisco's decision to upgrade the AWSS. Similar considerations played a role in Vancouver's decision to build its DFPS.

Major cities such as Vancouver, B.C. (Canada); Seattle, Portland, San Francisco, San Jose and Los Angeles (United States); Tokyo and Osaka (Japan); and Wellington (New Zealand); as well as others, have the potential for large earthquakes which each, with their large, flammable, densely built-up wood building inventories, combine to create a conflagration potential as large as existed in U.S. cities 100 years ago. And this is not to mention the problem of high-rise buildings. The 1988 First Interstate Bank Building (Los Angeles) (USFAa, n.d.) and 1991 Meridian Plaza (Philadelphia) (USFAb, n.d.) fires, to name only two of the more egregious of recent high-rise fires, show that such challenges can strain a major fire department to its limits. Unfortunately, events in the 2001 World Trade Center disaster show that such modern high-rise buildings, when fires go unfought, can even collapse.

The World Trade Center (WTC) disaster of 11 September 2001 provides a graphic illustration of the importance of alternative sources of water during extreme events. O'Rourke et al. (2003) show that damage to water distribution pipelines surrounding the WTC site was sufficiently severe that pressure losses interfered with fire fighting until isolation of damaged water lines could be achieved. Approximately two times the amount of water taken from distribution pipelines was supplied from the Hudson River by fireboats of the Marine Division of the New York City Fire Department at significant distances inland during the critical hours following collapse of the WTC towers. The WTC experience reinforces the lessons of the 1906 and 1989 earthquakes in the San Francisco Bay Area, and demonstrates that water can be conveyed rapidly to land-based sites from alternative sources, provided that appropriate planning and equipment acquisition have been undertaken.

Future earthquakes can cause hundreds of ignitions in large cities (Scawthorn et al. 2005), and fire departments will be called upon to respond to high-rise fires as well as to deal with potential conflagration situations. Their normal staffing cannot cope with such extraordinary demands. Only investments in the training of thousands of volunteers, such as has occurred in Los Angeles (see http://www.cert-la.com/), San Francisco, Tokyo, and Osaka, combined with emergency water supplies such as the PWSS, AWSS, and DFPS systems provide, offer the potential to stave off the inevitable. The lessons of San Francisco in 1906 and other great fires in U.S. cities of 100 years ago were dearly bought—constant vigilance by well-trained and -equipped fire departments supplied with reliable and adequate water supplies are the price for protecting our lives and property. These lessons are gradually being forgotten. The situation is not as precarious as it was a hundred years ago, due to advances in building and product safety codes. However, earthquakes can recreate the conditions of 100 years ago, in a matter of moments. We should not doubt this. Events such as the 1991 East Bay Hills fire and 2001 WTC disaster show how vulnerable our cities are. Each community needs to examine its defenses and develop a AWSS, PWSS, or other innovative measures for the day when an earthquake or other disaster strikes.

CONCLUSION

The 1906 fire following the San Francisco earthquake is the largest urban fire in U.S. history. Technical analysis was able to foresee just months beforehand the potential for this disaster, after which the world's largest seismically reliable water supply system was built. In the 1980s, technical analyses identified areas in need of improvement, based on which San Francisco's political leadership immediately acted to upgrade and further enhance the city's disaster preparedness. The infrastructure built following the 1906 earthquake and fire served the city well in the 1989 Loma Prieta earthquake, and continues to protect the city today. The lesson is that communities need to develop an integrated disaster preparedness and response capability, and be constantly vigilant in maintaining that capability given urban growth, economic and other pressures, and the normal wear and tear and deterioration of any infrastructure. Many other lessons can be gleaned from this experience, but that lesson is paramount.

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