ONE HUNDRED YEARS OF EXPERIENCE WITH GAS SYSTEMS AND FIRES FOLLOWING EARTHQUAKES

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ABSTRACT

Perhaps the most serious risk facing cities in seismic regions is the potential for numerous simultaneous fires while emergency response capabilities are weakened, infrastructure is damaged, a large percentage of the populace is away from home, traffic is impaired, communications are interrupted, water-distribution systems are impaired, humidity is low, or winds are high. Under such conditions, conflagrations similar to those following the 1906 San Francisco and 1923 Kanto earthquakes can occur. In 1906, San Francisco's officials devised the meter-clock test as a practical means of evaluating the worthiness of gas systems in the unburnt district. Gas-service restoration was delayed ten days, while all the gas meters were shut-off and tagged, and repairs to the water-distribution system were completed. Mandating the installation of seismic gas shutoff valves (SGSVs) is a cost-effective solution for minimizing the risk of post-earthquake fires and conflagration. The manual-reset requirement for modern SGSVs helps to assure there will be all the time needed to perform meter-clock tests; inspect gas piping, appliances, and flexible connections; pressurize repaired lines to verify their worthiness; and search for spilled flammables, overturned lamps, frayed wires, broken water lines, and other fire hazards before restoring gas service. SGSVs performed well during the 1994 Northridge earthquake. Los Angeles and several other U.S. jurisdictions, plus Italy, now require SGSVs to be installed on certain buildings. A global insurer of commercial and industrial buildings recommends installing SGSVs in fuel-gas and flammable-liquid lines. Tokyo's buildings all have seismic gas shutoff devices. Buildings throughout the San Francisco Bay Area and in other seismic regions should have this protection, too.

Introduction

The fires that raged in San Francisco for over three days following the 1906 earthquake riveted the world's attention, and put cities in seismic regions on notice about their risk from post-earthquake fires. Although cities no longer rely on oil and gas for lighting, factors such as increased building and population density, rush-hour traffic, higher gas and electricity usage, and new chemicals and gases have increased the risk from fire following earthquakes. Reviewing events associated with the 1906 San Francisco and other selected earthquakes of the past century can teach us valuable lessons about the post-earthquake fire risks of modern cities, abilities of individuals and emergency-services agencies to act following earthquakes to reduce fire risk or

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fight fires, steps that need to be taken before gas service is restored following an earthquake, and mitigation measures that can be implemented before future earthquakes.

M_W 7.7 (M_L 8.25), April 18, 1906, San Francisco, California, earthquake (5:12 AM, PST)

Sixteen fire alarms were reported from widely separated places within San Francisco, and nearly 50 fires were reported in the downtown area within the first 17 minutes. The primary sources of ignition were the upsetting of oil lamps, and oil and gas stoves; contact of flames from lamps and gas jets with combustible material; rupturing of chimneys and flues; and upsetting of boilers and furnaces. It took 2-1/4 hours to shut-off the City's gas supply (Jones 1906). The water mains and conduits were broken in hundreds of places by shaking-induced settlement of soft soils, and the pipelines from reservoirs to the south were broken at fault crossings and transitions from competent ground to soft soils and marshes, which rendered the water system inoperable. Contemporaneous fire experts surmised it was impossible for the fire department to efficiently handle so many fires at once, even had the water system not failed (Bronson 1986). Many fires that started in residential buildings were quickly extinguished by residents; however, because of the early hour, fires that started downtown grew to large proportions before firemen arrived. The fire department responded to over 20 major fires by 7:00 AM, but the hydrants were found useless—forcing the firemen to retreat. Within three hours, nine fires had evolved into conflagration. Winds were absent when the earthquake hit, but increased over the next three days, which spread the fires westward. Over 28,000 buildings were burnt within an area of ≈ 4.7 square miles, which comprised 490 city blocks and 32 partial blocks (≈ 60% of the City's developed area). Recent studies concluded that 2000—3000 persons died from the earthquake or fires (Hanson 1989). Although the gas mains for the unburnt district were repaired within 9 days of the earthquake, City officials delayed gas restoration until May 7—after all 38,000 gas meters had been shut off and tagged, and repairs had been completed to the water-distribution system. For buildings whose gas system failed a leakage test consisting of a visual inspection and a meter-clock test (whereby the meter's test dial was observed for two minutes with all the pilots turned off), the meter was disconnected, the houseline plugged, and the meter tagged with a warning that the house pipes must be repaired before gas service would be restored (Jones 1906).

M_W 7.8—7.9 (M_S 8.1), September 1, 1923, Kanto, Japan, earthquake (11:58 AM, local time)

There was a strong wind when the earthquake hit, and the water system broke in many places. There were 98 initial fires, of which 9 were attributed to gas leaks (Kobayashi 1984). Twenty two firemen died and 100 were injured fighting the blaze, which burned 447,128 buildings, including 140,000 of the 240,000 homes with gas-service connections. An estimated 100,000 of the ≈ 142,000 persons who died were believed to have perished from fire or smoke inhalation (Japan Bureau of Social Affairs 1926).

M_L 6.3, June 29, 1925, Santa Barbara, California, earthquake (6:44 AM, PST)

Customer gas piping was damaged in many buildings. Santa Barbara's primary water main broke, which dropped the water pressure to zero within 10 minutes (Nunn 1925). Fortunately, the gas utility's system operator shut off the city's gas supply within three minutes; that action, together with the prompt shut-off of the city's electricity system, was credited with preventing fires and a conflagration (Bivens 1925). It took five days to shut off and tag the City's 7000 gas meters. The gas utility warned citizens to not turn on their gas under any circumstances, and to wait for the gas man to make an inspection and restore their service. After discovering that a citizen was misrepresenting himself as a plumbing inspector and charging a dollar apiece to turn gas services on, the gas utility published the following warning:

> "To tamper with a gas meter may cost the life of every citizen in Santa Barbara and the destruction of all property in the city" (Anonymous 1925).

An engineer who inspected over 100 damaged buildings following the earthquake recognized the potential value of using seismic switches and seismic gas shutoff valves (SGSVs):

> "It is much easier and more nearly feasible to prevent a fire by such means than it is prudent to assume that water-supply mains will be uninjured during a period of seismic upheaval" (Alvarez 1925).

M_W 6.4, March 10, 1933, Long Beach, California, earthquake (5:54 PM, PST)

Fourteen fires were reported in Long Beach during the first hour. One account attributed 7 of 19 reported fires in Long Beach to leaking gas (Neumann 1935); while another reported that ≈ 20 fires were burning at midnight and that fires occurred through the next day (Du Ree 1941). Fires also occurred in Artesia, Bellflower, Compton, Huntington Park, Los Angeles, Watts, and Venice. It was fortunate that winds were light, because firefighting activities and leakage from ≈ 50 damaged water mains depleted Long Beach's water supply to 4% of capacity within 6 hours. Gasoline from ruptured refinery tanks poured into sewers beneath Compton, prompting officials to prohibit fires and electric lamps (Strand 1988). The Long Beach Gas Department (LBGD) directed citizens over the radio to shut off their gas, while its engineering personnel shut-off all the valves to the gas mains within two hours—including a modern Paul Revere ride of a meter foreman and his mother. The LBGD shut off all of its 46,307 gas meters and increased the odorant level to help detect leaks (Bryant 1934). The LBGD assigned two-man crews to visit every home to inspect appliances and check for leakage in the house lines. For homes deemed ready for service, they turned on the gas; for those with gas leakage, they notified the tenant and tagged the meter with a warning to leave the gas off until repairs were completed; and for those that were unoccupied, they left the meters off "…as the conditions of the appliances and house piping is, of course, unknown to the workers" (Anonymous 1933). In Long Beach, 30% of the gas services required second or third inspections. The prompt closure of the gas supply to the gas mains and individual services was widely credited with saving Long Beach from a conflagration:

> "Estimates have been made of the number of open flames burning at this particular time [5:54 PM], and the figure of 35,000 seems to be within reason—thereby giving us 35,000 potential fires, all starting at one time as stoves were overturned, buildings collapsed, service broken, and so on, with very little thought given by the occupants of the buildings to shutting off the gas before running out" (Du Ree 1941).

Thirty Los Angeles Fire Department (LAFD) firemen inspected homes, and tagged meters and notified residents where gas leaks were discovered (Du Ree 1941). A gas utility noted:

> "If the supply to a system which has been ruptured by the 'quake is not shut off, fire and/or explosion, with accompanying hazard to life and property, may result. It appears probable that where fire is caused by gas escaping into a building, ignition will in most cases occur immediately, due to pilot lights, open fire, broken wires, etc., within the building, and obviously such fires cannot be avoided by even a prompt decision to shut off the supply following the 'quake." (Bridge 1934)

An employee of the Los Angeles Gas and Electric Corp. expressed his opinion that SGSVs should be designed for use at individual structures, rather than in distribution mains:

> "…yet it is not satisfactory unless it could be individually designed for each service or supply point, for to have a safety factor that would assure the valve working under all conditions, the damage would be done and the inconvenience of cutting off the gas supply to a multitude of consumers would far offset the probability of the device doing any good in a severe 'quake." (Harris 1934)

Fires occurred at seven schools—primarily in science or chemistry buildings—prompting California to mandate SGSVs at public schools (California Department of Public Works 1941).

M_W 7.5, July 21, 1952, Arvin-Tehachapi, California, earthquake (4:52 AM, PDT)

In Tehachapi, 200 customers turned off their own gas, while gas was shut-off at the main to 18 downtown businesses; gas was also shut-off at all schools and the Tehachapi Women's prison. In Arvin, a man died from burns suffered when his gas stove exploded. In Bakersfield, a home exploded due to leaking gas, an explosion was reported inside a car agency, and 400—500 residential water risers were broken. Aftershocks on July 28, 1952 (M 6.1), and August 22, 1952 (M_L 5.8), caused more gas leaks and fires (Strand 1988). Sixty eight of the ≈ 700 SGSVs that had been installed at schools in the Los Angeles School District since 1933 were actuated by the mainshock (Steinbrugge 1954). The first national standard for SGSVs, which are valves that automatically shut-off the gas during strong earthquake shaking, was not published until 1981.

M_W 9.2, March 27, 1964, Alaska earthquake (5:36 PM, local time)

It was fortunate that Anchorage's electricity system failed, as there was no water supply for fighting fires (Richardson 1973). Anchorage's natural gas system was less than four years old, yet suffered extensive damage. Although the number of interior gas leaks is unknown, 700—800 domestic water heaters were repaired or replaced. The Anchorage Community Hospital was evacuated due to leaking gas and power failure. Landslides and ground settlement ruptured gas mains in over 200 places, which surely prevented many gas-caused fires. The utility closed a block valve 1.5 hours after the earthquake, which shut off the gas to 80% of Anchorage's service area; and doubled the odorant level to help locate damaged mains. Fires occurred at fuel-storage tanks in waterfront areas of Seward, Valdez, and Whittier. A film of spilled gasoline covering Cook Inlet prompted the Anchorage Fire Department to ban smoking for several days. A study of damaged piping systems revealed that most of the damage was to elbows, which was caused by repeated deflection of threads due to differences in vibration frequencies of adjoining pipe segments. Researchers recommended that "earthquake sensitive shut-off valves on gas service lines should be provided where maximum protection from gas leaks is required" (Ayres, Sun, and Brown 1973).

M_W 6.6, February 9, 1971, San Fernando, California, earthquake (6:01 AM, PST)

Thousands of gas leaks were reported in Los Angeles and neighboring cities. The gas utility turned off the gas at each home in the heavily damaged area. Of the 16,585 meters shut off by the utility, within two weeks 15,644 were restored to service, 117 were altered or repaired, 139 were disconnected or abandoned, 342 were restored but the customers were not ready for service, and 343 were removed due to structural damage or demolition (Bigglestone 1971). Fire-departments and roving patrols shut off the gas to many damaged customer gas systems just in time to prevent more explosions or fires (Simms n.d.). Serious damage to the Van Norman Dam forced the evacuation of ≈ 80,000 residents; ≈ 5800 of whom shut off the gas before leaving. Twenty fires due to leaking gas resulted in injuries or structural damage. Fifteen persons were treated in hospitals for burns, and two firemen were injured fighting a gas-caused dwelling fire in Solemint. Many gas-related fires were prevented in Sylmar by the rupturing of gas mains by ground movements. During the first 8 hours, the LAFD responded to 456 alarms, of which 128 turned out to be fires. Seventy four fire-insurance claims were filed. Winds were light, but 10 days later gusted to 50 mph (Strand 1988). Although the violent shaking lasted only 12 seconds, the 1971 San Fernando earthquake caused similar damage to piping systems as the 1964 Alaska earthquake, which lasted 20 times longer. Several failures of screwed fittings caused by repeated deflections of threads were observed (Ayres and Sun 1973). UCLA Professor Samuel Aroni recommended the widespread installation of SGSVs to minimize the fire hazard (Aroni 1971).

M 6.4, May 2, 1983, Coalinga, California, earthquake (4:42 PM, PDT)

Coalinga's four firetrucks had flat tires within 45 minutes from driving over nails, broken brick, and glass, according to Fire Chief Fred Fredericksen. Coalinga's gas department shut off the city's natural gas supply immediately following the mainshock, while many residents turned their gas off manually (Brown 1984). It took two weeks to inspect and reopen the gas lines.

M_L 5.9, October 1, 1987, Whittier, California, earthquake (7:42 AM, PDT)

The LAFD was overwhelmed with calls reporting gas leaks, gas odors, or other problems. Three gas-caused fires were reported by the LAFD; 6 by the Los Angeles County FD (LACFD); 1 by the Alhambra FD; 2 by the Downey FD; and 1 by the El Monte FD (Strand 1988). During the first 2 hours, the LAFD responded to 112 calls reporting gas leakage; it then adopted a new policy of giving instructions over the phone on how to shut off the gas. Through October 4, the LAFD responded to 242 calls reporting gas leakage, and shut off at least 72 gas services (Callahan 1987). Crews from LACFD's Whittier Station were dispatched to investigate 15 calls for gas leakage, but while in the field received 50 more requests from residents to check for gas leaks. Although the LACFD reported that it responded to 97 suspected gas leaks, it apparently responded to three times that many. The LAFD's and LACFD's figures are underestimated, because those agencies advised many persons over the phone without assigning an incident number (Schiff 1988). Most cities near the epicenter received many calls reporting gas leaks or odors. Because its fire department was overwhelmed, Santa Fe Springs dispatched 50 persons from its Public Works Department to patrol neighborhoods and assist residents with shutting off their gas. A resident told one of those crews that he had blown out all the pilot lights in his home; as he had not turned off the valve at the riser, the crew did that for him. The gas utility found 5938 leaks in customer piping, of which it attributed 2007 to the earthquake (Russell 1988). Prompt closure of gas services by residents, firemen, public works crews, and gas-utility crews prevented many gas-related fires. Fire Chief Frank Borden testified that the LAFD:

> "….believes natural gas leaks are a problem after earthquakes, and that the number and size of fires, life and property losses, and the number of responses could be reduced if earthquake-sensitive automatic gas shutoff valves were installed" (CSSC 1988).

M_W 7.2, October 17, 1989, Loma Prieta, California, earthquake (5:04 PM, PDT)

The fire that consumed a collapsed apartment building in the Marina District—in which a woman died—might have spread if strong winds had been present. Fortunately, that fire was close to the harbor, a fireboat was available, and there were no nearby fires, as no water was available from the severely damaged water-distribution system. San Francisco's Fire Marshal testified that gas fires posed a serious threat in the Marina District, and "it was lucky that the gas problem was handled quickly before a fire storm situation developed and spread out of control" (National Academy of Sciences 1994). Most residents were home—intending to watch a scheduled World Series baseball game between the local teams—so they were able to shut off the gas. The 911 emergency telephone system in Santa Cruz was overwhelmed by gas-leak calls (San Francisco Earthquake Research Project 1990). The electricity system—down for at least 6 hours in much of the heavily shaken area—was not re-energized for most of the downtown area for 33 hours, until crews finished surveying and repairing over 50 leaks. Pacific Gas and Electric (PG&E) shut down its distribution systems in Watsonville, Los Gatos, and the Marina District. In Watsonville, PG&E crews responded to gas leaks dispatched by PG&E's EOC, radioed by fire departments, pointed out by residents, or discovered on their way to other leaks. PG&E restored gas service for 156,355 customers during the first 10 days (Phillips 1990); and reported 30 gas-ignited fires and $\approx$ 3700 buildings with gas appliance or piping damage (PG&E 1994).

M_W 7.1, April 25, 1992, Cape Mendocino, California, earthquake (11:06 AM, PDT)

Five hundred customers shut off their gas. After a small fire in Ferndale, the volunteer fire department shut off all propane gas services downtown. Concerned they would be unable to stop even a small fire from spreading through the damaged buildings, firemen checked the gas services twice a day for four days to assure they remained off. Emergency bulletins noted that "there is a concern of fire with turning the gas back on" (Office of Emergency Services 1992).

M_W 6.5, June 28, 1992, Big Bear, California, earthquake (8:05 AM, PDT)

Ten of the 12 reported residential fires were attributed by fire districts to natural gas or propane leaks ignited by water-heater pilots (Levenson 1992). The gas valves at many vacation homes were in the closed position when the earthquake hit, and many persons shut off the gas for their home and their neighbors', which prevented many fires; ≈ 100 gas leaks were reported in Big Bear City (EQE 1992). The gas utility did meter-clock tests, and locked services that failed the test, until a plumber made the necessary repairs and certified that the piping was air tight.

M_W 6.7, January 17, 1994, Northridge, California, earthquake (4:31 AM, PST)

The LAFD reported 158 structure fires during the first 27.5 hours. However, fires at several mobile home parks were reported on one incident report at the same address, even though there were multiple ignitions and numerous dwellings burned (Scawthorn 1996); 58 mobile homes burned at one park, 54 at a second, and 22 at a third. In areas where the firefighting water supply failed, there were numerous backyard pools from which the LAFD was able to draft water. The LAFD used helicopters to drop water (over 15,000 gal) on some burning structures (Borden 1996). Within two weeks, the Southern California Gas Company (SoCalGas) restored 119,600 of the 151,000 gas-service outages; 9100 could not be restored due to structural damage, and 22,300 were waiting for the customer to return or for a determination that the building was structurally safe. SoCalGas found leaks in ≈ 20% (162 of 841) of the customer gas piping systems for which it was requested to reset a SGSV (SoCalGas 1994). SoCalGas also found 144 strapped water heaters that were damaged or leaking. SoCalGas testified that restoring gas is labor intensive because "you have to look and make sure that the appliances haven't shifted…" (Assembly Committee on Utilities and Commerce 1994). If the Northridge earthquake had occurred during the middle of a business day, there would have been many more fires. Fortunately, most residents were home to shut off the gas, traffic was light, humidity was not low, winds were light, the electricity system went down for six hours, the epicenter was near the outskirts of the urbanized area, the fire department was well prepared, and the aftershocks were not strong. SGSVs performed well during this earthquake (Strand 1998). LAFD Fire Marshall Davis Parsons testified that the LAFD supported the mandation of SGSVs in Los Angeles:

> "….the most devastating earthquake aftereffects have been due to fire….The bottom line for those who deal with the aftereffects of a major disaster is elimination of the sources of fire" (CSSC 1988).

Conclusions

Natural gas is a cost-efficient energy source for many useful functions under everyday conditions. In the aftermath of an earthquake, however, natural gas can become an agent for catastrophe as unextinguished pilots become potential ignition sources for escaping gas, spilled flammables, and fallen combustibles. Heavily shaken communities would be safer without natural gas service until their water-distribution systems have been fixed and their buildings inspected for damaged gas systems and other potential fire hazards. The best way to assure rapid closure of gas services in heavily shaken areas is to use one or more seismic gas shut off valves (SGSVs) for each building. Los Angeles has an ordinance requiring the installation of SGSVs—certified to the national (ASCE 25-97) and California (12-16-1) standards—on new construction, remodels, and ownership transfers; SGSVs must be installed in accordance with the sizing and installation policy outlined in Los Angeles' research reports. Los Angeles does not allow low-pressure excess flow valves (LPEFVs) to be used instead of a required SGSV. LPEFVs are flow-limiting devices that cannot be actuated by most hazardous gas leaks, do not shut-off the gas, can automatically reset before a required meter-clock test or other safety checks can be done, and create large pressure drops that make them incompatible with low-pressure gas systems (Ayres 2002; Strand 2002). Los Angeles requires a mechanical plan check for most installations of LPEFVs. FM Global recommends to its clients with buildings in seismic regions that they brace gas appliances, install flexible gas connections, and install SGSVs for fuel-gas and flammable-liquid lines (FM Global 2002). Tokyo Gas has installed a seismic gas shutoff device for each of its 9,000,000 customers. Cities throughout the San Francisco Bay Area and in other seismic regions should mandate the use of SGSVs to reduce their post-earthquake conflagration risk.

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