Earthquake Safety Implementation Program
The City and County of San Francisco

STUDY OF OPTIONS TO REDUCE POST-EARTHQUAKE FIRES IN SAN FRANCISCO

ESIP Task A.6.i
June 29, 2017

Applied Technology Council

Cover image: Market Street, San Francisco, in 1906 and 2011. (Images courtesy of Best of Web Shrine and Luis Villa del Campo.)

Study of Options to Reduce Post-Earthquake Fires in San Francisco (ESIP Task A.6.i)

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Summary

San Francisco faces a very high risk of fires igniting and spreading after earthquakes. After the 1906 earthquake, more than 25,000 buildings burned. After the 1989 Loma Prieta earthquake, 26 fires ignited, centered on the Marina District. Recent studies make it clear that devastating post-earthquake fires could be in the city's future. In 2010, the Community Action Plan for Seismic Safety (CAPSS) program estimated that a magnitude-7.2 earthquake on the San Andreas fault could burn 2,700 buildings, including 5,800 housing units. A larger earthquake, such as a repeat of the 1906 earthquake, or dry, windy weather at the time of an earthquake, could result in far greater losses from fire.

There are many things that can be done to reduce San Francisco's fire following earthquake risk and make the city more earthquake resilient. The purpose of this report is to identify and study options to reduce this risk.

This report presents seven top recommendations for steps the City should take to reduce the risk of post-earthquake fires:

1. The City should identify buildings that are especially vulnerable to post-earthquake fire, such as those housing vulnerable residents, high-rise residential buildings, and historic resources that are irreplaceable. A special program should address reducing the fire risk of these structures by using multiple risk reduction strategies, such as sprinkler systems or fire resistant glazing.

2. The City should advocate for operational earthquake early warning systems in the state of California, and should launch programs to make effective use of earthquake early warning signals to reduce post-earthquake fire risk. These programs should include efforts to effectively use warning information to improve City emergency response, and public awareness training for citizen actions when a warning occurs.

3. The City should seek to reduce post-earthquake ignitions caused by both gas and electricity through shut-off devices. To do this, the City should take the following steps:

- Identify the neighborhoods within the City that are most at-risk of post-earthquake conflagrations and would, therefore, benefit the most from gas and/or electric shut off devices.

- Study the implications of programs that require mandatory or triggered (e.g., at time of sale or renovation) installation of gas or electric shut off devices in all parts of the city or only in the most at-risk neighborhoods.

- Work with the local gas and utility providers to develop a transparent understanding of the City's risk due to fires arising from gas and electric systems and appliances after earthquakes.

4. The City should mount a strong campaign to educate and encourage the public to have household fire extinguishers and to use them effectively.

5. The City's key emergency response agencies, such as the Department of Emergency Management and the Fire Department, should develop a pilot project to enhance real-time situational awareness using Unmanned Aerial Vehicles (drones), and accompanying approaches to process, interpret, and make decisions with the resulting data. This should focus on identifying ignitions that have the potential to grow into conflagrations.

6. The San Francisco Fire Department should consider expanding the role of volunteer residents who are trained to suppress small fires and otherwise support professional firefighting efforts after an earthquake. This can be achieved by expanding the Fire Department Auxiliary Reserve Program and/or expanding the role of selected Neighborhood Emergency Response Team members.

7. The City should continue to invest in its work to make sure that all City neighborhoods are served by resilient and redundant water supply systems that can be used for post-earthquake fire suppression. It should explore all options to make sure water is available for post-earthquake fires through the Emergency Firefighting Water System.

Preface

The risks from future earthquakes in San Francisco have been well documented in the work conducted for the Community Action Plan for Seismic Safety (CAPSS). This work led the way to the development of a 30-year program to be implemented by the San Francisco Earthquake Safety Implementation Program (ESIP). In 2014, the Applied Technology Council (ATC) was awarded a contract to provide seismic safety and engineering consulting services to ESIP. This document is a part of a series of reports to fulfill the tasks identified in this contract under the ATC-119 project.

Charlie Scawthorn was the Lead Technical Consultant for this report and led the project workshop held on June 8, 2015. The Applied Technology Council is indebted to the leadership of David Bonowitz and Laura Samant, Co-Team Leaders on the ATC-119 project. Laura Samant also served as the lead editor for the final report. The names and affiliations of the project team are provided in the list of Project Participants at the end of this report.

ATC also gratefully acknowledges the staff of the City and County of San Francisco Office of Resilience and Capital Planning: Brian Strong (Chief Resilience Officer and Director), Stacey Lee (Project Manager), Micah Hilt (Planner), Jeno Wilkinson (Program Assistant) and Laurence Kornfield (Special Assisstant to the City Administrator), and Carrie Perna for ATC report production services.

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Chapter 1

Introduction

San Francisco has a significant earthquake hazard and fire following earthquake is a particularly high risk in San Francisco. The purpose of this report is to analyze options to mitigate post-earthquake fire losses in San Francisco and to provide recommendations for effective programs, as part of broader City resilience planning efforts. After the 1906 earthquake, more than 25,000 buildings burned. After the 1989 Loma Prieta earthquake, 26 fires erupted centered in the Marina District. In 2010, the Community Action Plan for Seismic Safety (CAPSS) program estimated that a magnitude-7.2 earthquake on the San Andreas fault could burn 2,700 buildings with even greater losses from a larger 1906-type event (ATC, 2010a). Older buildings, buildings located on steep hillsides or areas with poor soils prone to liquefaction, and buildings constructed with materials susceptible to burning are at the most risk.

However, there are many ways to reduce San Francisco's fire following earthquake risk and make the city more earthquake resilient. Actions taken to improve buildings before earthquakes strike can, for example, reduce ignitions and fire spread, and assure a more reliable fire response and water supply. Such actions will save lives, speed recovery, lessen economic losses from business interruption, reduce housing and job losses, and protect community values and the unique character of the City.

1.1 Overview of the Fire Following Earthquake Hazard and its Mitigation

The process by which an earthquake triggers fires and a community suppresses those fires has been detailed elsewhere (Scawthorn, 2010; TCLEE, 2005) and, in summary, consists of the following interrelated events:

- **Occurrence of the earthquake.** Earthquake shaking causes damage to buildings and contents, including damage as simple as knockings things over (such as candles or lamps).
- **Ignition.** Ignitions will occur due to earthquakes whether a structure has been damaged or not. Ignition sources are numerous and include overturned heat sources, abraded and shorted electrical wiring, spilled

chemicals having exothermic reactions, and friction of things rubbing together.

- **Discovery.** If the fire resulting from the ignition has not self-extinguished, it will be discovered. In the confusion following an earthquake, the discovery may take longer than it would otherwise.
- **Report.** If it is not possible for the person or persons discovering the fire to immediately extinguish it, Fire Department response will be required. For the Fire Department to respond, a report to the Fire Department must be made. Communications system dysfunction and saturation will delay many reports.
- **Response.** In the aftermath of a damaging earthquake, the response of the Fire Department is likely to be impeded by non-fire damage emergencies the firefighters must respond to (e.g., building collapses that trap occupants), as well as transportation disruptions.
- **Suppression.** If the Fire Department is successful in suppressing the fire, the firefighters move on to the next incident. If the Fire Department is not successful, the firefighters continue to attempt to control the fire, but if it spreads, it becomes a conflagration (and extensive fire). Numerous factors, including water supply functionality, building construction type, building density, wind and humidity conditions, manpower and equipment deployed, affect success of suppression. If the firefighters are unable to contain the fire, the fire typically ends only when the fuel is exhausted or when the fire comes to a firebreak.

Figure 1-1 shows these events, along with interventions that, in concept, have the potential for reducing fire following earthquake losses. As a note on jargon, San Francisco's Emergency Firefighting Water System includes numerous redundant water supply systems that could be used in an emergency such as an earthquake. San Francisco's high pressure pipe network (with tanks, reservoirs, pump stations, and fireboat manifolds), which was constructed following the 1906 earthquake and fire and has historically been termed the Auxiliary Water Supply System (AWSS). In addition, there are more than 100 cisterns constructed throughout the City that are not directly connected to the AWSS but have often been included when speaking of the AWSS. In the 1980s, a Portable Water Supply System (PWSS) was developed by the San Francisco Fire Department, consisting of hose tenders with about a mile of five-inch Large Diameter Hose and appurtenances. The San Francisco Fire Department is currently considering an additional new system consisting of twelve-inch Ultra Large Diameter Hose and appurtenances.

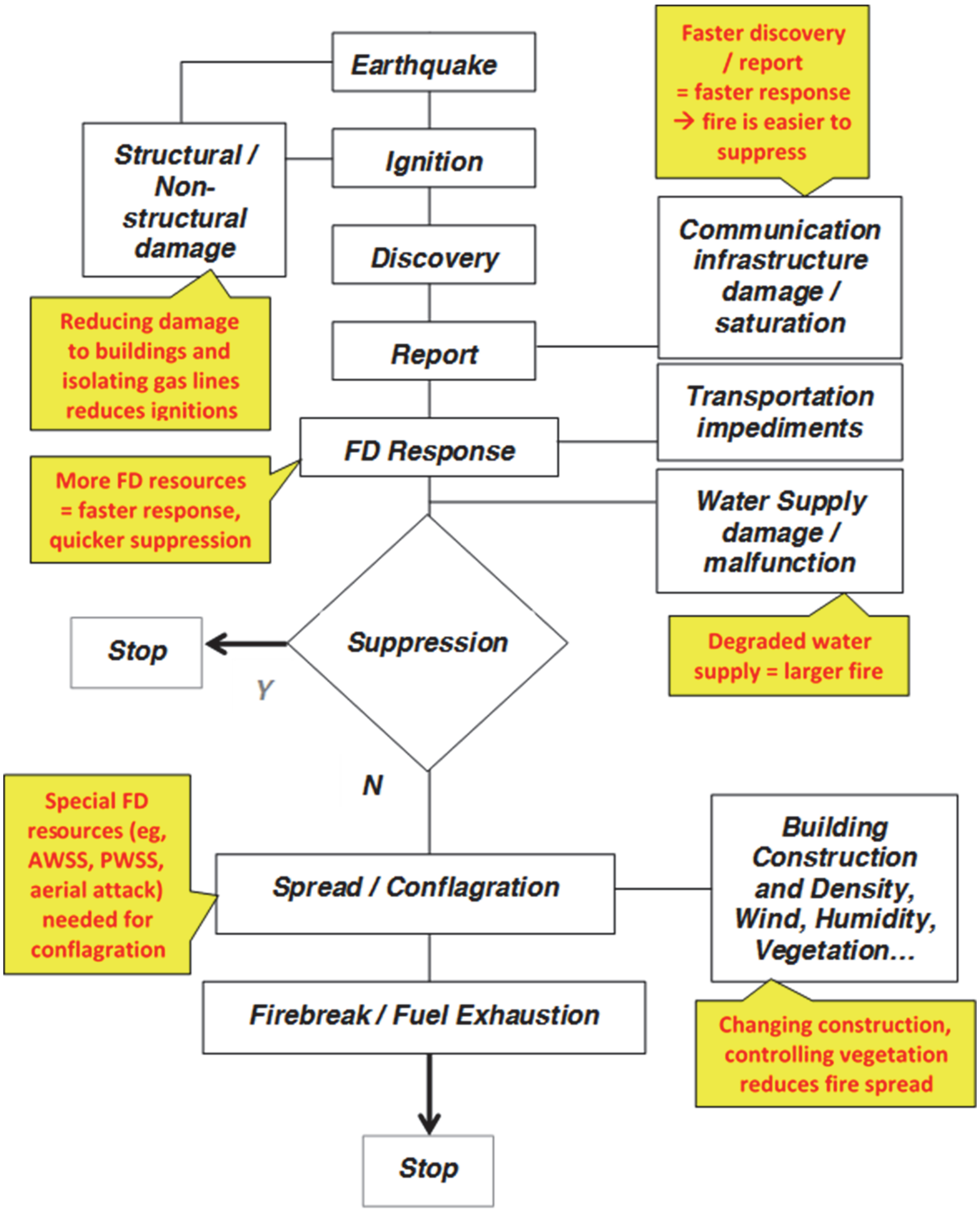

Figure 1-1 Fire following earthquake process, with opportunities for positive intervention (in yellow; TCLEE, 2005). FD stands for Fire Department. AWSS stands for the Auxiliary Water Supply System. PWSS stands for the Portable Water Supply System. The AWSS and PWSS are components of the Emergency Firefighting Water System.

In brief, reducing fire following earthquake risk can be accomplished by:

- Reducing ignitions
- Better fire reporting

- Reducing fire spread
- Enhancing firefighting capacity
- Enhancing water supply availability and reliability

1.2 Fire Following Earthquake Hazard in San Francisco

In 2010, the CAPSS program produced a detailed study of the scope of the city's fire following earthquake hazard and risk. A brief summary is provided in Table 1-1.

Table 1-1 Estimated Range of Losses to Buildings in San Francisco Due to Fire Following Earthquake (ATC, 2010a and b)

	25% ~ 75% Confidence Range		
Scenario	*Ignitions*	*Loss ($ billions)*	*Total Burnt Building Floor Area (million sq. ft.)*
San Andreas Magnitude 7.9	68 ~ 120	$ 4.1 ~ $ 10.3	11.2 ~ 28.2
San Andreas Magnitude 7.2	52 ~ 89	$ 2.8 ~ $ 6.8	7.7 ~ 18.6
San Andreas Magnitude 6.5	48 ~ 70	$ 1.7 ~ $ 5.1	4.7 ~ 14.0
Hayward Magnitude 6.9	27 ~ 46	$ 1.3 ~ $ 4.0	3.6 ~ 11.0

For example, a magnitude-7.2 earthquake on the San Andreas fault is estimated as likely to ignite more than 70 fires simultaneously, while impeding the San Francisco Fire Department's ability to respond quickly due to obstructed roads, damage to the water supply systems, competing demands, etc. This means some fires would burn unchecked for hours. An estimated 2,700 additional buildings could be destroyed by fire, including 5,800 housing units. Damage from fire could be much higher or lower than these estimates, depending on weather, wind, and many other factors.

In San Francisco most fires are expected to be due to ignitions and firespread in residential neighborhoods with primarily wood-frame buildings. Large fires in high-rise buildings are another major concern. There are no oil refineries or large process industries in San Francisco, although some neighborhoods have small industrial facilities with fuels or chemicals that could pose a risk.

1.3 Project Background

In early 2000, the San Francisco Department of Building Inspection (DBI) began work on the Community Action Plan for Seismic Safety (CAPSS) which resulted in a wide-ranging 10-year program of studies and recommendations involving staff, citizens, and experts to develop a basis for earthquake risk reduction and response policy decision-making by the City and County of San Francisco.

One of the primary products of the CAPSS project was the ATC-52-2 report, *Here Today—Here Tomorrow: The Road to Earthquake Resilience in San Francisco, A Community Action Plan for Seismic Safety* (ATC, 2010c). Based on the ATC-52-2 report, the City and County of San Francisco developed the *CAPSS Earthquake Safety Implementation Program Workplan 2012-2042* (CCSF, 2011). The *Workplan* "outlines a 30-year program, based on the extensive CAPSS analysis and community supported recommendations that will reduce San Francisco's most significant earthquake impacts. [Many of the plan's elements are] scheduled to start soon so that results can be achieved in time to reduce likely earthquake impacts". Accordingly, the Earthquake Safety Implementation Program (ESIP) was established within the City Administrator's office in 2012 with the purpose of carrying out the 30-year *Workplan.*

In July 2014, ESIP awarded a contract to the Applied Technology Council (ATC) to provide technical expertise in selected tasks from the 2011 *Workplan*. This report is final deliverable from work conducted under *Workplan* Task A.6.i, conduct study of fire-related initiatives.

1.4 Report Scope and Organization

This report provides an overview of the fire following earthquake hazard, and reviews literature and other sources of information to identify opportunities to reduce San Francisco's risk.

Initial work on this project developed a list of 26 options for mitigating San Francisco's fire following earthquake risk. The options were discussed and reviewed at a workshop held on June 8, 2015. Following this workshop, the risk reduction options were further investigated and examined from an approximate benefit-cost perspective, and the findings are summarized within this report. The most promising opportunities are identified in the Summary and are recommended to the City for implementation or further study.

Chapter 2 presents strategies for mitigating the City's fire following earthquake risk. Chapter 3 summarizes the June 8, 2015 workshop and feedback received. Appendix A presents in its entirety a report authored by Corey Reynolds, prepared for ESIP under a separate project; the report has not been reviewed or formatted by ATC. References and a list of participants are provided at the end of the report.

Chapter 2

Strategies for Reducing Fire Following Earthquake Risk

This section presents and discusses twenty-six strategies for reducing fire following earthquake risk in San Francisco. The discussion for each option is divided into to six sections:

Background Information. This section presents relevant background information for each option, including whether the option has been tried before in San Francisco or elsewhere, information specific to San Francisco related to the option, and insights from relevant literature.

Description of Option. This section describes the option and how it might be implemented. It explores various ways to implement each option, including voluntary, triggered, and/or mandatory programs, as appropriate.

Benefits. This section identifies and summarizes the qualitative benefits of the option, including how and roughly how much this option could reduce fire risk. While quantification of benefits was beyond the scope of this project, for selected options a rough order-of-magnitude estimate of the benefits derived by implementing the option given a magnitude-7.9 scenario event (ATC, 2010a and b) is provided. Cost impacts are based on 2015 dollars.

Feasibility. This section discusses the feasibility of implementing each option and identifies potential implementation challenges.

Cost. This section provides a rough estimate of the cost of implementing the option, in 2015 dollars. The cost estimate is for the entire cost to implement the option, including costs borne by individuals, the City, and others.

Recommendation. This section presents the recommended course of action for each option. Recommendations are based on the workshop input (see Chapter 3), discussions with City agencies, a review of relevant literature, and the experience of the report author.

The estimates of benefits and costs are based on judgments of the ATC Lead Technical Consultant. Where possible, any quantitative basis for these estimates is provided.

A complete list of all options are listed in Table 2-1.

Table 2-1 Options for Reducing Fire Following Earthquake Risk in San Francisco

Overall Intervention	Option No. and Title	
Reduce Ignition	1	Earthquake early warning
	2	Gas seismic shutoff devices
	3	Mandatory gas valve wrenches
	4	Finer gas blocking and valving
	5	Gas appliance bracing
	6	Electric shut off panels, meters, or plugs
	7	Improved high school chemistry lab housekeeping
	8	Improved commercial/industrial chemical housekeeping
	9	Seismic retrofit of additional buildings
	10	Household required fire extinguishers
Timely Reporting	11	Remote sensing / drones
	12	Smartphone 911 capability
Reduce fire spread	13	Protection of openings
	14	Intumescent paint
	15	More sprinklers
Enhance Firefighting Capacity	16	More San Francisco Fire Department staffing
	17	Expanded NERT and Auxiliary Reserve
Enhance Water supply reliability	18	Increased foam capacity
	19	Additional AWSS pipe network
	20	Flexible water supply system
	21	Third AWSS pump station
	22	More cisterns
	23	More robust potable water supply distribution network
	24	AWSS dedicated engineer
	25	Third fireboat
Reduce casualties	26	Buddy system for vulnerable populations

2.1 Earthquake Early Warning

Background Information. Earthquake early warning is an emerging technology that can provide seconds to tens of seconds of warning that earthquake shaking will occur at a given location. Earthquake early warning systems take advantage of the fact that electronic signals can travel much faster than damaging earthquake S-waves. First, sensors detect earthquake shaking. Then, rapid analysis is conducted to assess the size and location of the earthquake. Finally, a warning is transmitted to nearby communities or facilities. This entire process of detection, processing, and transmission of warning can be accomplished in a few seconds, such that warnings can be received seconds to tens of seconds in advance of damaging shaking, depending on the distance from the earthquake epicenter to the population at risk (Kanamori et al., 1997; Scawthorn and Kanamori, 2008).

Earthquake early warning systems have been developed and implemented in Japan (Fujinawa and Noda, 2013), Turkey (Erdik, 2005), and Mexico (Espinosa-Aranda et al., 2005). Japan's system had its first major test in the 2011 Tohoku earthquake, during which it provided 5 to 10 seconds of warning to coastal residents close to the shore and 30 seconds for residents of Tokyo. These warnings were distributed via television, radio, internet, and cell phone to residents (USGS, 2012).

In California, earthquake early warning prototype systems exist (Grapenthin et al., 2014; Given et al., 2014). ShakeAlert is a prototype earthquake early warning system for the west coast, developed and operated by the U.S. Geological Survey and university partners (see www.shakealert.org). Figure 2-1 shows a screenshot of the ShakeAlert Earthquake Early Warning system during testing (that is, not during a real earthquake warning). ShakeAlert currently is in the demonstration phase. It has provided warning for some small California earthquakes. For example, it provided 5 seconds of warning to test users in Berkeley and 9 seconds of warning to test users in San Francisco during the 2014 South Napa earthquake (USGS, 2014). Selected fire stations in California have limited deployment of Shakealert, but full deployment and availability of timely warnings to the public is not yet available.

The City of San Francisco currently can receive warnings of shaking from the ShakeAlert system, but has not yet integrated these warnings comprehensively into City functions. For example, San Francisco fire stations are not yet connected to the system. The City has already acknowledged the importance of advancing the use of earthquake early warning in San Francisco in *Resilient San Francisco* (CCSF, 2016).

Description of Option. The City should identify, assess, and implement ways to use the earthquake early warning information it already receives from ShakeAlert to reduce post-earthquake fire risk.

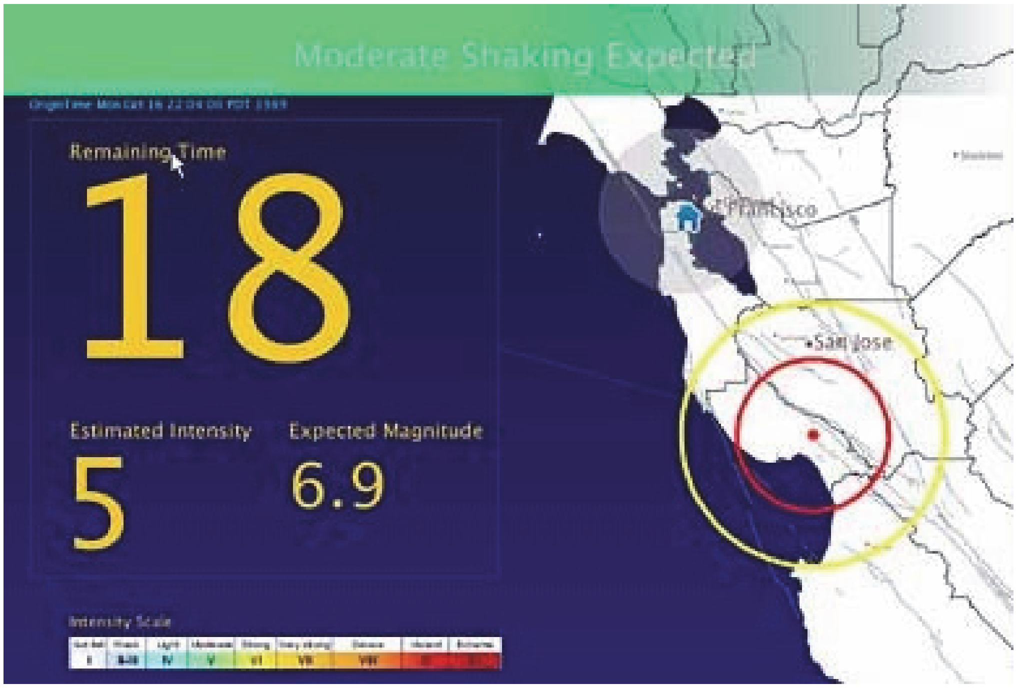

Figure 2-1 ShakeAlert Earthquake Early Warning screenshot (sample, not real earthquake; from www.shakealert.org, last accessed June 2017).

While the development of an established earthquake early warning system is in the hands of others, San Francisco could pursue several strategies for this option:

- Advocate for a funded, operational earthquake early warning system in California.
- Implement programs to use and test the prototype ShakeAlert system in the San Francisco Fire Department.
- Plan public awareness programs for the public using the prototype system. This messaging could focus on specific actions the public and businesses should take when a warning occurs. Education of the public for earthquake early warning has been implemented in Mexico and Japan (Fujinawa and Noda, 2013).

Benefits. A functional earthquake early warning system could help reduce San Francisco's post-earthquake fire risk in a number of ways, including the following:

- Fire fighting apparatus could be made more accessible by automatically opening fire station doors.
- Some ignition sources could be removed via automated shut down when a warning occurs. The number and types of sources are very large,

ranging from households to large industrial processes. Automated shutdown would require development and installation of such devices; such technologies are becoming increasingly available.

- Individuals and businesses can manually shut off stoves and other sources of open flame or ignition when a warning occurs. This requires education of the public, as well as widespread transmittal of the warning to the public.

It is difficult to precisely quantify the benefits of earthquake early warning, particularly since the information can be used in a variety of ways. Sources of ignition vary with region and time of day. A rough breakdown of ignition sources in the 1994 Northridge earthquake is provided in Table 2-2. If it is assumed that a fraction of ignitions, for example electrical sources, would be reduced by 20% given earthquake early warning (i.e., a reduction from 56% to 45%, which is probably optimistic), this is a net reduction of total ignitions of 11% due to earthquake early warning only (it is noted that gas seismic shutoff devices, which are discussed in the next section may require a different signal for shutdown). The fire following earthquake process is non-linear, and it is possible that reducing overall ignitions by 11% might reduce fire following earthquake losses for the magnitude-7.9 scenario event by as much as $1 billion.

Table 2-2 General Sources of Ignition, Los Angeles Fire Department Data, Northridge Earthquake (Scawthorn et al., 1998; TCLEE, 2005)

Source	Fraction
Electrical	56%
Gas-related	26%
Other	18%

Feasibility. As discussed above, earthquake early warning systems are operational in Japan, Turkey, and Mexico, thus, such systems are technically feasible. It appears that the general obstacle to implementing an earthquake early warning system in California is mainly institutional and financial.

Cost. The cost of implementation is challenging to estimate. As an example, if it is assumed that $100 per San Francisco resident is budgeted towards implementation of earthquake early warning in fire stations, schools, and public buildings, the cost would be $80 million, not considering private sector implementation. Considering that the benefits of implementing this system are not limited to fire following earthquake, but also to provide safety due to earthquake shaking, with a likely benefit of $1 billion, the cost of implementing the system would be far outweighed by the benefit.

Recommendation. Earthquake early warning is highly beneficial in many regards, not least of which is in reducing the potential for fire following earthquake. Earthquake early warning is already operational in Japan, Mexico City, and Turkey, and is feasible in California. Given the proximity of the San Andreas and Hayward faults to San Francisco, earthquake early warning may in some cases only be a few seconds, but in other cases could be significantly longer. In either case, its benefits are clear and tangible, especially with automatic actions.

It is recommended that the City of San Francisco:

- Strongly encourage the U.S. Geological Survey (USGS), the California Geological Survey (CGS) and other agencies to move forward in a timely manner to operationalize earthquake early warning in California.
- Strongly encourage the state and federal government to provide the necessary funding to accomplish operationalization.
- Begin preparing for an operationalized earthquake early warning capability within the next few years. Examples of preparation include development of warning dissemination methods, such as annunciators, sirens, and mobile phone messages, training of staff and children at schools, hospitals, emergency responders, City employees, commercial and industrial sectors, and citizens in general on what to do in case of an earthquake early warning.
- Begin researching and deploying automatic systems that use the earthquake early warning signal to reduce ignitions and assist emergency response.

2.2 Gas Seismic Shutoff Devices

Background Information. Natural gas is widely used in most homes in California for cooking and heating. In San Francisco, it is distributed by Pacific Gas and Electric (PG&E) via buried pipe to each customer's location, where it passes through a meter and into the piping within the customer's building. Buried pipes can break and cause major fires, which occurred in the 1994 Northridge earthquake. Table 2-3 shows the number of ignitions related to gas in a selection of earthquakes. More significantly, the piping and gas appliances within a building are displaced during shaking and might leak gas, which has happened in a number of earthquakes. Leaking gas by itself does not result in fire, but ignition sources are common, and leaking gas will often ignite. Thus, it is important to prevent gas leaks following an earthquake.

Table 2-3 Summary of Building Fire Ignitions for Recent Earthquakes (ASCE, 2002)

Earthquake	Magnitude	Earthquake Fire Ignitions	Gas-Related Fire Ignitions
1964 Alaska	9.2	4-7	0
1965 Puget Sound	6.7	1	?
1971 San Fernando	6.6	109	15
1983 Coalinga	6.2	1-4	1
1984 Morgan Hill	6.2	3-6	1
1986 Palm Springs	6.2	3	0
1987 Whittier	5.9	6	3
1989 Loma Prieta	7.2	67	16
1994 Northridge	6.7	97	54
1995 Kobe	6.9	205	36

Devices to restrict unwanted gas flow in the event of an earthquake are termed gas seismic shutoff devices, which can refer to several different kinds of devices (ASCE, 2002):

1. **Seismically actuated gas valves.** In-meter or post-meter in-line devices that are triggered by shaking and close the gas service line, either by triggering closure of a valve or dropping a ball or other object that plugs the line.

2. **Excess flow devices.** In-meter or post-meter in-line devices that are triggered when the gas flow exceeds a specified amount, on the assumption that a large flow is extraordinary and probably due to a leak or break. Strictly speaking, excess flow devices are not specifically triggered by an earthquake and will permit gas to flow as long as the flow does not exceed the specified limit, but can be beneficial following an earthquake.

3. **Manual shutoffs.** Installed by the gas utility before the meter, and which can be manually closed by the owner or others, usually requiring a wrench.

4. **Network block valves.** Valves within the gas utility's distribution system can be closed, manually, sometimes remotely or even automatically, and thus isolate one or more city blocks or areas. Even if closed, however, residual gas in pipes can leak and fuel fires.

Seismically actuated gas valves are required in a number of jurisdictions in California. For example, Los Angeles requires seismically actuated gas valves in newly constructed buildings; commercial buildings conducting additions, alterations, or repairs of more than $10,000; buildings sold; and when the gas meter is replaced. Figure 2-2 provides more information about the Los Angeles requirements.

CITY LA DBS DEPARTMENT OF BUILDING AND SAFETY

INFORMATION BULLETIN / GENERAL INFORMATION

REFERENCE NO.: LAMC 94.1219.0 L.A. Ords. 171874, 174478 and 180670 — Effective: 01-01-2008 Revised: 10-22-2009

DOCUMENT NO.: **IB P/PC 2008-001**

Previously Issued As: IB P/PC 2002-001

SEISMIC GAS AND EXCESS FLOW SHUT-OFF VALVES REQUIREMENTS

Los Angeles City Ordinance 174478 and Section 1219.0 of the Los Angeles Plumbing Code (2008 Edition) require that seismic gas shut-off valves shall be installed on designated buildings within the City. Seismic gas shut-off valves are designed to automatically shut off the supply of natural gas to a building during a major earthquake to prevent a fire or explosion from occurring due to the possible accumulation of gas in the building. Excess flow shut off valves are designed to automatically shut off when a significant gas leak or over pressure surge occurs downstream of the valve.

The provisions of this Ordinance shall apply to:

- All new buildings constructed after September 1, 1995.
- Commercial buildings performing additions, alterations, or repairs with a building permit issued after September 1, 1995 and a valuation of greater than $10,000.
- Residential buildings performing additions, alterations, or repairs with a building permit issued after January 10, 1998 and a valuation of greater than $10,000.
- All buildings sold in the City after February 5, 1998. A seismic gas valve must be installed prior to entering into an agreement for sale or prior to the close of escrow when an escrow agreement has been executed in connection with the sale.
- Alterations or additions to the fuel gas piping system which involve the replacement of the gas meter.

Figure 2-2 City of Los Angeles Seismically Actuated Gas Valve requirement.

San Francisco currently does not require seismically actuated gas valves. The gas utility serving San Francisco, PG&E, is non-committal on the subject of seismically actuated gas valves, as shown in the statement appearing in Figure 2-3.

Figure 2-4 shows one type of in-line seismically actuated gas valve currently available in California. This is an after-market device installed by the customer downstream of the meter, at his/her own expense. In Japan, the use of in-meter or “intelligent meter” seismically actuated gas valves is required by law.

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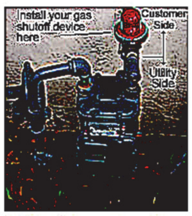
Gas Shutoff Devices

Gas Service Shutoff Valves

Manually turning off the gas service shutoff valve is the most common method to stop the flow of gas serving a building, or part of a building, in case of an emergency. Gas service shutoff valves are installed by PG&E at all gas meter locations or outside locations if the meter is not accessible from the outside.

- Keep a 12 to 15-inch adjustable pipe wrench or Crescent-type wrench available to close the valve in case of an emergency. Earthquake wrenches with fixed openings may not fit a particular valve, so an adjustable type is best. To minimize the possibility of unauthorized operation of the valve, wrenches should be located nearby, but not at the gas meter location.
- Shut off the gas service shutoff valve only if you smell gas, hear gas escaping, see a broken gas line, or if you suspect a gas leak.
- To shut off the gas, rotate the valve a quarter turn in either direction; the valve is closed when the tang (the part you put the wrench on) is crosswise to the pipe.
- In addition, most gas appliances have a gas shutoff valve located near the appliance that lets you turn off the gas to that appliance only. Know which of your appliances use gas, and where the appliance gas shutoff valves are located. In some cases, turning off the gas at the appliances shutoff valve will suffice.

Automatic Gas Shutoff Devices



Some cities and counties have regulations that require the installation of automatic gas shutoff devices, which may include excess flow gas shutoff valves and/or earthquake actuated gas shutoff valves. Regulations vary, but generally apply to new building construction, or significant alterations or additions to existing buildings. Check with your local city or county agency to see if regulations apply in your area.

If a customer installs an excess flow gas shutoff valve or earthquake actuated gas shutoff valve, it should be one that is certified by the State of California and it should be installed by a licensed plumbing contractor in accordance to the manufacturers instructions. PG&E does not install or service seismic actuated or excess flow gas shutoff valves, or recommend specific contractors for customer applications.

The State of California is required to approve all excess flow gas shutoff valves and earthquake actuated gas shutoff valves used in the State of California. The State of California is required to approve all excess flow gas shutoff valves and earthquake actuated gas shutoff valves used in the State of California. A list of approved valves is available on the DSA Gas Shut-off Valves Certification Program webpage.

Excess flow gas shutoff valves and earthquake actuated gas shutoff valves must be installed on the buildings gas houseline piping (the gas pipe connecting your appliances to the gas meter) downstream of the utility point of delivery; i.e. after the PG&E gas shutoff valve, pressure regulator (if installed), meter(s), and the service tee. No attachments or connections of any kind are allowed on utility facilities prior to the point where the service tee connects to the gas houseline piping. Once installed, the valve must not obstruct the operation or serviceability of PG&E's piping, gas service shutoff valve, gas meter or gas pressure regulating equipment.

In the event that a gas service shutoff valve or an automatic gas shutoff device is closed, there may be a considerable delay before PG&E can turn your service on, but do not turn it on yourself. PG&E or another qualified professional should perform a safety check, restore gas service, and relight any appliance pilots, even if the closure was not caused by an earthquake.

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Figure 2-3 PG&E statement regarding seismically actuated gas valves (information from Pacific Gas and Electric company website, 2015).

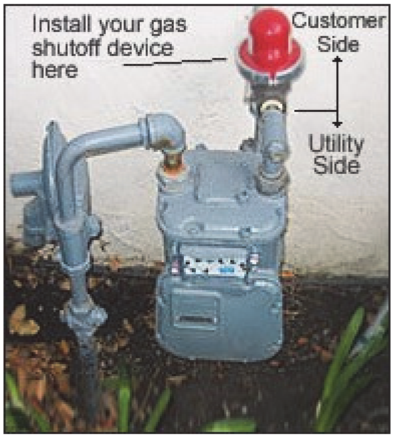


Figure 2-4 In-line seismically activated gas valve (colored red) for a typical residential meter. Commercial/industrial installations would be larger (PG&E, 2015).

Description of Option. This option focuses only on seismically actuated gas valves, valves that shut off gas service when earthquake shaking occurs. The City could pursue a number of approaches to implement a gas seismic shutoff device program. However, as noted below, such programs would only lead to meaningful reductions in fire ignitions if a critical mass of buildings have the devices. Based on past experiences, voluntary and incentive-based programs are unlikely to achieve this, so they are not mentioned here. The City could pursue two effective options:

- Mandate that all buildings install gas seismic shutoff devices by a specific date. This mandate could be applied citywide or only in targeted neighborhoods that are particularly dense or otherwise at high risk of post-earthquake fire ignitions.

- Require all new construction to incorporate gas seismic shutoff devices and trigger a required installation of the devices when buildings are sold or change ownership; undergo additions, alterations, or repairs; or replace their gas meters. This is akin to the approach taken in Los Angeles. Again, this could be applied citywide or only in specific, at-risk neighborhoods. Within a couple of decades, this would result in widespread gas seismic shutoff device installation.

Benefits. Installing seismically actuated gas valves on only some buildings in a densely built-up neighborhood is likely to be relatively ineffective. For example, a San Francisco neighborhood of 4,000 buildings (equivalent to an area of eight by ten city blocks in the Richmond) subjected to the magnitude-7.9 scenario earthquake shaking intensity would average about one major fire. If 10% of those buildings (i.e., 400 buildings) install gas seismic shutoff devices, they reduce the probability of ignition by only 2.5%, in other words, very little. If all 4,000 buildings install gas seismic shutoff devices, the probability of ignition is reduced by about 25%. The situation is analogous to vaccination for an epidemic: universal vaccination is required to prevent the disease.

It is difficult to precisely quantify the benefit of seismically actuated gas valves. If all gas-sourced ignitions were prevented, ignitions might be reduced on the order of 25%. The fire following earthquake process is non-linear, and reducing ignitions by this amount might reduce fire following earthquake losses for the magnitude-7.9 scenario event by perhaps as much as $2 billion. On a percentage basis, the benefits for smaller magnitude events may be even greater.

One significant concern associated with seismically actuated gas valves is that, after an earthquake, utility providers would need to restore natural gas service in every building in which the valves were closed. This involves performing a meter-by-meter safety check, reviewing any possible gas leaks in the building (including checking all appliances), restoring gas service, and relighting any appliance pilots, which requires access inside units. This is labor intensive and would likely require a significant length of time to be completed and for gas service to resume for all customers. The City might need to provide heat and cooking facilities for vulnerable residents, such as seniors, during this time.

Feasibility. Installation of gas seismic shutoff devices is clearly feasible as it is required in a number of California cities (see Appendix A). A peculiarity of gas installations is that the gas line up to the meter is the property of the gas utility, so that in-line gas seismic shutoff devices have to be installed after the meter. In a multi-unit dwelling, each unit typically has its own meter, so that a ten-unit building, for example, would require ten gas seismic shutoff devices. In-meter gas seismic shutoff devices, such as those used in Japan, similarly require each meter to be replaced. A program to replace all meters with these devices might be similar to PG&E's recently completed "SmartMeter" program, in which several million meters were replaced so as to permit automated rather than manual meter reading.

Cost. Data on the number of natural gas customers in San Francisco are not readily available. However, according to the 2010 Census there are 345,000 households and 32,000 business establishments in San Francisco, so a reasonable estimate of the number of meters might be approximately 400,000. The cost of an installed in-line gas seismic shutoff device is in the range of $500 to $1,000, so that the cost of a mandatory program might be on the order of $200 to $400 million. This cost is less than but on the same order of magnitude as the benefit derived, considering only the economic value of the damage. If the cost of destroyed homes, in terms of possessions, lack of habitability, displacement, loss of a labor force, is considered, the benefit would be significantly greater than the cost in the case of a major conflagration.

Recommendation. Gas seismic shut off devices have been available for decades, with thousands of homeowners installing them at their own expense. However, to be effective, particularly in high density neighborhoods such as Russian Hill and the Mission, gas seismic shut off devices have to be installed on essentially all gas service lines. Similar to inoculation for contagious disease, partial measures are inadequate. Los Angeles for the last decade has required gas seismic shut off devices on all new buildings and major renovations, and San Francisco should study taking similar steps.

It is recommended that:

- The City's Lifelines Council should work with the local gas utility to develop a transparent understanding of the City's risk due to fires arising from gas services and appliances in an earthquake. This should include understanding how quickly operators can isolate portions of the gas network within the City.
- The City should assess which neighborhoods are most at risk due to fire following earthquake and, thus, where gas seismic shut off devices would be most cost-beneficial, because not all portions of the City may need gas seismic shut off devices.
- The City, with or without the cooperation of the local utility, should develop a program, either mandated or triggered by renovations or other events, with the goal of having neighborhoods identified as at high risk of fire following earthquake be protected in a timely manner by gas seismic shut off devices.

2.3 Mandatory Gas Valve Wrenches

Background Information. As noted above, gas lines have manual shutoff valves. This means that a human with a wrench is a "gas seismic shutoff device." Currently, the San Francisco Building Code Section 712 (CCSF, 2017) requires apartment houses and hotels to have gas valve wrenches close to their gas meters. This is not currently required for smaller residences.

Description of Option. This option consists of simply requiring all gas meters to have a suitable wrench attached to the gas line near the manual shutoff valve, as shown in Figure 2-5. This is an expansion of the existing code requirement mentioned above. In the event of an earthquake, anyone can conduct a quick quarter-turn of the valve with the wrench and shut the gas off.

Figure 2-5 "Earthquake wrench" tied to gas line, ready for use.

A City mandate could include a public outreach campaign informing residents of the mandate, where to purchase appropriate wrenches, and how to use them.

Benefits. If 100% of gas services are shut off, the savings might be as much as $2 billion. However, not all services will be quickly shut off, due to distractions, confusion, occupants being away from the premises, and oversight following an earthquake, so a significantly lower benefit is more appropriate. Like the previous option, any time gas lines are shut off, it can be costly and time-consuming to restore service, potentially leading to an extended period without gas service (and, therefore, heat, hot water, and cooking facilities) in some homes and businesses.

Feasibility. While mandatory programs of any kind can be resented and an uphill battle politically, this mandate is very inexpensive and easy to fulfill, which might reduce opposition. A key issue is assuring compliance over time. Ideally, this would be incorporated into regularly occurring inspections for multi-unit dwellings and businesses, and perhaps real estate transactions for San Francisco homes (similar to strapping water heaters).

Cost. Purpose-made gas shutoff wrenches are very inexpensive, as indicated in Figure 2-6, and would be even less costly if bought in bulk. The cost for the entire city would be a maximum of several million dollars, so that the benefit-cost is very large.

Figure 2-6 Sample online pricing for an emergency gas shut-off wrench, viewed November 2015.

Recommendation: This option is low cost and could reduce fire ignitions; however, due to the challenges of implementing a mandatory program, efforts are likely best spent on other options. The City should continue voluntary programs to increase the number of gas wrenches and improve efforts to educate the public about their proper use.

2.4 Finer Gas Blocking and Valving

Background Information. Natural gas is distributed via a buried pipe network in San Francisco. This system is described in *Lifelines Interdependency Study* (CCSF, 2014) as follows:

> *"San Francisco receives natural gas from three gas transmission lines that enter from the Peninsula and meet at a single point in San Francisco. Gas is then distributed throughout the City. Damage in two or three transmission lines could result in a pressure loss and gas service would be curtailed throughout the City. Flexible gas distribution lines installed throughout the city are not likely to have significant damage. Any gas*

leaks would be controlled through 2,200 manually operated valves located throughout the City."

It is worth noting that not all gas pipelines in the city are flexible. Non-flexible pipelines, including service laterals, could experience damage in an earthquake.

In the event of an earthquake, damage to the transmission and distribution network can be isolated by manually operated valves. It will take some time, however, for utility personnel to travel to and close such valves.

Tokyo Gas, on the other hand, developed a sophisticated damage assessment system in the 1990s that allows quick estimation of network damage after an earthquake, which can then be isolated via remotely operated valves (Nakayama et al., 2004). Figure 2-7 presents a discussion of Tokyo's system.

SUPREME 超高密度リアルタイム地震防災システム

SUPREME by Tokyo Gas is an earthquake disaster prevention system that utilizes a high concentration of installed seismographs. The system has the capacity to gather earthquake information from approximately 4,000 locations and monitors the safety of the area through its ability to remotely stop the supply governor, as well as estimate the damage sustained by gas pipes. When a large-scale earthquake occurs, the system utilizes the data that it acquires from its seismographs to ascertain the damage within five minutes from the start of the initial shaking. By around ten minutes after the start of the earthquake, supply governors are remotely operated to stop gas supplies to areas where large-scale damage is expected, thus acting swiftly to provide safety.

Figure 2-7 A description of Tokyo's remotely operated gas valves.

Description of Option. This option proposes a system of seismically triggered or remotely operated valves to isolate gas transmission and distribution line damage after an earthquake, reducing fire spread.

Benefits. This option could result in nearly a 30% reduction in fire spread, worth perhaps a billion dollars. The system would also assure quick isolation in the event of a non-earthquake pipeline break, such as that occurred in 2010 in San Bruno.

Feasibility. Technically, this option is quite feasible. It has been implemented in Tokyo and the San Francisco Fire Department has a series of seismically-triggered automatic shutoff valves for the Auxiliary Water Supply System (AWSS) that employ a similar technology since the early 1990s.

The City and County of San Francisco can advocate for this to occur, however, decision-making and implementation of this option rests with the Public Utilities Commission and utility providers, outside of the City's control.

Cost. The costs of this option are difficult to assess. As an estimate, if each seismically triggered valve were to cost, say, $2 million (including prorated Supervisory Control and Data Acquisition (SCADA) cost), the 49 square miles of San Francisco could be gridded into half mile grids (i.e., about 200 valves) for $400 million. While a very substantial cost, this equates to $5 per capita and is significantly less than the $2.8 billion cost (to date) of the San Bruno gas explosion (see Baker, 2015).

Recommendation. This option could reduce post-earthquake fire ignitions. However, implementation of this option is not in the hands of the City. It is recommended that the City maintain dialogue with gas utility providers through its Lifelines Council and discuss this option through that forum.

2.5 Gas Appliance Bracing

Background Information. Gas appliances can cause fires due to their pilot lights or, in the case of stoves, due to the cooking flame. Current code requires tip prevention devices, flexible gas piping, and excess flow valves to be installed at appliance connections for gas ranges, furnaces, water heaters, dryers, and gas log fireplaces. Bracing is already required for water heaters, illustrated in Figure 2-8, but is not required for stoves or furnaces. Bracing of water heaters is specifically noted as a disclosure at time of residential real estate transactions. However, it is important to note that, although required, not all water heaters are properly braced. Anecdotally, some experts state that a notable percentage of water heaters are inadequately braced and are not in compliance with existing regulations. Water heaters, due to their pilot lights and tall, heavy tanks are especially prone to tipping and causing ignitions during earthquake shaking. Figure 2-9 shows a typical brace for the foot of a stove.

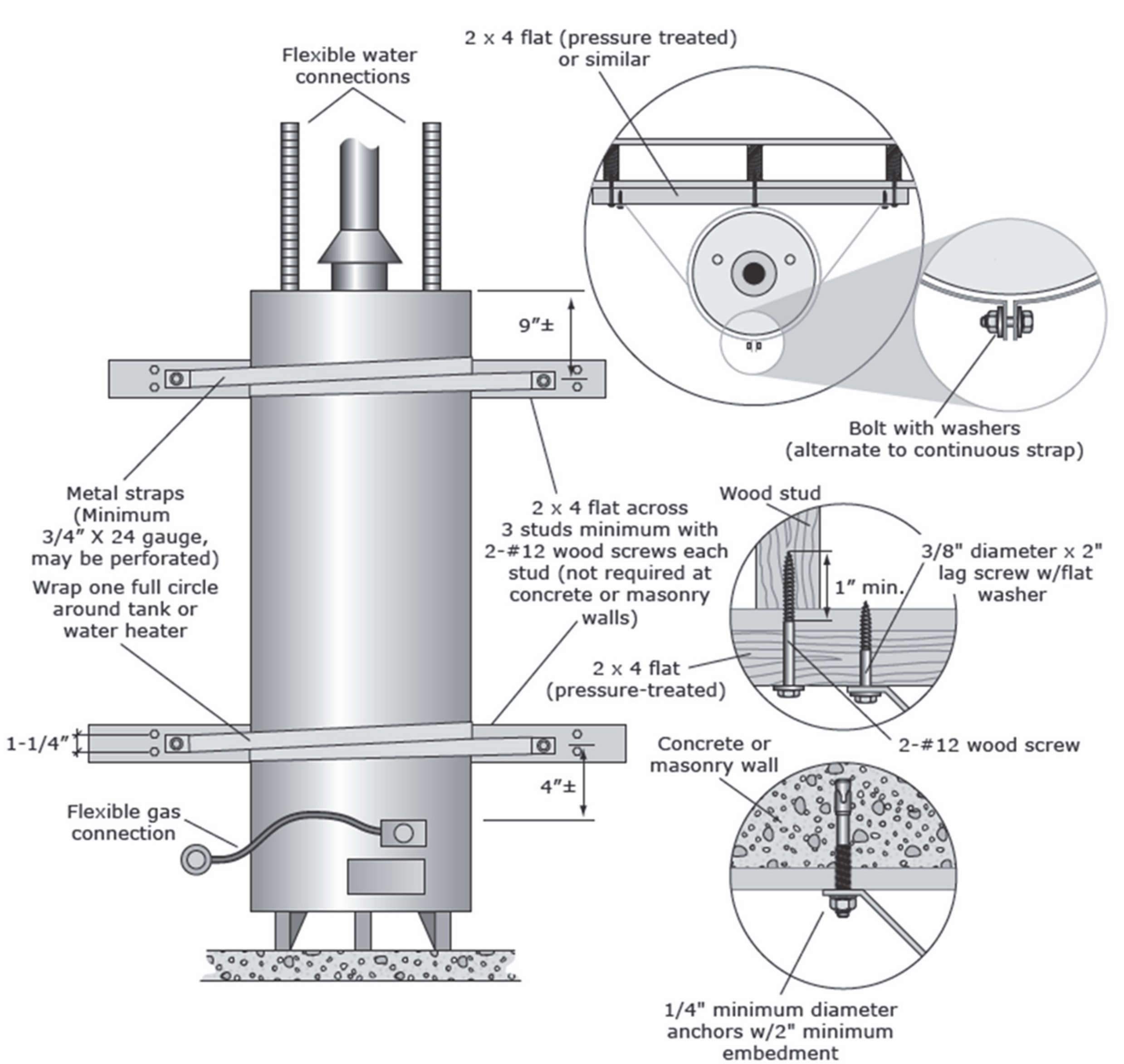


Figure 2-8 Water heater bracing according to FEMA (2012).

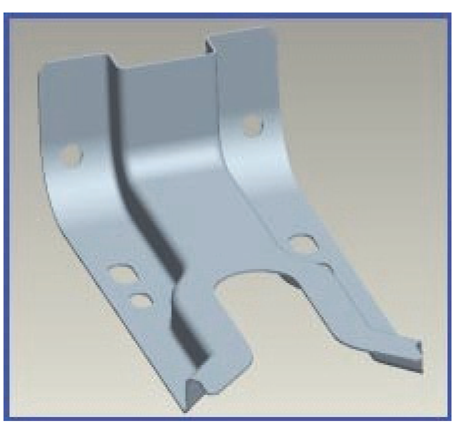


Figure 2-9 Brace for stove leg.

Description of Option. This option would require seismic bracing of stoves and other gas appliances. It could also include a program to improve compliance with existing water heater bracing regulations, such as training inspectors and installers.

Benefits. This option would reduce gas-related ignitions by some fraction, with perhaps an overall ignition reduction of 5%, equivalent to several hundred million dollars.

Feasibility. Water heater technicians have a legal requirement to brace water heaters when they are replaced, and with the average life of a water heater being about seven years, the majority of water heaters are now braced. Bracing stoves, furnaces, and other gas appliances could be pursued in a similar way. Technicians could be required to install bracing when appliances are installed. Ensuring compliance and proper bracing could be a challenge, since installations are not always accompanied by inspections. This challenge has been observed in water heater bracing; anecdotal reports indicate that many are improperly braced. Over time, however, the percentage of appliances that are braced would increase notably.

Cost. Assume $100 per household, or a total cost in the City of perhaps $30 million.

Recommendation. This option could potentially reduce fire ignitions. The City should study the costs and effectiveness of this option more. Perhaps most cost effective approach would be for the City to develop training programs to improve compliance with existing water heater bracing regulations.

2.6 Electric Shut Off Panels, Meters, or Plugs

Background Information. In recent earthquakes, electricity has been responsible for approximately half of all ignitions (see Table 2-2). Electric seismic shutoff devices curtail electric power in the event of an earthquake. Figure 2-10 illustrates two types of electric seismic shutoff devices: a switch and a panel board. These and similar devices shut off electrical service to a specific piece of equipment or an entire building when earthquake shaking occurs. Potentially, electric shutoff devices could eventually be linked with earthquake early warning system signals.

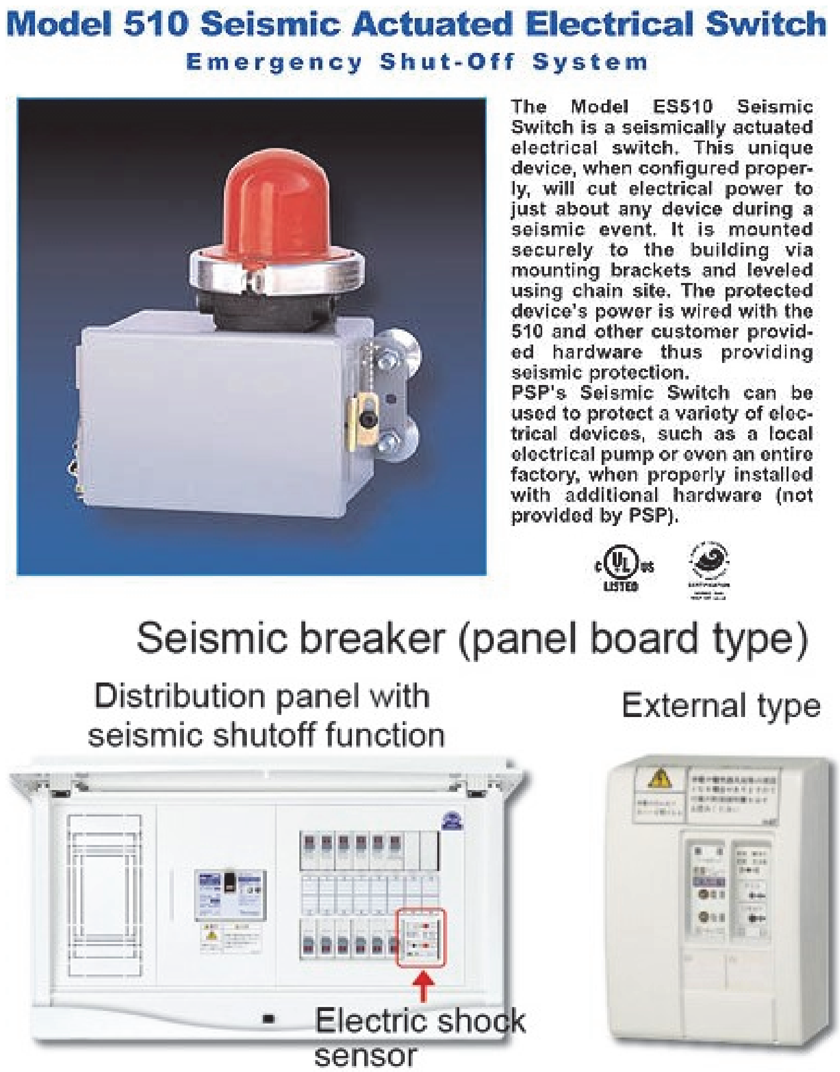


Figure 2-10 Examples of electric seismic shutoff devices: switch and panel board types (Pacific Seismic Products, 2014; City of Yokohama, 2014).

Description of Option. Two options for implementing installation of electric seismic shutoff devices are:

- Mandate all buildings to install electric seismic shutoff devices by a specific date. This mandate could be applied citywide or only in targeted neighborhoods that are particularly dense or otherwise at high risk of post-earthquake fire ignitions.
- Require all new construction to incorporate electric seismic shutoff devices and trigger a required installation of the devices when buildings are sold or change ownership; undergo additions, alterations, or repairs; or replace their electric meters.

Benefits. The efficacy of these devices depends on whether all electric usage is affected (e.g., panel device) or only selected appliances. It also depends on whether or not electric service is disrupted by the earthquake; after most recent earthquakes of notable size, electricity has gone out for some length of time. However, recent efforts to improve electrical systems could mean that there is a higher likelihood of continued service after an earthquake. Note that electrical shutoff devices do not have the same "relight" concern as gas shutoff devices (see Appendix A). Consumers can generally restart their electrical service safely on their own.

Since about half of all ignitions are electric-related, the potential reduction could be significant if all or many buildings in San Francisco had these devices, although it is difficult to quantify the benefits at present. A rough estimate is that widespread installation of these devices might reduce ignitions by, perhaps, 20%, equivalent to more than $1 billion.

Feasibility. Similar to gas seismic shutoff devices, these devices would have to be widely employed to be effective. Thus, electric seismic shutoff devices would have to either be a triggered or mandated program, on the assumption that either approach would result in near total or universal device installation over time.

Cost. The cost of this option is difficult to determine. As a rough estimate, it is assumed to cost $500 per capita, which results in approximately $400 million total cost. This cost is comparable in order of magnitude to the benefit.

Recommendation. This option could reduce fire ignitions and is closely related to the option focused on gas seismic shutoff devices.

It is recommended that:

- The City work with the local power utility to develop a transparent understanding of the City's risk due to fires arising from electrical services in an earthquake.
- The City should assess which neighborhoods are most at risk due to fire following earthquake and, thus, where electric seismic shut off devices would be most cost-beneficial, because not all portions of the City may need such devices.
- The City, with or without the cooperation of the local utility, should develop a program, either mandated or triggered by renovations or other events, with the goal of having neighborhoods identified as at high risk of

fire following earthquake be protected in a timely manner by electric seismic shut off devices.

This work should be done as part of a comprehensive study on reducing ignitions caused by both gas and electrical sources.

2.7 Improved High School Chemistry Lab Housekeeping

Background Information. High school chemistry labs have been a source of ignitions in past earthquakes, due to spilled chemicals causing exothermic reactions (Scawthorn and Donelan, 1984). The San Francisco Unified School District currently has programs to eliminate chemical spills, including lips on shelving, stabilizing cabinets, inventories of chemicals at each site, avoidance of glass containers, and other good housekeeping practices. San Francisco also has a number of private high schools; their chemical laboratory housekeeping practices are unknown.

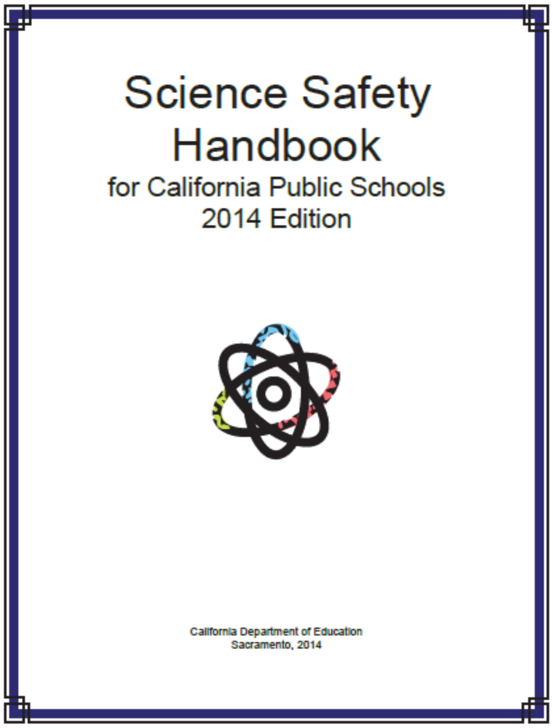
Description of Option. This option would increase administrative diligence about safe storage of hazardous materials in schools. The City could ensure that school officials remain cognizant of the importance of chemical housekeeping practices to limiting post-earthquake fires.

Benefits. Better housekeeping and enforcement of existing rules could reduce the number of ignitions by a small amount, although public schools already pursue good housekeeping. Figure 2-11 shows an excerpt from a state manual on safe storage of hazardous materials in schools.

Feasibility. Current practices in public schools on this issue might already be adequate.

Cost. Costs would be small. Since both costs and benefits are small, the benefit-cost is moderate.

Recommendation. This option could have a small impact on post-earthquake fire ignitions. It is recommended that the City keep the role of school chemistry labs in post-earthquake ignitions in mind, and raise the topic with public and private schools if concerns arise.

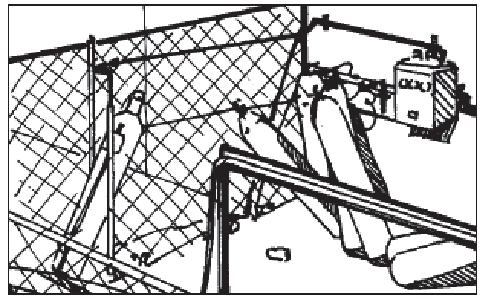


Yes No

2. **Hazardous/toxic materials**

a. Is there a current inventory of hazardous chemicals that would allow someone to check the chemicals after an earthquake? ☐ ☐

b. Are compressed gas cylinders tightly secured, with a nylon strap or strong chain near the top and near the bottom, or stored on a rack designed to restrain cylinders? ☐ ☐



Improperly stored gas cylinders

c. Are laboratory chemicals stored on shelves restrained by a wire, lip, or other barrier? ☐ ☐

d. Have chemicals been stored by compatible groups to reduce the likelihood of mixing them and causing reactions? ☐ ☐

e. Have chemicals been stored in plastic or other unbreakable storage containers? ☐ ☐

Figure 2-11 Public school chemistry laboratory housekeeping, handbook cover and example content (California Department of Education, 2014).

2.8 Improved Commercial/Industrial Chemical Housekeeping

Background Information. There are a number of commercial and industrial facilities in San Francisco that house chemicals that could contribute to post-earthquake fire ignitions and spread. Currently, hazardous materials are regulated by the state and enforced by the San Francisco Health Department and Fire Department. Locations that exceed certain quantities of designated substances are subject to special laws, and receive inspections and annual review. The state program is titled the California Accidential Release Prevention Program (CalARP; see http://www.caloes.ca.gov/FireRescueSite/Documents/CalARP%20Regulations%200101 2015.pdf). CalARP requires businesses with large amounts of regulated substances to develop a risk management plan, which analyzes accident risks at the site and identifies mitigation measures to reduce those risks.

Description of Option. This option would improve chemical housekeeping in commercial/industrial occupancies in San Francisco. This could be implemented in a few ways:

- For sites with significant quantities of chemicals of concern, require onsite inspections twice a year, instead of the currently required once a year.
- Require facilities with chemicals of special concern to have access to their own 24-hour response team to respond to incidents.
- Review current procedures, including education efforts for industrial site owners and inspectors and requirements for seismic bracing of tanks, piping, etc., to ensure that they are adequate or to develop improvements considering post-earthquake fire risk concerns.

Benefits. These steps could reduce ignitions a few percentage points.

Feasibility. Implementation of this option is eminently feasible through existing regulatory systems; however, this option would probably be seen as a regulatory burden to industry and could face opposition.

Cost. Some funding would be required for additional inspections but the greatest costs would be borne by commercial/industrial owners.

Recommendation. This option could potentially reduce fire ignitions. The City should conduct further study on the costs and benefits of this option.

2.9 Seismic Retrofit of Additional Buildings

Background Information. Collapsed buildings have historically had a high ignition rate. Preventing collapses can significantly decrease ignitions. Any City program to require or encourage seismic retrofits of buildings that could collapse would reduce the expected post-earthquake ignitions.

Description of Option. These programs could take a variety of forms—mandatory, triggered, or voluntary—with mandatory programs resulting in by far the highest number of retrofits, as discussed in other sources (e.g., CCSF, 2013), and therefore the largest reductions in post-earthquake ignitions.

Benefits. This approach is most effective if applied to many buildings, and is insignificant if only a few buildings are retrofitted. If many collapse hazard buildings are retrofitted, this option could reduce ignitions by a significant percentage, although this is difficult to assess quantitatively. The primary benefit of any retrofit program would be reduced shaking damage, with reduced ignitions as a secondary benefit.

Feasibility. The City is already undertaking an ambitious mandatory retrofit program for wood frame, soft-story buildings with three or more stories and five or more residential units. This program will reduce ignitions after future earthquakes. Mandatory retrofit programs for other collapse-hazard buildings, such as smaller residential wood frame soft-story buildings (especially three- and four-unit buildings), are programmatically feasible.

Cost. The cost of this option is very high, so that benefit-cost is low to moderate from the perspective of post-earthquake fire risk reduction, although the benefit-cost from an overall community resilience perspective would be much higher.

Recommendation. This option could reduce post-earthquake ignitions, but the implementation cost is high. While the City might pursue seismic retrofit programs for other reasons, post-earthquake fire risk reduction should be considered a supplementary benefit rather than the driving purpose for such programs.

2.10 Household Required Fire Extinguishers

Background Information. Having a fire extinguisher in every household, such as the type shown in Figure 2-12, could reduce the spread of fire following an earthquake as well as being good for fire safety in general. Currently, single family homes are not required to have fire extinguishers. Proper use of fire extinguishers is included as part of Neighborhood Emergency Response Team (NERT) trainings. It is important to note that fire extinguishers require regular maintenance to ensure that they remain effective and safe for use over time.

Figure 2-12 Home fire extinguisher.

Description of Option. The City could increase the number of households with fire extinguishers in a number of ways, such as conducting a public awareness campaign about the benefits of maintaining a fire extinguisher in each household, or requiring a functioning fire extinguisher in residences at the time of sale. Information on the City's emergency preparedness website (see www.sf72.org) could be supplemented with user-friendly information about proper use and maintenance of fire extinguishers.

Benefits. This option would make occupants better equipped to extinguish small ignitions, and would reduce the number of ignitions that grow into fires requiring professional response. This would also be very beneficial for non-earthquake fire reduction (Juås and Mattsson, 1994). The overall reduction in ignitions after an earthquake is difficult to assess, but would be perhaps a few percent.

Feasibility. A mandatory requirement may be politically difficult. A public voluntary campaign might help. One concern is that residents should prioritize their own safety over fire suppression; if in doubt, they should evacuate rather than using a fire extinguisher to suppress a fire. The City does not want to encourage untrained citizens to take inappropriate risks.

Cost. If many San Francisco households invested $15 for a fire extinguisher, this would total approximately $5 million. If this reduced even one large fire, the benefit-cost would be high.

Recommendation. It is recommended that the City mount a campaign to educate and encourage the public to have household fire extinguishers. This campaign should also cover how to use and maintain extinguishers. This program should investigate effective ways to encourage extinguishers in homes, such as educating school children who bring information home to parents, or programs similar to Neighborhood Watch. It should also explore ways to lower the cost, such as marketing campaigns by area retailers. Possibly there could be collaboration with new public housing projects or partnerships with local organizations such as Rebuilding Together.

2.11 Remote Sensing/Drones

Background Information. Confusion reigns following an earthquake. Locating and prioritizing fires that require response is a real challenge. Every minute of delay in fighting fires makes the problem worse. After a large earthquake, the Emergency 911 system is likely to be saturated with calls, as occurred after the Loma Prieta earthquake in 1989.

Unmanned Aerial Vehicles (UAVs), also known as drones, are uniquely capable of providing rapid visual and other information for firefighters. Such technology is increasingly being used in other communities, as shown in Figure 2-13.

San Francisco just lifted a temporary ban on the use of UAVs by City agencies, and now their use is allowed when adhering to specific guidelines (SFCOIT, 2017). Official UAV usage can raise privacy concerns and other issues. According to participants at the project workshop (see Chapter 3), in recent large fires, private owners of UAVs have voluntarily assisted the San Francisco Fire Department by using their drones as part of firefighting efforts. The City's new policy allows responsible use of drones by the Fire Department itself.

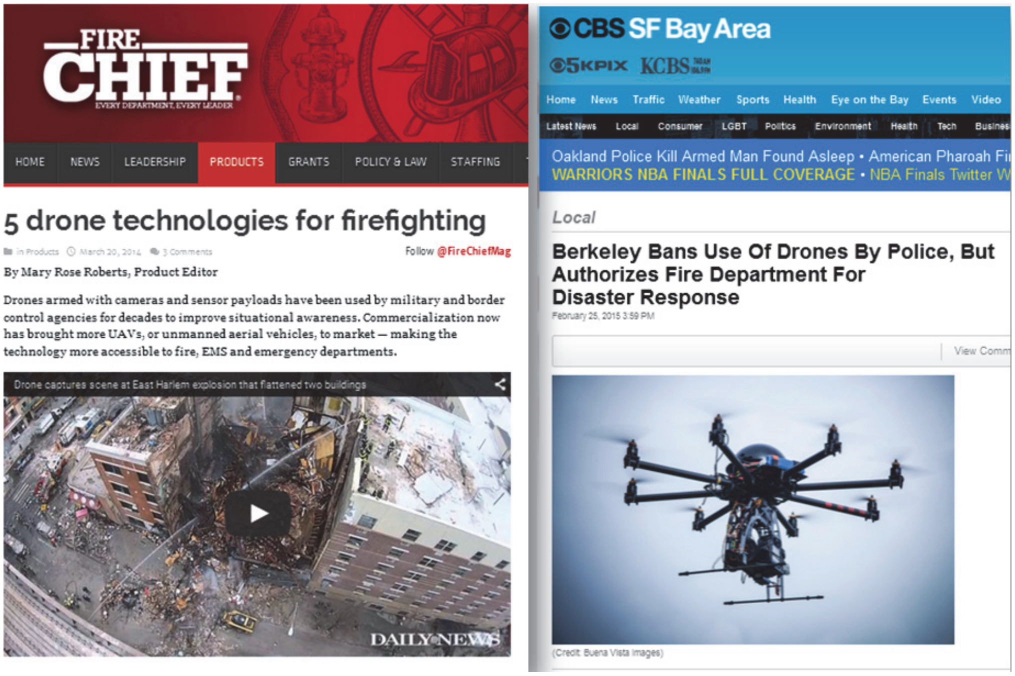


Figure 2-13 Remote observation emerging as a firefighting tool.

Description of Option. This option entails employing remote sensing technology through UAVs or drones to provide San Francisco Fire Department and/or the Department of Emergency Management with improved capacity to quickly obtain situational awareness after an earthquake. The SFFD could launch a pilot project to build capability in remote sensing and identify the best equipment, staffing support, and procedures.

Benefits. A very strong case can be made that UAVs are a critical tool for fighting fires, both after an earthquake and in general. Better situational awareness means faster response and more efficient utilization of resources (Lattimer, 2015). The benefit is difficult to quantify, but is significant.

Feasibility. Legitimate concerns exist regarding privacy rights, which are being addressed in City policy. In addition to drones, the Fire Department would also need a drone operator for each device, and would need staff and capability to analyze the incoming data.

Cost. This option would require purchase of drones and potentially specialized cameras with thermal/infrared scanning capabilities that cost tens of thousands of dollars for equipment, with costs decreasing as the technology matures. The option would also require staff training and time allocated to this purpose. Still, the benefit-cost of this option is high.

Recommendation. It is recommended that the City's key emergency response agencies, such as the Department of Emergency Management and the Fire Department, develop a pilot project for improving real-time situational awareness using UAVs. This capability will require not only data acquisition, but also improved methods of data processing, interpretation, and decision-making. A key focus of this program should be identifying ignitions that have significant conflagration potential, and real time projection of fire growth and spread, similar to that routinely employed for wildfires.

2.12 Smartphone 911 Capability

Background Information. There are many ways that a smartphone application could enhance the City's firefighting capability, such as an app that would allow the City to take advantage of citizen reports by smartphone after an earthquake. Smartphones, now ubiquitous, enable rapid multi-mode (i.e., voice, GPS location, camera) transmission of critical information to the Emergency 911 system. Figure 2-14 shows an example of software for this purpose.

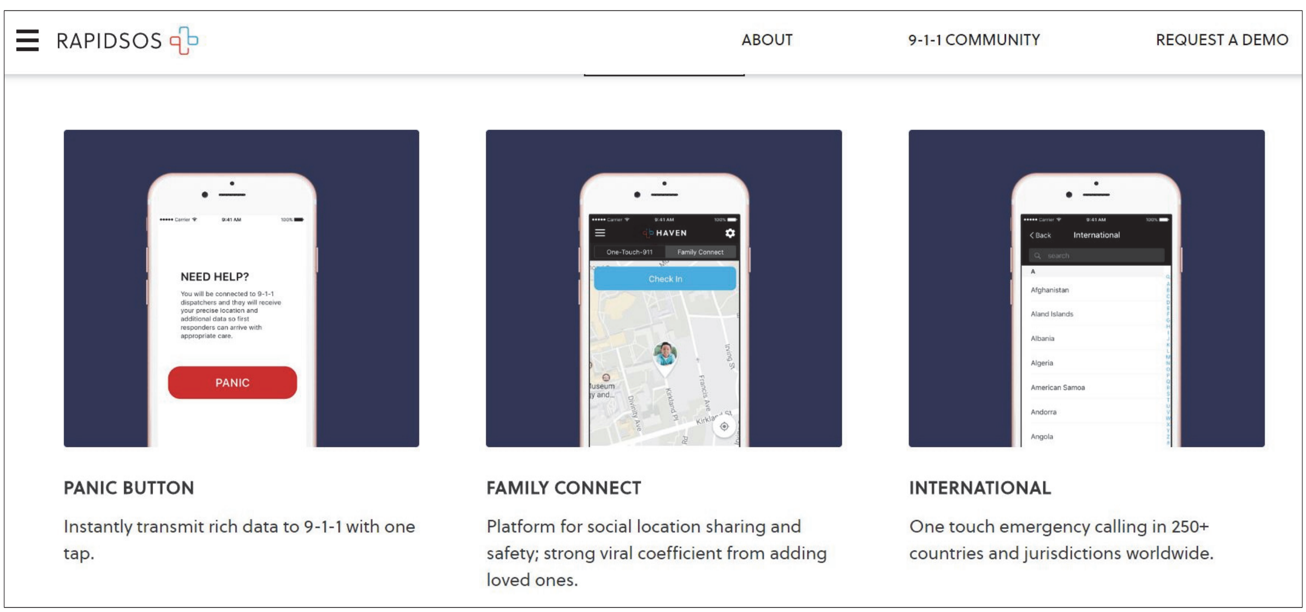


Figure 2-14 An example emergency 911 smartphone app description (Rapid SOS, 2017).

After an earthquake, cellphone capability might be disrupted, but it is expected to return relatively rapidly. The City is currently exploring a number of ways to improve its 911 system, including smartphone applications.

Description of Option. To develop this capability, the City could work with and encourage technology innovators to develop a standardized emergency reporting system for smartphones. The system could be semi-automated and not voice-dependent, allowing location, photos and other critical information to be quickly transmitted with the push of a few buttons.

San Francisco is at the heart of Silicon Valley and the cutting edge development of social media. Several major technology companies are headquartered within sight of San Francisco City Hall. In contrast, emergency reporting is still largely via telephone, and could potentially be greatly improved via smartphone 911 applications. Such development goes beyond San Francisco, and should be a standardized national application, so collaboration with Department of Homeland Security and California Office of Emergency Services, as well as other cities such as San Jose and Los Angeles, would be beneficial.

Benefits. These types of applications have the promise to enable faster reporting, more robust systems, reduced load on 911 centers, elimination of duplication, and improved location information. However, such applications also have risks. For example, in the short-term, these systems could increase the volume of information received by the 911 system without necessarily improving outcomes, requiring additional staff to effectively manage the data.

Feasibility. This is a simple concept that is only now emerging and does not yet appear to have been widely implemented. Technology in this area is rapidly changing, and systems are likely to be very different in a handful of years.

Cost. Unknown. The benefit-cost could be very high, but this depends on successful implementation.

Recommendation. At this time, it is recommended that the City keep up-to-date with technological developments in this area so that a beneficial system can be deployed when the technology matures.

2.13 Protection of Openings

Background Information. Fire often spreads from building to building via openings such as windows. This was a noted source of fire spread in the 1906 conflagration, particularly along "zero lot lines," when neighboring buildings are immediately adjacent to each other, a common occurrence in San Francisco.

Description of Option. This option would require some sort of protection for openings, such as exterior sprinklers, shutters (as shown in Figure 2-15), fire resistant glazing, or other devices. To be effective, this measure would have to be widely implemented, similar to previously discussed options. This suggests that a retroactive (that is, applying to existing buildings) mandatory or triggered program would be needed.

Figure 2-15 Example of protected openings, in this case, roll-down shutters (image from www.ERSshading.com).

Benefits. Such protection would slow fire spread dramatically.

Feasibility. This option would be difficult because it would require changes to the building code, and retrofits for existing buildings, particularly homes. In some cases, changes to the building exterior might be required, which could relate to Planning Code regulations, as well.

Cost. The cost to fully implement would probably be many billions of dollars, thus the benefit-cost is low.

Recommendation. This option could reduce post-earthquake fire spread, however it has a number of implementation challenges, including but not limited to cost. It could be considered for selected application in the future, such as for especially vulnerable or irreplaceable buildings, including historic structures, public housing, single room occupancy buildings, and high-rise residences.

2.14 Intumescent Paint

Background Information. Intumescent paint builds up a fire resistant surface as it burns, significantly reducing fire spread on those surfaces. Currently, this product is mostly used on structural members, but it can be used to paint other surfaces as well. It can be used to obtain a fire rating.

Description of Option. This option could take a variety of forms. Two examples include the following:

- Require or incentivize buildings in locations at high risk of post-earthquake fire to use intumescent paint when they are repainted.
- Require or incentivize buildings used for specific purposes, such as assisted living facilities, single room occupancy, affordable housing, or public housing to use intumescent paint when they are repainted.

Benefits. Intumescent paint used in a building's interior slows initial fire spread significantly (Dowling, 1997). Figure 2-16 shows the outcome of an intumescent paint test conducted by the San Francisco Department of Building Inspection. The structure with intumescent paint performed significantly better than the structure with typical paint. Intumescent paint also has benefits for non-earthquake related fires.

Feasibility. Use of this product is feasible; however, it is more costly and challenging to apply than ordinary paint, requiring specific application methods and thicknesses for efficacy. Application of this product requires precision, and inspections could be an important component. Maintenance is also required; when a structure is repainted, fire resistance only persists if intumescent paint is again used.

Participants at the project workshop (see Chapter 3) asked whether use of intumescent paints has environmental or health concerns, such as off-gassing, which would need to be investigated. Whether these risks exist of not, numerous stakeholders need to learn about and become comfortable with this product before its widespread use.

Cost. The incremental cost of intumescent paint is unclear and would require more research. Benefit-cost is difficult to determine.

Recommendation. Intumescent paint has significant potential to reduce fire spread. However, questions remain about costs, maintenance, and environmental concerns. It is recommended that the City study this topic more.

Figure 2-16 Intumescent paint test conducted by San Francisco Department of Building Inspection. Note large fire in unpainted building on left, little/no fire growth in intumescent painted building on right, both at 4:55 minutes following ignition.

2.15 More Sprinklers

Background Information. Fire sprinklers are a time-tested method of reducing fire spread, but are often considered expensive by builders. New building codes require fire sprinklers in most new buildings.

In recent years, San Francisco required single room occupancy residences to install fire sprinklers, at the expense of building owners. According to workshop participants, the result has been a dramatic decrease in fires.

Description of Option. San Francisco could require fire sprinklers in all new residential construction, or could require fire sprinkler installation when buildings undergo major renovations.

Benefits. Sprinklers undoubtedly reduce fires from all causes significantly, and post-earthquake ignitions by perhaps as much as 30%. However, after an earthquake, sprinklers can use significant quantities of water at a time when water may be limited and is needed by professional fire fighters. Sprinkler pipes and supply lines are prone to damage in earthquakes, and can inundate structures where no fire has occurred, which can cause costly damage that inhibits building reoccupancy after an earthquake.

Feasibility. Sprinkler installation in new and existing buildings is technically very feasible and required in most new construction. As discussed below, cost would be a political and economic obstacle.

Cost. Cost of a residential sprinkler retrofit is currently about $5 per square foot, so that the total cost for installing sprinklers in all San Francisco buildings might be on the order of $3 billion. Thus, the benefit-cost from a purely fire following earthquake perspective is low. There can also be costs associated with water damage caused by broken sprinkler lines in the absence of any ignitions, which has been observed in recent earthquakes.

Recommendation. This option could greatly reduce fire spread but it is currently quite costly. It is recommended that the City consider this option for highly vulnerable occupancies, e.g., Single Room Occupancy residences.

2.16 More San Francisco Fire Department Staffing

Background Information. San Francisco Fire Department staffing has been declining for years. Table 2-4 provides a comparison of the department's staffing today with its staffing in 1906. Will there be enough firefighters after the next earthquake? In addition, today many of the City's firefighters live outside of San Francisco, meaning that off duty firefighters will require time to reach San Francisco after an earthquake and could be delayed by damage to transportation networks. However, this was also the case in 1989, and firefighters who lived outside the City responded within several hours.

Description of Option. This option entails hiring additional professional firefighters.

Benefits. Trained firefighters are needed following an earthquake. Mutual aid will take time.

Feasibility. Increased staffing is always problematic, due to cost.

Cost. Adding a single firefighter requires hiring approximately 4.3 employees in order to maintain 24×7 capability. If one firefighter is added to each engine company, this equates to a net present value investment (i.e., of having 4.3 added employees from now into the far future) of $860 million. The benefit of these additional firefighters is difficult to estimate, but might be of the same order of magnitude.

Table 2-4 Comparison of San Francisco Fire Department, 1906 and Today (Scawthorn, 2010; ATC, 2010a and b)

SFFD Element	1906	2010
Population Protected (thousands)	400	815
Area Protected (sq. mi.)	21	46.7
SFFD personnel[a]	585	1,750
Engine companies	38	42
Fireboats	-	2
Auxiliary Water Supply System (AWSS)	Proposed	Yes
Cisterns	23	172
Total SFFD Pumping Capacity (gallons per minute, gpm)		
Pumping Capacity (gpm)		
engines only	35,100	50,400
engines + fireboats	35,100	70,400
engines + fireboats + AWSS	35,100	90,400
Pumping Capacity per Capita (gpm pc)		
engines only	0.09	0.06
engines + fireboats	0.09	0.09
engines + fireboats + AWSS	0.09	0.11
Pumping Cap. per Firefighter (gpm/ff)[c]		
engines only	60	29
engines + fireboats	60	40
engines + fireboats + AWSS	60	52

[a] In 1906, all 585 firefighters resided in San Francisco, while today a significant number of SFFD personnel reside outside the City.

[c] Based on all 1750 uniformed personnel– if only on-duty firefighters are considered, or on-duty plus those likely to quickly return to duty in a major earthquake, the 52 gpm/ff would be closer to 150-250 gpm/ff.

Recommendation. This option could improve post-earthquake fire suppression but with long-term costs. It is recommended that the City consider post-earthquake fire fighting needs when it reviews its Fire Department staffing levels.

2.17 Expanded NERT and Auxiliary Reserve

Background Information. The San Francisco Neighborhood Emergency Response Team (NERT) has trained more than 24,000 citizens in light search and rescue and emergency response (SFFD, 2015). Figure 2-17 shows NERT volunteers in a practice drill. It is an exemplary program, but more could be done by this highly motivated and engaged group to further reduce the fire following earthquake problem.

Figure 2-17 San Francisco NERT volunteers in practice drill.

San Francisco also has an Auxiliary Reserve Program (see http://sffd-fire-reserve.org/). This is a volunteer organization with the mission to provide trained support for the Fire Department during large scale emergencies, including earthquakes. Reservists are trained in basic first responder techniques including fire suppression, search and rescue, and emergency medical skills. Currently, there are approximately 30 members.

Citizen fire suppression has been shown to be highly effective at containing post-earthquake fires. In some Japanese cities, over half of post-earthquake fires have been suppressed by trained citizen volunteers (Kobayashi and Kornfield, 2002).

Description of Option. This option could include providing more training to volunteers in fire suppression and support activities, and/or providing neighborhood equipment caches to assist these volunteers to fight fires. Figure 2-18 shows example contents of a community cache. After a large earthquake that sparks fires, citizen volunteers are likely to attempt to suppress fires on their own initiative. This option would provide some training to and supplies for them, so they can be effective and safe while doing so.

Figure 2-18 An example neighborhood cache.

Benefits. Training citizen volunteers to suppress small fires would result in quicker suppression of some fires and prevention of those fires growing, allowing San Francisco Fire Department firefighters to focus on the most dangerous fires. The benefit is difficult to quantify, but preventing a few small fires from becoming large fires should be worth many tens if not hundreds of millions of dollars.

Feasibility. There are safety concerns associated with having volunteers suppressing active fires, and ensuring that volunteers take appropriate risks. However, other communities have successfully deployed caches of equipment and trained citizen volunteers to suppress small fires.

Cost. If $20,000 were spent per team for emergency equipment caches, the total cost would be on the order of several million dollars, with a high benefit-cost. The cost of training volunteers in light fire suppression are unknown.

Recommendation. NERT is a major and successful program of the Fire Department, and involves thousands of citizens. The Auxiliary Reserve Program, which currently includes fire suppression training for its members, is a smaller but extremely valuable program. It is recommended that the City develop an expanded cadre of volunteer residents that are trained to suppress small fires and otherwise support professional firefighting efforts after an earthquake. This cadre could draw from either or both of these existing volunteer programs, as appropriate.

It is also recommended to explore the idea of caches of emergency equipment for use by an expanded and trained cadre of citizen volunteers. A focus of this equipment and training should be large fire exposure protection. Other communities have explored and implemented similar programs from which San Francisco can learn.

This recommendation complements the City's Community Resilience Plan, *Resilient San Francisco*, which calls for an expanded NERT with enhanced training and responsibility (CCSF, 2016).

2.18 Increased Foam Capacity

Background Information. Firefighting foam is a "water-multiplier" for structural firefighting (USFA, 1996) and showed its effectiveness in, for example, the 2010 San Bruno gas explosion (Davidson at al., 2012). Figure 2-19 shows San Francisco equipment in use during the San Bruno event. The San Francisco Fire Department has foam carried on many fire engines in limited supply (e.g., 5 or 10 gallons), and some additional in a central reserve. Its major foam capability is within the Airport Division at San Francisco International Airport (which responded to the San Bruno gas explosion).

ARFF Vehicle responding to the PG&E San Bruno Fire (9/9/10)

Capacity: 4500 gallons of water; 540 gallons of foam

Figure 2-19 San Francisco Fire Department Airport Division foam-equipped apparatus (image from http://sf-fire.org/aircraft-rescue-firefighting-arff-vehicles-sfo).

Foam is typically used to suppress fuel fires, which could occur due to gas leaks after an earthquake. However, there are concerns that foam might be carcinogenic. Further, after a fire is suppressed using foam, clean-up is difficult, and foam can get in the sewer system, can back up into residential toilets, and there is concern it could cause environmental pollution.

Description of Option. This option would provide additional specialized foam units for the San Francisco Fire Department, such as shown in Figure 2-19.

Benefits. This option would increase fire suppression capability, with less need for water. The benefit is difficult to quantify, but limiting a few fires from becoming large fires should be worth many tens if not hundreds of millions of dollars. There is also an additional benefit for ordinary firefighting, considering water shortages in San Francisco due to potential drought conditions.

Feasibility. The clean-up, environmental, and health concerns associated with foam are problematic.

Cost. Foam units for in-city use do not have to be similar to the Airport Division apparatus. It is reasonable to assume costs of several million dollars for 5 to 10 foam units. However, foam itself is also relatively expensive and has a limited shelf life (approximately five years). This means that ongoing costs and maintenance could be burdensome.

Recommendation. Foam can be a valuable tool to fight fires when water supplies are limited (which could occur after an earthquake). The San Francisco Fire Department states that its current foam capabilities are adequate, particularly given the shelf-life and environmental concerns.

2.19 Additional AWSS Pipe Network

Background Information. The San Francisco Auxiliary Water Supply System (AWSS) is part of San Francisco's Emergency Firefighting Water System. The AWSS was proposed in 1905 but rejected as "too expensive," and then built following the 1906 earthquake and fire (Scawthorn et al., 2006). It is the world's largest purpose-built high-pressure fire water supply system, with approximately 200 km of large diameter seismically-resistant pipe, almost 200 cisterns, two pumping stations and other features (Scawthorn et al., 2006). Figure 2-20 shows the status of this system as of September 2015. The system has been the subject of several expansion and upgrade programs (1930s, 1960s, 1980s) and is currently undergoing a major expansion and upgrade via the Earthquake Safety and Emergency Response (ESER) 2014 bond (see http://www.sfearthquakesafety.org/eser-2010.html).

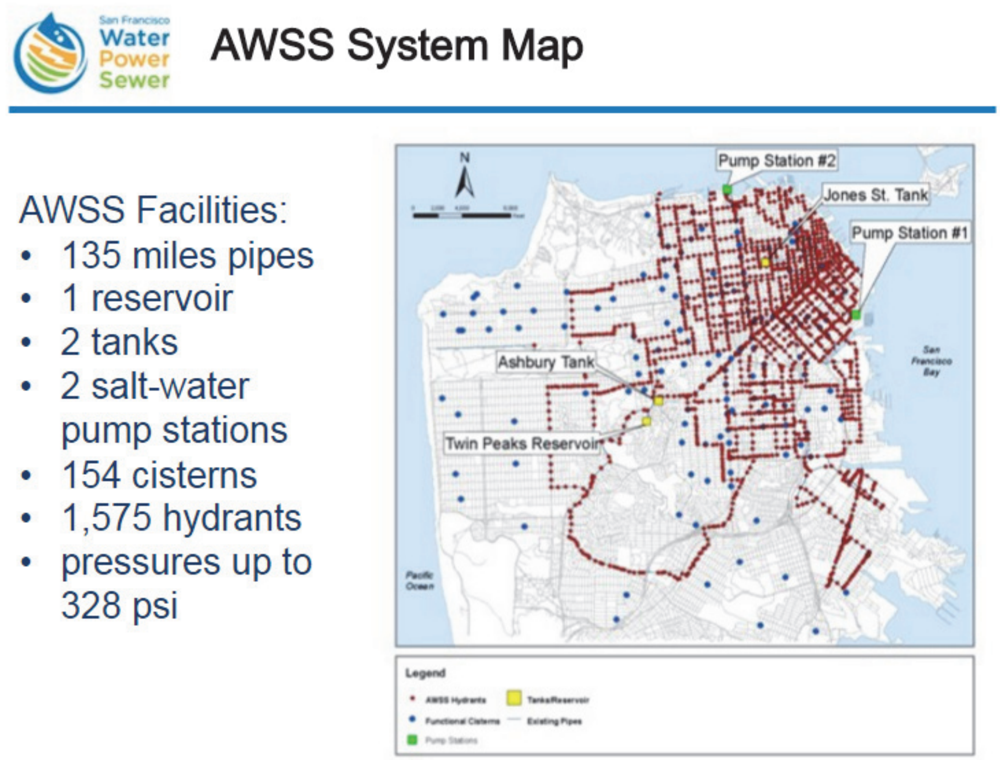


Figure 2-20 AWSS status as of June 2015 (from http://slideplayer.com/slide/10267606/) .

Description of Option. This option would further extend the AWSS pipe network beyond current plans, and involves adding tens of miles of buried pipe. Figure 2-21 provides an illustration of this option. This option is included for sake of comprehensiveness, as well as confirming actions already under consideration by the City.

Benefits. This option would result in improved water supply reliability, with reduced fire losses following an earthquake perhaps in the hundreds of millions of dollars.

Feasibility. San Francisco voters have consistently approved funds for this system.

Cost. This option would cost tens to hundreds of millions of dollars. The AWSS is an excellent system, and San Francisco Public Utilities Commission studies have shown the benefits, especially to the Richmond, Sunset, and other outlying areas, which are at high risk of water supply disruption after an earthquake. The City is currently studying the most effective ways to spend funds improving the City's Emergency Firefighting Water System, and it is unclear whether this is the best investment if limited funds are available.

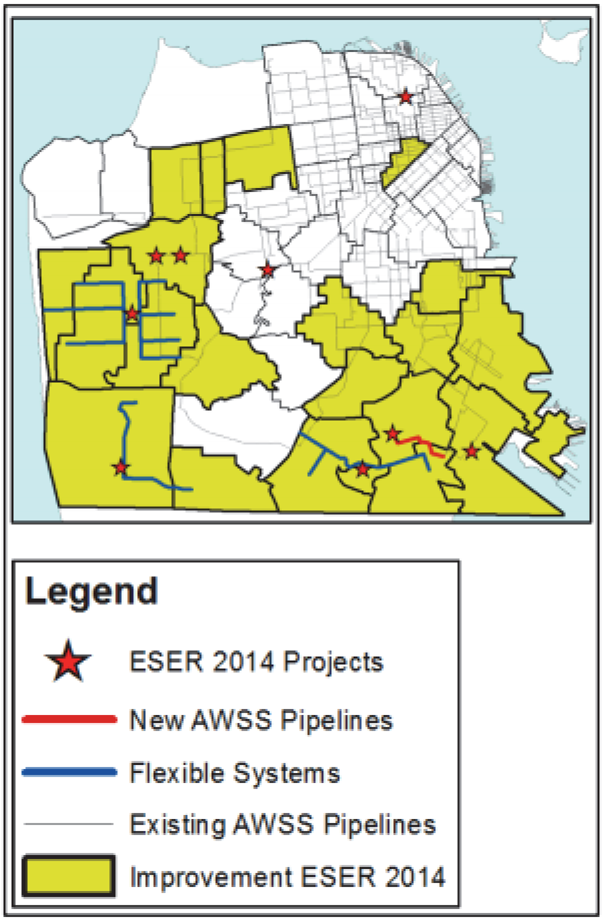


Figure 2-21 Potential (post-ESER 2014) AWSS projects, as of November 2015 (AECOM/WRE, 2015).

Recommendation. The City has a well-organized program to ensure the functionality and adequacy of the water supply system after an earthquake. It is recommended that the City continue to invest in the Emergency Firefighting Water System, in the most cost-effective ways.

2.20 Flexible Water Supply System

Summary Description. In the 1980s the San Francisco Fire Department developed the Portable Water Supply System (PWSS), which consists of several “hose tenders” (i.e., fire vehicles), which each carry about a mile of five-inch diameter hose, also called Large Diameter Hose, as well as appurtenances such as adapters, valves, and hose ramps. This is part of the City’s Emergency Firefighting Water System. The PWSS showed its value in the 1989 Loma Prieta earthquake at the fire in the Marina, and has continued to clearly be a valuable asset.

Description of Option. This option would add a number of additional PWSS hose tenders (e.g., perhaps eight more) and Large Diameter Hose, as well as an even larger Flexible Water Supply System, consisting of hose tenders with twelve-inch diameter hose ("Ultra Large Diameter Hose"). This option is included for sake of comprehensiveness as well as confirming actions already under consideration.

Benefits. The Flexible Water Supply System complements the PWSS, in that the PWSS is a tactical system for use at or near a fireground. The PWSS is limited to moving water about 1 mile whereas the Flexible Water Supply System (due to better hydraulics) can move water much larger distances. The Flexible Water Supply System can serve large demands for firefighting water supply, and can also, in an emergency, serve as a potable water distribution system.

Feasibility. Ultra Large Diameter Hose systems were developed and have been in use in Europe for several decades. The City of Berkeley Fire Department purchased a Flexible Water Supply System consisting of six miles of Ultra Large Diameter Hose, pumps, and other equipment several years ago, specifically for fire following earthquake purposes. The San Francisco Flexible Water Supply System should be compatible with Berkeley's system.

Cost. The Flexible Water Supply System for San Francisco would involve not only the Ultra Large Diameter Hose and vehicles, but also construction of special under-crossings at a number of locations in the City, and manifolds and other fittings at several tanks and reservoirs. The total cost would be on the order of several tens of millions of dollars. If the Flexible Water Supply System served to limit even one large fire, the benefit would exceed the cost. The City is currently studying the most effective ways to spend funds improving the City's Emergency Firefighting Water System, and it is unclear whether this is the best investment if limited funds are available.

Recommendation. The City has a well-organized program to ensure the functionality and adequacy of the water supply system after an earthquake. It is recommended that the City continue to invest in the Emergency Firefighting Water System, in the most cost-effective ways.

2.21 Third AWSS Pump Station

Background Information. The current AWSS has two pump stations (at Townsend and Second Streets, and at Aquatic Park), which were both constructed as part of the original AWSS in 1912. They are part of the City's Emergency Firefighting Water System.

Description of Option. This option involves adding an additional pump station to the AWSS pipe network. Candidate locations include sites at Lake Merced, Hunters Point, and Lands End. Participants at the June 2015 project workshop (see Chapter 3) advised that the City is in discussions about a Hunter's Point location for an additional pump station. This option is included for sake of comprehensiveness as well as confirming actions already under consideration by the City.

Benefits. This option would provide additional water supply for post-earthquake Firefighting, particularly for the western and southern portions of the City.

Feasibility. This option is feasible. Two stations have existed for 100 years, and a new station would use more modern technology, enabling a smaller, unobtrusive footprint.

Cost. The estimated cost is several million dollars, due to synergies with existing installations. The benefit-cost would be high. The City is currently studying the most effective ways to spend funds improving the City's Emergency Firefighting Water System.

Recommendation. The City has a well-organized program to ensure the functionality and adequacy of the water supply system after an earthquake. It is recommended that the City continue to invest in the Emergency Firefighting Water System, in the most cost-effective ways.

2.22 More Cisterns

Background Information. Currently, there are about 180 operational cisterns in the City, with approximately 30 under construction or planned, funded from the Earthquake Safety and Emergency Response (ESER) 2010 and 2014 bond programs. These are part of the City's Emergency Firefighting Water System. Figure 2-20 shows the locations of existing cisterns.

Description of Option. This option consists of construction of additional cisterns at locations to be determined but, for example, in the southern portion of the City. Figure 2-22 shows cisterns under construction (as of June 2015). This option is included for sake of comprehensiveness as well as confirming actions already under consideration by the City.

Benefits. This could result in more reliable firefighting water supply, particularly for the western and southern portions of the City. However, there are more flexible ways to provide for post-earthquake water sources, and use of water in cisterns is limited by the number of pumps available.

Figure 2-22 New cisterns under construction (image from phttp://slideplayer.com/slide/10267606/)

Feasibility. This option is quite feasible, as cisterns have existed for over 100 years and are under construction now.

Cost. Current costs to construct a cistern are estimated to be less than one million dollars per cistern. The total cost depends on the number of cisterns to be constructed. If the added cisterns serve to limit even one large fire, the benefit would exceed the cost. The City is currently studying the most effective ways to spend funds improving the City's Emergency Firefighting Water System.

Recommendation. The City has a well-organized program to ensure the functionality and adequacy of the water supply system after an earthquake. It is recommended that the City continue to invest in the Emergency Firefighting Water System, in the most cost-effective ways.

2.23 More Robust Potable Water Supply Distribution Network

Background Information. This option concerns the City's potable water supply distribution network (termed the City Distribution Division), as opposed to the Emergency Firefighting Water System. In most cities, the potable water supply distribution system is the primary source of firefighting water. San Francisco is almost unique in having the AWSS, and a number of options discussed in this report address increasing the capacity and reliability of water supply for post-earthquake firefighting, with most focused on the AWSS. However, the potable water supply distribution system should not be overlooked as a source of post-earthquake firefighting water.

San Francisco's City Distribution Division pipe network has not been analyzed in detail. Preliminary estimates of pipe breaks were performed for the CAPSS project and are shown in Figure 2-23. The seismic resistiveness or "robustness" of the City Distribution Division system can be enhanced in many ways.

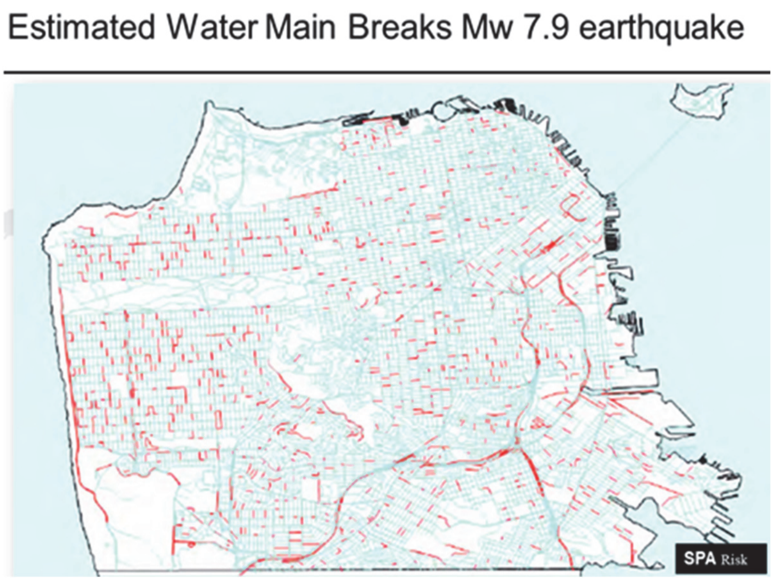


Figure 2-23 Preliminary estimate of breaks in City Distribution Division potable water supply distribution network (ATC, 2010a and b).

Participants at the June 2015 project workshop (see Chapter 3) advised that the City is currently in the process of replacing very old 8-inch water mains and other backbones of the water system throughout the city. At its current rate of work, the City estimates it would take 30 to 50 years to reach "seismic reliability" for the potable water system, although the system already provides a higher level of reliability than available in most cities.

Description of Option. The specific option considered here would be the development of one or more section of larger trunk mains hardened so as to survive an earthquake and also relatively isolated from the normal water mains, so as not to be quickly drained by the breaks in those mains. Such sections of trunk mains would most beneficially be routed in areas not served by the AWSS, and can be termed "co-benefit mains," in that they serve both ordinary drinking water supply needs, and also post-earthquake firefighting needs. Hardening can be accomplished via choice of materials and pipe design (e.g., seismically resistant pipe joints) and isolation can be accomplished via limiting the number of connections to the normal distribution network, and seismically triggered valves at selected connections. This option is included for sake of comprehensiveness as well as confirming actions already under consideration.

Benefits. This option would improve water supply reliability, with reduced fire losses following an earthquake perhaps in the hundreds of millions of dollars. It would also have benefits for providing potable water after an earthquake.

Feasibility. This option is quite feasible, with no obstacles except special design and construction.

Cost. The cost depends on the number and length of co-benefit mains. Such mains are required for potable needs, so the actual cost is just the incremental cost of hardening and isolation. If a co-benefit main serves to limit even one large fire, the benefit would probably exceed the cost. Participants at the June 2015 project workshop (see Chapter 3) advised that the City estimates that an additional $50 million would make “seismic reliability” 10 years away.

Recommendation. The City has a well-organized program to ensure the functionality and adequacy of the water supply system after an earthquake. It is recommended that the City continue to invest in the Emergency Firefighting Water System, in the most cost-effective ways.

2.24 AWSS Dedicated Engineer

Background Information. The AWSS was until recently owned and operated by the San Francisco Fire Department, independent of the potable water supply system. The San Francisco Fire Department employed its own Engineer of the AWSS for the purpose of assuring construction standards. Figure 2-24 provides a historical notice of the appointment of this position. This position was eliminated in the 1980s.

Description of Option. This option is to reestablish and fund a position similar to the AWSS Engineer. Recently, the San Francisco Fire Department and the San Francisco Public Utilities Commission (SFPUC) entered into an arrangement whereby SFPUC will maintain and operate the AWSS. As part of this arrangement, the two departments have agreed to fund a full-time position with the Fire Department to monitor the maintenance and operation of the AWSS. This option is included for sake of comprehensiveness as well as confirming actions already under consideration.

PERSONALS

BURNHAM, D. H., Chicago, Ill., one of the foremost architects of the world, died June 1, at Heidelberg, Germany, aged 66 years. Mr. Burnham's most notable work in the civic field was the designing of the Chicago plans.

COMSTOCK, GEORGE, San Francisco, Cal., has been appointed Chief Engineer of the auxiliary water supply system.

- Municipal Journal, v. XXXII, p. 919 (June 13, 1912)

Figure 2-24 An entry from the San Francisco Municipal Journal of June 13, 1912 announcing the appointment of the Chief Engineer of the AWSS.

Benefits. This option would increase reliability of the AWSS via independent monitoring of maintenance and operation to assure that the Fire Department's needs are being met.

Feasibility. The Fire Department monitor is very similar to the previous Engineer of the AWSS, for which historic precedent exists. This option is in the process of being implemented.

Cost. Cost of one full time Fire Department officer. Benefit is difficult to assess, but would appear to be a warranted measure.

Recommendation. The City has already effectively implemented this option.

2.25 Third Fireboat

Background Information. San Francisco is surrounded on three sides by the largest body of water on earth, yet burned down in 1906 due to lack of firefighting water. Fireboats are mobile pump stations that can flexibly provide large amounts of water for fighting fires following an earthquake, as the Phoenix did in the Marina after the Loma Prieta earthquake of 1989.

The two existing San Francisco Fire Department fireboats (the Phoenix and the Guardian) are "floating pump stations" that assure redundant water supply for post-earthquake firefighting. However, both fireboats are more than 50 years old and require a lot of time and money to maintain and keep operationally ready. On October 17, 2016 (coinciding with the 27th anniversary of the 1989 Loma Prieta earthquake), the San Francisco Fire Department added a third fireboat to its fleet.

Description of Option. In addition to purchasing a new boat, the City could keep both of its older boats. One of the older boats would not be staffed, but could be deployed in an emergency.

Benefits. This option would improve San Francisco post-earthquake firefighting abilities.

Feasibility. This measure is feasible and has the historic precedent of current and previous fireboats.

Cost. In 2013, the Federal Emergency Management Agency (FEMA) awarded the San Francisco Fire Department 7.6 million dollars to fund the project. The completed boat had a cost of $11.5 million. If the fireboat main serves to limit even one large fire (as in the 1989), the benefit exceeds the cost.

Recommendation. This option is included for sake of comprehensiveness as well as confirming actions already implemented.

2.26 Buddy System for Vulnerable Populations

Background Information. Vulnerable populations need special assistance in emergencies. The NERT program, discussed above, includes some training on helping individuals with disabilities or special needs, but more could be done to ensure that everyone in need receives the help they require. Participants at the June 2015 project workshop (see Chapter 3) discussed that that current efforts are not adequate to really protect such populations.

Description of Option. This option would establish a program that matches people with disabilities with one or several "buddies" that would assist them during a disaster, such as a post-earthquake fire. Figure 2-25 provides information from the state on buddy systems.

Benefits. This option would provide assistance to vulnerable people in time of need, reduce injury and life loss, and reduce the burden on emergency responders. Economic benefits are difficult to quantify.

Feasibility. This option currently exists to some extent, demonstrating its feasibility. The crux of this program would be more support and emphasis on this for vulnerable populations and the groups serving them.

Cost. A few million dollars over several years should be sufficient to get this system well-grounded, with lesser sustaining funding thereafter. Benefit-cost is difficult to quantify but substantial.

Recommendation. It is recommended that the City, via NERT or other programs, develop and maintain a census of vulnerable populations and their needs, and that ways be found to match every vulnerable person to a buddy.

This activity could be synergistic with the City's proposed Disaster Recovery Case Management Program and Database, which intends to provide post-event assistance to vulnerable populations (The City and County of San Francisco, 2016). It also could link with plans for post-disaster interim/transitional housing, which are seeking to address housing needs for vulnerable populations after an earthquake (Harvard Kennedy School, 2014).

EDD Employment Development Department State of California

CALIFORNIA Governor's Committee on Employment of People with Disabilities

DISASTER PREPAREDNESS *for* PEOPLE WITH DISABILITIES

EMERGENCY PLANNING

Establish a "Buddy" System

Identify people who are nearby and can assist you in the event of an emergency. It is good to have more than one "buddy", particularly in different areas where you spend most of your time, such as in the work place, at home, or school. The more people who know where you might be, and are alerted to come look for you, the better. You may wish to give your "buddies" lists of crucial information, such as the location of medications, special equipment or batteries to operate it.

Figure 2-25 California Employment Development Department "buddy system" guidance (EDD, 2010).

Chapter 3

Workshop

3.1 Description of Workshop

On June 8, 2015, a workshop was convened by the Earthquake Safety Implementation Program to discuss risk reduction for fire following earthquake. The workshop was intended as an information exchange among a broad base of interested and knowledgeable parties, with the specific purposes to:

- Inform key people related to fire risk issues that this project is developing recommendations on fire following earthquake risk mitigation.
- Share information regarding ongoing work in City departments and other initiatives planned or ongoing in the City.
- Present a set of mitigation options developed by the project team for discussion, review, and comment. Discussion sought to identify the technical, economic, and political pros and cons of each option. The discussion also permitted participants to suggest options not already identified.

A total of 27 persons participated in the workshop, including representatives of the Mayor's Office, Chief Administrator's Office, the Building and Office Managers Association (BOMA), the San Francisco Public Utilities Commission (SFPUC), the San Francisco Fire Department (SFFD), the San Francisco Unified School District (SFUSD), the Department of Building Inspection, the Department of Emergency Management and Earthquake Safety Implementation Program (ESIP). Table 3-1 lists workshop participants. Figure 3-1 shows the workshop in progress.

Table 3-1 List of Attendees at June 8, 2015 Workshop

Attendee	Organization
Benjamin Aymes	Human Services Agency
Brian Barry	SFPUC
Sherlyn Bura	SFUSD
Kevin Connolly	SFUSD
Dan Decossio	SFFD
Jason Elliot	Mayor's Office
Joanne Hayes White	SFFD
Carla Johnson	Mayor's Office on Disability
Jennifer Johnston	Chief Administrator's Office
Nick Majeski	Chief Administrator's Office
Katie Miller	SFPUC
David Myerson	SFPUC
Rafael Picazo	SFUSD
Corey Reynolds	Hagerty Consulting
Ryan Rusler	Har-Bro/BOMA SF
Brian Strong	Office of Capital Planning
Frances Zemore	DEM
James Zhan	DBI
Patrick Otellini	ESIP
Micah Hilt	ESIP
Laurence Kornfield	ESIP
Stacey Lee	ESIP
Jeno Wilkinson	ESIP
Charles Scawthorn	ATC team
David Bonowitz	ATC team
Ayse Hortacsu	ATC team
Laura Samant	ATC team

Figure 3-1 Workshop, June 8, 2015.

Figure 3-2 shows the workshop agenda, which began with introduction of attendees and an overview of the fire following earthquake problem. The bulk of the workshop centered on a structured presentation of the mitigation options discussed in Chapter 2.

There were a total of 26 options presented to the workshop, where the Option groups focused on:

- Reducing ignitions
- Better fire reporting
- Reducing fire spread
- Enhancing firefighting capacity
- Enhancing water supply reliability
- Reducing casualties due to fire

For each option, the presentation was restricted to one PowerPoint slide and less than 2 minutes of presentation, structured as follows:

Summary. What is the mitigation measure?

Benefits. In what way might it reduce fire following earthquake risk? What amount might it reduce risk?

Disadvantages. What problems might occur if the measure is implemented?

Feasibility. Is the measure currently possible, or are there obstacles to implementation?

Cost. Approximate cost to implement?

Agenda

9:00 am	Welcome / overview of ESIP goals	(Otellini)
9:10 am	Overview of ATC 119 project	(Samant)
9:15 am	Purpose of this meeting Self-introduction of workshop attendees (2 minute oral report on the post-earthquake fire risk reduction activities of their organization)	(Scawthorn)
9:45 am	Brief overview of San Francisco's post-earthquake fire risk	
9:55 am	How today's group discussion will be structured	
10:00 am	Moderated group discussion of options to reduce post-earthquake fire risk • presentation of options • discussion of pros and cons of each option • group discussion of feasibility and effectiveness of each option • solicitation of additional options	
11:40 am	Summary of group discussions and opinions How the results of this workshop will be used	
11:50 am	Thanks and Closure	(Samant)

ESIP

2

Figure 3-2 Workshop agenda, June 8, 2015.

Attendees were asked to complete a Feedback form, shown in Figure 3-3, which requested participants to rate each option using a Scale of 0 to 6, where 0 represented 'of no merit' and 6 represented 'highly worth implementing'.

Participants were permitted to provide anonymous feedback through the workshop form. It was emphasized that their rating and feedback was of value to the project, but that it was not binding for project recommendations. That is, the project would be informed by but not required to adhere to any ranking resulting from their ratings.

Earthquake Safety Implementation Program

Workshop on Post-Earthquake Fire Risk Mitigation

8 June 2015

FEEDBACK ON MITIGATION OPTIONS

Please rate each option using a Scale of 0~6, where **0 = 'of no merit'** and **6 = 'highly worth implementing'**. Also, please provide any other comments in column at left (and on reverse if you need more space).

At *your* option, you can remain anonymous, or provide your name: ______________________.

On the reverse, please also comment on the usefulness of this Workshop.

No.	Option	Est. $ Cost*	Rating 0~6	Your Comments
1	Earthquake Early Warning (EEW)	0~80		
2	Seismic gas shut off valves	200		
3	Mandatory gas wrenches	1		
4	Finer gas blocking and valving	100s		
5	Gas appliance bracing	30		
6	Electric shut off panels, meters or plugs	400		
7	Improved high school chem lab housekeeping	Little		
8	Improved commercial/industrial housekeeping	v. large		
9	Mandatory retrofit of more buildings	billions		
10	Household required Fire extinguishers	5		
11	FD/OES real time situational awareness capability (eg, remote sensing)	0.1s		
12	Smartphone 911 capability	1		
13	Protection of openings	billions		
14	Intumescent paint	billions		
15	More sprinklers	3 billion		
16	More SFFD staffing (cost of firefighters???)	860		
17	Expanded NERT (cost for caches)	2		
18	More AWSS	100s		
19	More foam capacity	Few mill		
20	More PWSS	10		
21	3rd AWSS pump station	100		
22	More cisterns (~100)	100		
23	More robust CDD	100s		
24	AWSS dedicated Engr	10		
25	3rd fireboat (i.e., keep *Phoenix* and *Guardian*)	little		
26	'buddy' system for vulnerable populations	~NERT		

*Rough order of magnitude estimated cost, millions of dollars.

Figure 3-3 Workshop feedback form.

3.2 Feedback from Workshop

Figures 3-4 presents the raw feedback ratings received from workshop participants. The two rows at the bottom beyond the options indicate the average and standard deviation of each participant's set of ratings are provided. Figure 3-5 lists the average and standard deviation for each option's ratings.

No.	Option	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
		Ratings by each participant																			
1	Earthquake Early Warning (EEW)	6	4	4	5	6	6	6	3	6	4	6	2	4	5	4	6	6	-	3	4
2	Gas seismic shutoff devices	6	5	6	5	4	5	4	5	2	5	5	4	2	6	4	1	6	6	4	6
3	Mandatory gas valvewrenches	4	3	5	5	5	6	6	6	6	4	6	1	0	6	6	-	6	3	3	6
4	Finer gas blocking and valving	4	6	6	5	6	5	6	6	3	4	5	3	4	5	3	6	4	-	3	6
5	Gas appliance bracing	3	6	2	5	3	4	6	3	5	4	6	1	2	5	6	1	3	6	3	6
6	Electric shut off panels, meters, or plugs	3	6	5	3	0	5	6	0	6	3	3	3	0	5	3	6	3	3	3	5
7	Improved high school chem lab housekeeping	2	1	3	3	1	4	6	6	6	5	4	6	0	3	6	-	6	3	3	3
8	Improved comm./indust. chemical housekeeping	2	1	4	3	3	5	4	6	3	5	5	3	0	4	3	-	6	4	4	4
9	Seismic retrofit of additional buildings	5	1	3	6	3	4	6	0	0	5	3	3	6	5	3	6	3	5	2	6
10	Household required fire extinguishers	5	4	6	4	4	6	6	4	3	2	4	-	3	6	6	6	6	5	1	5
11	Remote sensing/drones	2	3	3	5	6	6	6	0	5	6	5	-	6	6	3	6	5	3	6	2
12	Smartphone 911 capability	4	6	6	5	6	6	6	3	5	5	6	-	2	5	4	-	6	5	4	6
13	Protection of openings	2	4	3	5	1	1	3	0	1	4	3	-	0	3	3	6	2	5	2	5
14	Intumescent paint	4	0	4	5	1	2	4	0	4	4	2	-	2	2	6	1	2	4	0	3
15	More sprinklers	2	0	5	6	6	3	6	6	2	6	5	-	3	4	6	0	4	6	1	6
16	More SFFD staffing	6	2	6	6	6	5	2	6	6	5	2	-	6	1	6	6	6	s	3	5
17	Expanded NERT	4	1	6	6	6	6	6	3	6	6	2	-	6	5	6	-	3	6	2	4
18	Increased foam capacity	6	6	6	4	6	6	4	6	6	-	3	-	1	-	6	2	6	3	5	6
19	Additional AWSS pipe network	6	5	4	6	6	6	6	6	5	-	4	-	6	-	3	6	6	6	5	6
20	Flexible water supply system	6	6	5	7	6	6	6	6	6	-	4	-	4	-	6	6	6	4	5	6
21	Third AWSS pump station	6	3	5	7	5	2	6	6	-	-	2	-	2	-	2	6	6	5	3	5
22	More cisterns	6	2	6	6	3	1	4	3	2	-	2	-	4	-	1	6	4	3	1	2
23	More robust potable water supply distribution netwo	6	-	4	5	6	6	5	0	5	-	5	-	4	-	2	1	4	5	4	5
24	AWSS dedicated engineer	2	0	2	6	6	6	1	6	0	-	0	-	1	-	4	0	3	5	2	4
25	Third fireboat	6	2	6	6	6	6	6	6	5	6	4	-	6	-	6	6	6	5	4	5
26	Buddy system for vulnerable populations	2	5	6	6	6	6	6	6	3	6	5	-	1	-	2	1	6	6	1	6
	average of scores per participant	4.2	3.3	4.7	5.2	4.5	4.8	5.1	3.9	4.0	4.7	3.9	2.9	2.9	4.5	4.2	4.0	4.8	4.6	3.0	4.9
	std. deviation of scores per participant	1.7	2.2	1.4	1.1	2.0	1.7	1.4	2.5	2.0	1.1	1.6	1.5	2.2	1.5	1.7	2.6	1.5	1.2	1.5	1.3

Figure 3-4 Compiled feedback received from workshop participants. Note that: (1) some items listed differ slightly in name from Options listed in Figure 3-3; and (2) numbering of Option 18 and Option 19 are reversed in this table compared to those of the feedback form in Figure 3-3.

There are a number of ways to process and interpret these ratings. Table 3-2 presents the top ten set of options ranked using three different methods:

1. **Average Rating.** The ten options with the highest average of all participants' ratings for that option are shown in the first column of Table 3-2.

2. **Rating without Minimum and Maximum.** The ten options with the highest average rating, after omitting the lowest and highest rating for each option are shown in the second column of Table 3-2. Omission of highest and lowest scores is a common technique, employed to avoid a 'dominant voice' skewing rankings.

3. **Normalized Rating.** The ten options with the highest average ratings, with the average calculated after each participant's ratings have been normalized by the average of that participant's ratings, are shown in the last column of Table 3-2. This is another common technique employed to dilute the effect of a particular person routinely scoring much higher or lower than others.

No.	Option	avg.	std.
1	Earthquake Early Warning (EEW)	4.7	1.3
2	Gas seismic shutoff devices	4.6	1.5
3	Mandatory gas valvewrenches	4.6	1.8
4	Finer gas blocking and valving	4.7	1.2
5	Gas appliance bracing	4	1.7
6	Electric shut off panels, meters, or plugs	3.6	2
7	Improved high school chem lab housekeeping	3.7	1.9
8	Improved comm./indust. chemical housekeeping	3.6	1.5
9	Seismic retrofit of additional buildings	3.8	2
10	Household required fire extinguishers	4.5	1.5
11	Remote sensing/drones	4.4	1.8
12	Smartphone 911 capability	5	1.2
13	Protection of openings	2.8	1.8
14	Intumescent paint	2.6	1.8
15	More sprinklers	4.1	2.2
16	More SFFD staffing	4.7	1.8
17	Expanded NERT	4.7	1.7
18	Increased foam capacity	4.8	1.7
19	Additional AWSS pipe network	5.4	1
20	Flexible water supply system	5.6	0.9
21	Third AWSS pump station	4.4	1.8
22	More cisterns	3.3	1.8
23	More robust potable water supply distribution networ	4.2	1.8
24	AWSS dedicated engineer	2.8	2.4
25	Third fireboat	5.4	1.1
26	Buddy system for vulnerable populations	4.4	2.1
	average	4.2	1.7
	standard deviation	0.8	0.4

Figure 3-5 Averages and standard deviations of the compiled feedback received from workshop participants. Note that: (1) some items listed differ slightly in name from Options listed in Figure 3-3; and (2) the numbers of Option 18 and Option 19 are reversed in this table compared to those of the feedback form in Figure 3-3.

The differences in top ten rankings that results from the three methods are very minor. All ten of the options based on average rating (first column) are also in the top ten when ranked without minimums and maximums (second column); nine of the options based on average rating are in the top ten normalized rating (third column).

For each scheme, the highest average rated option was No. 20, Flexible Water Supply System, with an estimated cost of tens of millions of dollars. It is noted that when ranked without minimums and maximums (second column), gas seismic shutoff devices, appear in the top ten, in place mandatory gas wrenches.

Table 3-2 Top Ten Options

Ranked by Raw Rating	*Ranked without Minimum and Maximum*	*Ranked by Averaged Normalized Rating*
Flexible water supply system	Flexible water supply system	Flexible water supply system
Additional AWSS pipe network	Third fireboat	Additional AWSS pipe network
Third fireboat	Additional AWSS pipe network	Third fireboat
Smartphone 911 capability	Smartphone 911 capability	Smartphone 911 capability
Increased foam capacity	Increased foam capacity	Increased foam capacity
Earthquake early warning	More SFFD staffing	Finer gas blocking and valving
Finer gas blocking and valving	Earthquake early warning	Earthquake early warning
More SFFD staffing	Expanded NERT	More SFFD staffing
Expanded NERT	Mandatory gas wrenches	Gas seismic shutoff devices
Mandatory gas wrenches	Finer gas blocking and valving	Expanded NERT

Appendix A

Minimizing Risk by Reducing Ignitions

This appendix presents a report developed outside of the ATC project. This report was developed by Corey Reynolds, at the request of the Earthquake Safety Implementation Program (ESIP) and completed in May 2014. The report is provided here in its entirety, including appendices and references. The report has not been reviewed or formatted by ATC.

Post-Earthquake Fires in San Francisco: Minimizing Risk by Reducing Ignitions

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The author conducted this study as part of the program of professional education at the Goldman School of Public Policy, University of California at Berkeley. This paper is submitted in partial fulfillment of the course requirements for the Master of Public Policy degree. The judgments and conclusions are solely those of the author, and are not necessarily endorsed by the Goldman School of Public Policy, by the University of California or by any other agency.

Table of Contents

Executive Summary

Due to its high building density and large stock of wood structures, the City and County of San Francisco faces significant risk of fire following an earthquake. One way to minimize this risk is to require owners to install various products on their properties or perform various actions that are known to minimize ignition potential after an earthquake.

Because natural gas is understood to be a leading cause of these post-earthquake ignitions, some of which have the potential to turn into catastrophic conflagrations, an ordinance requiring earthquake-triggered automatic gas shutoff valves on all properties has been proposed to City leaders many times. In reality, though natural gas is an important contributor to San Francisco's risk of post-earthquake fires, electrical systems are now thought to contribute to more than half of fires following earthquake.

As such, the City and County of San Francisco must not only understand the implications of an earthquake-triggered automatic gas shutoff valve ordinance, but also the potential effectiveness, ease of implementation, cost, and social impacts of other possible solutions that can address the City's risk of post-earthquake fire ignitions—from both gas and electricity.

Recognizing the potential for these post-earthquake fires caused by gas, electricity, or a combination of the two, this report analyzes seven solutions that can minimize risk by reducing ignitions. There is no silver bullet solution to the problem of post-earthquake fire. In order to choose the "right" solution, the City and County of San Francisco must engage the community to determine the most important policy goals, an acceptable level of risk, and answers to tough questions: for instance, are significant social impacts acceptable if a solution is highly effective? Is a program's low cost more important than its ease of implementation? Due to the highly sensitive nature of this issue, any policy must be made with considerable public input. Tradeoffs are significant and must be understood. This report presents discussion on such tradeoffs and a framework for confronting them.

Fortunately, through its experience with developing the Community Action Plan for Seismic Safety (CAPPS), the City and County of San Francisco is well equipped to manage such a community engagement process. Using this report as a guide, this City should:

- Convene a working group to specifically study post-earthquake fire (both gas and electric) and inform City policy. This report can serve as both a background and a framework for analysis, however community involvement is critical for successful policy development.
- Conduct further study, including a cost-benefit analysis of earthquake-triggered automatic gas shutoff valves and excess flow valves, barriers to market for hybrid gas valves and earthquake-related electrical fire solutions, and alternatives to reduce fire risk through improving discovery, reporting, response, and suppression, and reducing fire spread.

- Develop inexpensive programs to incubate an industry around hybrid-style gas shutoff systems and earthquake-caused electrical fire prevention solutions.
- Leverage existing (and inexpensive) opportunities for public education on fire risk, detecting gas leaks, and manually shutting off gas valves. A public that understands when and how to manually shut off gas has significant potential to minimize risk under certain conditions.

Chapter 1

Introduction

Although no one knows when the next "big one" will strike San Francisco, scientists estimate that a magnitude 6.7 or larger earthquake will occur in the Bay Area within the next 30 years; the U.S. Geological Survey forecasts that a major earthquake is nearly twice as likely as not to strike the region.[1] Risk for fire will increase dramatically following this major earthquake. In fact, fire risk will rise after an earthquake of any significance, though losses from post-earthquake fires are, on average, less than shake damage.[2]

When fires do occur there is potential for them to escalate into dangerous and deadly conflagrations—consuming wide swaths of an urban area and leaving destruction in their wake. The City and County of San Francisco faces unique risk due to its status as a "conflagration breeder"—a densely populated area composed mainly of wood structures.[3]

Previous experience in San Francisco has led to a public highly sensitive to this post-earthquake conflagration risk. Images of citywide fires in 1906 and the Marina in flames in 1989 remain fresh. This fire risk is usually associated with natural gas, though the threat of gas fire following an earthquake is not as great as public perception would have it; natural gas contributes to somewhere between 20 and 50 percent of all earthquake-related fires.[4]

To address this risk, a citywide mandate for the installation of earthquake-triggered automatic gas shutoff valves has been proposed many times. Such valves are required in some other cities, notably Los Angeles, but are not required by any state code or other regulation. San Francisco today does not require these valves, in no small part because of the potential for significant social disruption associated with unnecessary triggers and the length of time until utility companies can restore gas service to individual structures after valves shut off gas.

Local governments have responsibility for the overall safety of their citizens and infrastructure. As such, the City and County of San Francisco wishes to minimize damage caused by fire following earthquakes—from all sources. This can be approached in through many different ways: reducing damage from ground shaking, improving how fires are discovered and reported, reducing ignitions, reducing spread, and/or improving fire suppression. Earthquake-triggered automatic gas valves have the potential to help reduce fire ignitions caused by natural gas, however other solutions should also be analyzed for their effectiveness, cost, ease of implementation, and potential for social disruption. In addition, before any new citywide policy addressing fire following earthquake risk is developed, solutions that could reduce fire damage by improving discovery and reporting of fire, decreasing fire spread, or improving fire suppression should be assessed against the same policy goals.

Report Focus

Though large conflagrations in urban areas following an earthquake are today relatively rare events, if they do occur there is the potential for hundreds of casualties and billions of dollars of property losses, depending on the magnitude and type of earthquake and other post-event environmental conditions. There are a range of measures, including installation of earthquake-triggered automatic gas shutoff valves, that property owners can take to reduce the occurrence, severity, and spread of post-event fires. Before developing policy or regulation around these measures, the City must understand their broader implications.

This report answers the following question: What can be done before an earthquake, and without knowing the particulars of magnitude, location, and post-event environmental issues, in order to reduce the number of fire ignitions, thus reducing risk of property damage and loss of life due to fire following earthquake?

The purpose of this report is to inform, frame, and guide a policy-making process for the City and County of San Francisco. This report summarizes current understanding of San Francisco's fire following earthquake risk, explores benefits and drawbacks of earthquake-triggered automatic gas shutoff valves, and assesses other solutions that could reduce post-earthquake fire ignitions.

Community Action Plan for Seismic Safety (CAPPS)

The City and County of San Francisco's Community Action Plan for Seismic Safety (CAPPS), a public policy-driven program that articulated acceptable resilience goals and earthquake impacts for the City, identifies 17 important actions for the San Francisco city government to take in order to reduce the impact of future earthquakes in San Francisco, six of which are related to mitigating fire following earthquake in San Francisco:

- Mandatory retrofit of large wood frame soft story structures. These buildings are susceptible to collapse and vulnerable to fire.
- Require all buildings to be evaluated for seismic risk upon sale. The evaluation would include fire ignition and spread risk.
- Require retrofits of vulnerable buildings over a period of time. This would ensure that owners of vulnerable buildings that threaten the broader community ultimately improve those buildings.
- Require automatic gas shutoff valves on select buildings in specific areas. Require owners of certain vulnerable buildings and buildings in fire department-designated post-earthquake high fire hazards areas to install automatic gas shutoff valves.
- Evaluate measures to reduce post-earthquake fires. Multiple city departments would work together to evaluate and implement measures to reduce fire ignitions and spread, and improve fire suppression capacity following earthquakes.

- Address the hazards from damage to building systems, appliances, equipment and non-structural building elements. Damage to building systems, such as fallen ceilings and fixtures, broken pipes, and overturned equipment and appliances, increase the potential for fire ignitions and spread.

The implementation side of the adopted CAPPS is the Earthquake Safety Implementation Program (ESIP). The ESIP program spans a 30-year implementation schedule, with 50 individual tasks, ranging from the recent adoption of a soft-story seismic upgrade program to developing small business resilience strategies. This report is developed in support of *Study Item A.6.i.* of the ESIP work plan, initiating discussion on one of many fire-related earthquake resilience topics.

Chapter 2

Post-Earthquake Fire Risk and Damage

Fire following earthquake poses the most significant risk in large, densely populated urban areas. San Francisco, being the most densely populated large city in California and second-most in the United States, clearly faces unique risk of fire following earthquakes. Its stock of wood structures only enhances this risk.

Fire following earthquake can be modeled through the following six-step process[5]:

1) **Occurrence of the Earthquake:** First, the earthquake causes damage to buildings and infrastructure, due to ground shaking.
2) **Ignition:** Ignition can occur with or without structural damage. Sources of ignition are discussed in depth in Section 2.3 below.
3) **Discovery:** The fire is then discovered, which in the confusion of an earthquake event may take longer than usual.
4) **Report:** If the fire cannot be extinguished by its discoverer, it will be reported to the fire department for assistance.
5) **Response:** The fire department must then respond to the event. Response may be hampered by transportation problems and the sheer amount of resources required following a major event.
6) **Suppression:** Once the fire department arrives, it must have the resources (e.g., water) to fight the fire. If suppression is not successful, the fire can evolve into a conflagration.

Figure 1. Fire following earthquake process.

Damage caused by fire following earthquake can be mitigated by “breaking the cycle” anywhere in the above process to better prevent conflagration. Examples include:

Step in Process	Example Solutions to Mitigate Risk
Occurrence of the Earthquake	Improving building code to ensure buildings and infrastructure can better withstand shaking.
Ignition	Reducing potential for gas and electrical ignitions through gas or electric shutoff devices, appliance bracing, and/or public education.
Discovery	Requiring methane detectors or installing alarm systems.
Report	Ensuring capability of 911 system to receive reports after a major event
Response	Improving response times after a major event, when transportation disruptions abound, through planning and exercises.
Suppression	Improving fire department capabilities for fire fighting, including, most importantly, water supply.

Table 1. Reducing Risk Through All Steps of the Fire-Following Earthquake Process.

The focus of this report is **reducing ignitions** (highlighted in the table above), though "breaking the cycle" at any of the six steps certainly deserves further study.

2.1 Magnitude of the Problem

Historical earthquakes in California and beyond can provide insight into the magnitude of the fire following earthquake problem. However, caution is required when using data from past earthquakes to inform future policy decisions, as seismologic characteristics of each quake vary widely and infrastructure damage changes significantly as cities develop. Additionally, variables like earthquake magnitude, time of day, and weather conditions, among other factors, can have significant impacts on observed damages.

Three past California earthquakes provide useful illustrations for the purposes of this report.

The Great 1906 San Francisco Earthquake

Scientists believe that the magnitude of the Great 1906 San Francisco Earthquake was somewhere between 7.7 and 8.3 on the Richter scale.[6] The earthquake and its memorable post-shaking fires caused 3,000 deaths and destroyed 28,000 buildings, totaling $524 million in damages (1906 dollars). Fires caused 80% of that damage.[7]

It is important to note from the outset that today's risks for large conflagrations are lower than in 1906 because improvements to the reliability of the water supply, advancements in firefighting technology and emergency response, improvements in building codes and construction related to earthquakes, and improved communications (See Section 2.4 for discussion of today's risk).

1989 Loma Prieta Earthquake

The October 9, 1989, the 6.9-magnitude Loma Prieta earthquake caused 62 deaths and damaged 18,000 homes. It sparked 31 ignitions in San Francisco, including the Marina fire, which was caused by a toppled water heater igniting leaking natural gas from a ruptured line.[8] Even considering the iconic image of part of the Marina neighborhood in flames, fire damages were minor compared to overall structural damage.

Causes of fire in the 1989 Loma Prieta earthquake provide insight into today's risk of post-earthquake fires in San Francisco. Important to note is that at least 45% of fires after Loma Prieta were caused by electrical systems.

Cause	Number	Percent of Total
Electric Wiring	6	19
Electrical Equipment	8	26
Stove	9	29
Water Heater	1	3
Other Gas Appliance	2	6
Gas Explosion	1	2
Miscellaneous or Unknown	5	16

Table 2. Causes of post-earthquake fires after 1989 Loma Prieta Earthquake.[9]

1994 Northridge Earthquake

The 1994 Northridge Earthquake, magnitude 6.7, occurred in the San Fernando Valley of Los Angeles on January 17, 1994. With 57 fatalities, more than 5,000 injuries, and more than $20 billion (in 1994 dollars) of property damage from shaking, fire, and landslides, the Northridge Earthquake remains one of the costliest natural disasters in United States history.[10]

The affected area saw 67 post-earthquake fires. Even with 14,000 leaks in natural gas lines reported, less than half of fires after the earthquake were caused by gas.[11]

2.2 Sources of the Problem

As demonstrated above, fire following earthquakes is caused mainly by two sources: gas and electricity. In addition to gas and electricity, post-earthquake fires can also be caused by reactions from spilled chemicals; open flames from stoves, candles, fireplaces, and grills; and arson.[12] These rare ignitions are out of scope of this report.

For a fire to occur, there must be a fuel source and an ignition source present. Thus, it is clear how gas and electricity can interact and both become factors in post-earthquake fires (See Table 3).

Gas

Natural gas most commonly contributes to post-earthquake fire when gas leaks are ignited by sparks or flames. The following process models the sequence of events in gas fires[13]:

1) Following an earthquake, stress in the piping system or movement of an appliance occurs
2) A gas leak develops
3) The leak goes undetected and gas accumulates in an enclosed area
4) Gas intensity reaches an ignitable level
5) An ignition source is activated

The greatest post-earthquake, natural gas-caused fire risk is seen in large, multi-unit structures. The risk of a gas-related fire in residential structures following earthquakes is generally very low because of these numerous conditions necessary for gas ignition.[14]

A review of the literature finds that of fire ignitions in recent earthquakes it is estimated that natural gas has played a role in 20% to 50% of ignitions. In contrast, it is estimated that electrical systems could be a factor in as many if not more ignitions. In some cases, both could be a factor.[15]

Electricity

Electricity contributes to most of the remainder of post-earthquake fires, most commonly though electrical shorts, frayed wires, tipped appliances, excessive friction of electrical wires and cords with one another, electrical problems due to swinging lamps and other suspended fixtures, and overloads at extension cords.[16] Despite the fact that fires caused by electricity-related ignitions are equally or even more common than gas related ignitions, the risks and potential mitigation options have received significantly less attention in the existing literature and in many vulnerable jurisdictions.

Electric power often fails in large earthquakes, due to automatic system trips as well as damage to the system – however, the power failure usually takes several seconds, during which power is a source of many ignitions. Certain electric appliances (e.g., those with heating elements) can still cause fires even after power is cut.[17]

The interaction of gas and electric systems are also responsible for post-earthquake fires. The table below summarizes common sources of post-earthquake fire caused by both gas and electric systems.

Gas	Electric	Either/Both
Appliance is overturned or moved, rupturing the gas line, and the released gas is ignited by a flame or spark.	The earthquake interrupts electrical service and an electric-powered device is displaced or damaged and comes into contact with fuel. When electric power is restored to the building, the device causes the flammable fuel to ignite.	A gas pipe in a building is broken and an electric spark from damaged electrical wiring is present, igniting the released gas.
A gas pipe is broken due to building damage and the released gas ignites.	Arcing from crossed wires or transformer damage ignites brush near a structure.	Bottles and/or open cans of flammable liquids are thrown to the floor by the earthquake, and an open gas flame or an electric spark ignites the vapors from the spilled liquid.
		Cooking oils and other kitchen fuels are spilled during the earthquake, and either electrical or gas-based cooking equipment ignites them.
		An open flame from a candle or Bunsen burner contacts a quantity of fuel.

Table 3. Common ignitions from gas and/or electric sources.[18]

Frequency

More than half of the fires caused by the Loma Prieta and Northridge earthquakes were due to electrical systems or other sources, not natural gas, and a review of other recent earthquakes shows similar trends.

Year	Earthquake	Magnitude	Total Post-Earthquake Fires	Gas-Related Fires	Percent Gas-Related Fires
1971	San Fernando	6.6	109	15	14%
1983	Coalinga	6.2	1-4	1	25-100%
1984	Morgan Hill	6.2	3-6	1	17-33%
1986	Palm Springs	6.2	3	0	0%
1987	Whittier	5.9	6	3	50%
1989	Loma Prieta	7.2	67	16	24%
1994	Northridge	6.7	110	54	49%
1995	Kobe	6.9	205	36	18%

Table 4. Gas-related fires as compared to total fires in past earthquakes.

2.4 Factors Impacting Risk and Damage

Other factors can significantly impact the extent of the damage and determine whether a single ignition is quickly extinguished or if it evolves into a conflagration. These factors include:

Reliability of water supply: A common factor in each of the three historical California earthquakes explored above was disruption to the water supply that affected post-earthquake fire suppression. San Francisco's emergency water supply is known to be vulnerable.[19]

Time of day: Whether people are present to take action to mitigate ignition risk and/or discover and report fires in the immediate aftermath of an earthquake matters immensely. Depending on the time of day, the risks could be greatest in residential areas (during the day), or in commercial areas (during the night).[20]

Weather conditions: Weather conditions after an earthquake significant impact fire response, suppression, and spread, with wind speed and humidity playing the greatest role. High winds and low humidity present the greatest challenges for suppression.

Building density: The higher building density, the greater the risk of fire spread.

Construction features: Wood buildings serve as a source of fuel for a fire and thus areas with a large stock of wood buildings are most vulnerable to post-earthquake conflagration.

Fire response problems: Fire departments face myriad challenges in providing effective response, including impaired communications, an overload of requests for assistance, damage to fire stations, transportation problems due to congestion and road damage, and delays in mutual aid from neighboring fire districts.

2.5 San Francisco's Risk Today

The historical data explored above provide general insight into the potential for fire following earthquake, however the City and County of San Francisco has placed significant resources into more precisely determining its risk today through various risk analyses. Two probabilistic studies provide important information in understanding San Francisco's risk of post-earthquake fires.

CAPPS Fire Following Earthquake Analysis

Part of the CAPPS effort included an analysis of potential fire impacts in San Francisco given four different earthquakes:

- A 7.9 magnitude earthquake on the San Andreas Fault
- A 7.2 magnitude earthquake on the San Andreas Fault
- A 6.5 magnitude earthquake on the San Andreas Fault
- A 6.9 magnitude earthquake on the Hayward Fault

The CAPPS analysis shows that fire following earthquake, has a 50% chance of causing somewhere between 27 and 120 fires in San Francisco, resulting in $1.3 billion to $10.3 billion in damages (depending on the fault and magnitude). Consequently, there is a 50% chance of impacts outside that range (higher or lower). Because the analysis is probabilistic in nature, it does not provide information on exactly where ignitions will occur or the size of the burnt area. The average number of fires and average dollar loss for each earthquake scenario under study is presented below.

Scenario	Average # of Fire Ignitions	Average $ of Fire Loss (billions)
Magnitude 7.9 on San Andreas	95.1	7.674
Magnitude 7.2 on San Andreas	73.1	5.122
Magnitude 6.5 on San Andreas	57	3.387
Magnitude 6.9 on Hayward	37.8	2.947

Table 5. CAPPS fire following earthquake projections.[21]

Risk Management Solutions Study

Based on the scenario of a 7.9 magnitude earthquake on the northern section of the San Andreas Fault, similar in location and magnitude to the 1906 San Francisco Earthquake, a Risk Management Solutions (RMS) study concluded that $260 billion in damages to residential and commercial property and insured losses from $50-$80 billion could occur. The study estimated that insured property losses from fire following earthquake would be around 15% of the total insured loss or $6 billion. Still, that loss estimate came with the caveat that losses could escalate if fires spread unimpeded because of high winds or lack of water.[22]

Chapter 3

Earthquake-Triggered Automatic Gas Shutoff Valves

3.1 Background and Description

What is an Earthquake-Triggered Automatic Gas Shutoff Valve?

An earthquake-triggered gas shutoff valve is an automatic, passive valve—normally installed on a customer's natural gas houseline piping near the gas meter—that senses vibration and automatically shuts off gas to the structure. The valves, which cost between $100 and $300, require installation from a licensed professional (a certified plumber or specialty contractor), as the valve must be appropriately sized given the plumbing and appliance load. Anytime the valve is activated and gas is shut off, qualified personnel (e.g., PG&E) must re-establish gas service; the homeowner should not attempt to reset the valve and restore service.

How Does it Work?

During an earthquake, a sensing mechanism in the valve detects vibration, and as a result, a valve mechanism shuts off the flow of gas. Unlike excess flow valves (see Section 4.2.1) seismically actuated gas valves are not sensitive to changes in gas flow or pressure. These valves are triggered when there is shaking, regardless if there are failures in the gas system or not. The benefit of these valves is that someone does not need to be present to ensure shutoff. The gas source can be shut off when shaking is severe enough to potentially cause damage to structures, piping, and appliances. One the valve is triggered, pilot lights would be extinguished and thus the potential for ignition decreases.

Regulation

Earthquake-triggered automatic gas shutoff valves must be certified by the California Division of the State Architect.[*]

Cost

An earthquake-triggered automatic gas shutoff valve costs between $100 and $300, not including the cost of installation, which must be performed by a trained professional. Installation costs also range from $100 to $300.

[*] California has adopted the American Society of Civil Engineers standard ASCE 25-97, Earthquake Actuated Automatic Gas Shutoff Devices, in Title 21, Division 1, Chapter 1, Sub 5 of the CA Code of Regulations as the basis for certification.

3.2 San Francisco's Current Approach

To date, San Francisco has not required the installation of earthquake-triggered automatic gas shutoff valves. An informal policy study conducted by the CAPSS team in 2005 and 2006 concluded that the use of such valves would result in significant social disruption and would disproportionately endanger vulnerable populations such as the elderly, who would be left for weeks or months without gas for heat, hot water, or cooking. Relocating such residents to shelters would not meet the City's "Shelter-in-Place" resilience goals.[23] These conclusions have thus far guided the city's policy and regulatory approach.

3.3 Benefits and Drawbacks

Benefits

By far the most significant benefit of earthquake-triggered shutoff valves is the protection they provide when an earthquake causes a gas leak in a building and no one is present or able to manually shut off a gas valve. When the gas valve is triggered, gas is shut off and pilot lights extinguished. This may also protect other areas of a gas system (e.g., vents and flues). Other benefits worthy of consideration in developing policy and regulation include:

- A program at the State level exists to certify these valves.
- Because other jurisdictions require these valves (see Appendix B), a market exists. Numerous manufacturers and distributors sell these gas valves to California property owners and contractors.

Drawbacks

As discussed above, a main concern of the City and County of San Francisco is the potential for significant social disruption as a result of a blanket earthquake-triggered gas valve regulation. This is because once the valves shut off gas to a building, a "qualified person"[†] must restore gas service. Experience has shown that a well-coordinated mutual aid system (i.e., best-case scenario) has allowed utilities to check and restore services at a rate of 10,000 to 20,000 customers per day.[24] This translates to weeks or months before the entire City is restored following a widespread outage. Data on gas service restoration times from historical California earthquakes are presented in Table 6.

[†] As defined by ASCE 25-97, a "Qualified Person" is "any individual, firm, corporation, or company that is experienced in such work and is familiar with all precautions required based on manufacturer's instructions, local codes, and the authority having jurisdiction."

Earthquake	Number of Customer Outages	Restoration Time
Northridge	120,000	12 days
Loma Prieta	156,355	9 days
Whittier	20,600	10 days

Table 6. Post-earthquake gas restoration times.

Clearly a blanket, citywide ordinance requiring earthquake-triggered automatic gas shutoff valves could lead to widespread outages. The potential for these widespread outages lasting several weeks has led to concern about extended lack of heat and hot water, especially for elderly or otherwise vulnerable residents whose gas didn't need to be turned off in the first place. These social impacts could be magnified because seismically actuated gas valves can also reactivate during aftershocks, thus increasing the demand for multiple service restorations.

Additionally, though earthquake-triggered automatic gas shutoff valves on the market today have greatly improved, there is still potential for valves to be triggered and gas shut off from non-earthquake shaking (e.g., from being bumped). Due to the nature of the valve, an earthquake will trigger it and service shut off regardless of whether there is damage to the gas system or not. And because of the uncertainty associated with earthquake prediction, the valves are “biased toward actuation at lower levels of ground shaking.”[25]

There is concern that this extended service restoration time may entice residents to attempt to restore gas service on their own. Because necessary precautions may not be taken, this can increase the risk of injury and death. This has been witnessed in Japan, where many buildings have earthquake-actuated shutoff valves.[26] Extended service outages could also encourage many residents to leave the city, delaying recovery and not meeting San Francisco’s “shelter-in-place” goals.[27]

Lastly, because gas contributes to less than half of post-earthquake fires, it will be important for the public to understand that installing an earthquake-triggered automatic shutoff valve does not completely reduce risk for post-earthquake fire. It is not a “silver bullet” solution, and complacency after installation is a legitimate concern.

3.4 Implementation Considerations

If it is determined that an earthquake-triggered automatic gas shutoff valve program should be implemented, the following strategies and tactics could be employed to reduce harmful social impacts discussed above:

- The requirement to install valves could be targeted to only the most vulnerable neighborhoods (e.g., those with high building density and a large stock of wooden buildings). These targeted installations can ensure gas is shut off in areas with a potential for rapid fire spread.
- The City (with gas companies and/or the Public Utilities Commission) could establish standards and guidelines that would make it easier for automatic valves to be reset rapidly.
- Large building property managers could be trained and certified to reset automatic valves and check for leaks.
- A registry of residences with vulnerable occupants could be created. These locations would become a priority for service restoration. Locations of nursing homes and “residential care facilities” are known today and mapped.[28]
- A corps of plumbers and contractors could be trained and certified to reset valves.

Chapter 4

Options to Address Post-Earthquake Ignitions

This chapter presents various alternatives to the earthquake-triggered automatic gas shutoff valve that can also reduce post-earthquake fire risk and damage. As discussed in Chapter 1, this report focuses on strategies to reduce ignitions. In order to best present the benefits and drawbacks of these alternative solutions, we must first identify the goals the City and County of San Francisco is trying to achieve. Next, solutions that reduce ignitions from gas will be explored, followed by tactics for reducing electric fire ignitions. Finally, a summary of each of the options is presented.

4.1 Policy Goals

Four high-level goals are considered in the analysis of each alternative to potentially reduce the number of post-earthquake fire ignitions: that it is effective in reducing post-earthquake ignitions, that it is easy for both the City and property owners to implement, that it low cost, and that there are minimal associated social impacts. The trade-offs are significant: for instance, a highly effective solution may also be extremely expensive or difficult to implement. Solutions with little or no negative social impacts on vulnerable populations may be less effective at addressing the problem of ignitions after an earthquake. Discussion of each of the policy goals is integrated into the analysis of each alternative, and is summarized in a table in Section 4.4.

Effective in Reducing Post-Earthquake Ignitions

First and foremost, the solution should be effective at reducing post-earthquake fire ignitions, and thus reducing risk and damage. None of these alternatives are free, and City and property owner resources should be invested in solutions that have the greatest potential for reducing post-earthquake fire ignitions.

Easy to Implement

Ease of implementation is also important for the City and County of San Francisco. This goal takes two forms: ease for property owners and ease for the City. For property owners, considerations may include how easy a product is to find, install, and use. For the city, considerations may include the level of education, inspection, and enforcement required.

Low Cost

Cost also must be considered for both the City and for property owners. For property owners, cost may include the cost of the actual equipment required or the cost of its installation. For the City, costs could include those associated with public education and outreach, inspection, and enforcement.

Minimal Impacts on Vulnerable Populations

As made clear in the above discussion on social impacts that could be associated with a widespread earthquake-triggered automatic shutoff valve program, we must take into account any solution's potential for social disruption. This is especially important given the post-disaster environment and related system demands.

4.2 Reducing Post-Earthquake Fire Ignitions Related to Gas Systems

Earthquake-Triggered Automatic Gas Shutoff Valves

See discussion above, in Section 3.

Excess Flow Valves

Excess flow valves are another automatic, passive solution to shut off gas flow when the potential for danger is present. These valves sense gas flows are above a set flow rate (varies by structure and gas appliance demand) and automatically restrict gas flow under these conditions—most likely when damage to the infrastructure causes a gas leak downstream. This helps mitigate dangerous gas build up.

Similar to earthquake-triggered automatic gas shutoff valves, excess flow valves are required to be certified by the State of California.[‡] Current code requires excess flow valves to be installed at appliance connections—at gas ranges, furnaces, water heaters, dryers, gas log fireplaces, etc. If a leak is sensed downstream or there is damage to the appliance or its connection, the valve actuates and gas is shut off.

Excess flow valves can also be installed where gas is delivered to the entire structure (where the earthquake-triggered valves would be also installed). This is not required by code in San Francisco. Installation of these types of excess flow valves requires a thorough understanding of the property's gas demands; excess flow valves come in various sizes.

Once the downstream leak or damage to the gas line is corrected, the gas valve re-opens, allowing the gas system to function normally. No action is required on the part of the property owner. Because of this feature, even with correct valve sizing and adequate installation, excess flow valves will never completely cut flow. A small, residual flow is required for the system to automatically restore once the danger passes. Thus, the social impacts associated with earthquake-triggered valves do not apply with excess flow valves, but gas is never completely shut off.

[‡] CSA Requirements for Excess Flow Valves Number 3-92

Excess flow valves at appliance cost anywhere between $5 and $15, with installation coming in around $100 to $300, depending on the number of gas appliances in the property. Excess flow valves at the meter cost around $100 (more or less depending on valve size) and also cost between $100 and $300 for professional installation, including the assessment of the size of valve required given the property's gas demands.

Excess Flow Valves: A Summary		
Benefits	Drawbacks	Cost
Someone does not need to be present to ensure shutoff. Can reset automatically once the downstream leakage is eliminated. For the most part, cheaper than earthquake-triggered automatic gas shutoff valves.	Will not shut off gas if leakage is below the triggering flow rate, even if a slow leak exists. Will not completely shut off gas flow, due to its automatic reset function. Requires very specific and tailored specifications to be effective. May not activate if occupant changes gas systems downstream without modifying the device.	**To Property Owner:** *Equipment:* At Appliance: $5-$15 At Meter: $100 *Installation:* $100-$300+ **To City:** Requires investment in enforcement and inspection.

Manual Shut Off

Property owners can be trained on leak detection and how to properly shut off gas in emergencies. This, traditionally, has been San Francisco's approach to reducing gas-related ignitions (i.e., a "Let Current Trends Continue" alternative).

Public education is critical for this option to be most effective. Once the smell of natural gas is detected (and only if natural gas is detected), property owners must know where the manual gas shutoff valve is located, must have an appropriate tool located near the valve, and must know how and be physically able to turn the gas off. Thus, training on gas leak detection as well as the mechanics of a manual shutoff is of utmost importance.

Past experience in California earthquakes shows that large numbers of property owners shut off gas as a precautionary measure, not just when they smell gas or there is damage to gas lines or appliances. As many as 120,000 to 150,000 customer gas outages have occurred in recent California earthquakes, and many of those are due to a customer turning off gas unnecessarily.[29] Once the gas is turned off, it must be restored by the gas company. Thus, the social problems associated with widespread outages are possible with manual shutoffs.

Aggressive public outreach is required to combat this problem. Fortunately, the City and County of San Francisco can take advantage of existing forums and structures to reach the public (Neighborhood Emergency Response Teams [NERTs] and Community Emergency Response Teams [CERTs], for example).

Clearly this is the lowest cost option for property owners; the correct wrench costs around $5. For this option to be most effective, however the City must invest in more public education and outreach.

Manual Shut Off: A Summary		
Benefits	Drawbacks	Cost
Valves that can be shut off with a wrench are already installed. Guidance is already provided in many public information documents and online. The most inexpensive solution, by far, for property owners.	Only effective if someone is present, knows the valve location, has access to the valve, and has a wrench suitable to close the valve. Requires an understanding of when it is appropriate to shut off gas, otherwise widespread outages could be seen. Can be difficult for disabled, elderly, or injured residents.	**To Property Owner:** *Equipment:* $5-15 *Installation:* None **To City:** Requires investment in public education and outreach to be most effective.

Gas Appliance Bracing

Toppled appliances cause many post-earthquake fires; the greatest risk of damage in residential buildings comes from the movement of appliances, with water heaters the most vulnerable.[30] As such, seismic restraints can help prevent water heaters and other gas appliances from moving during ground shaking.

This solution specifically targets a component of the gas system with the most risk of damage and potential for ignition. A toppled water heater caused the Marina fire after the 1989 Loma Prieta earthquake, for instance.[31] It has been estimated that bracing gas appliances correctly can reduce the risk of an ignition at the appliance by more than 80%.[32] Tangential benefits also exist: securing gas appliances can prevent damage to the appliances themselves. If a water heater is adequately braced and survives ground shaking, the homeowner has the benefit of 40 to 50 gallons of drinking water.

Current codes require seismic bracing for new and/or replacement water heaters.[§] However, much water heater bracing is done incorrectly, significantly impacting the effectiveness of this type of solution. Enforcement is difficult, however an upcoming "in-law" unit amnesty program may provide City inspectors an opportunity to check out water heater bracing in numerous homes.[33]

At $15-$50, off-the-shelf appliance bracing is inexpensive and does not necessarily require professional installation. However, an education campaign—and significant inspection and enforcement—would be required given this high number of incorrect bracings seen throughout San Francisco. Hiring a plumber to bolt the appliance to the floor with a steel brace is a more expensive, but more effective, solution than property owner installation of off-the-shelf products (e.g., plumber's tape and lag screws).

Gas Appliance Bracing: A Summary		
Benefits	Drawbacks	Cost
Appliance bracing, especially water heaters, is an inexpensive option to reduce risk of post-earthquake fires. Targets part of the gas system with the most risk of damage. When a water heater survives ground shaking, the homeowner has 40 to 50 gallons of drinking water. Effective appliance bracing is thought to reduce fire risk at the appliance by 80%.	Because many water heater braces are installed by homeowners themselves, it is known that many appliances are not braced correctly. Enforcement of water heater bracing code is difficult and expensive.	**To Property Owner:** *Equipment:* $15-50 per appliance *Installation:* $0-$100 per appliance **To City:** Requires investment in public education and outreach, inspection, and enforcement.

Hybrid Devices

Though hybrid gas valves that can address some of the drawbacks of both earthquake-triggered automatic gas shutoff valves and excess flow valves are gaining in popularity, they remain expensive and less available than other solutions. Hybrid gas valves are actuated by a combination of motion detection, excess flow, and/or natural gas, carbon monoxide, or smoke detection. These devices can sound alarms and notify alarm companies as well as shut off gas. These solutions can be customized

[§] California Health and Safety Code, Section 19211.

for individual needs and specific risk situations. For instance, the valve can be set to only shut off gas when it detects a combination of ground shaking, excess flow, and the detection of leaking natural gas.[34] This could clearly address some of the problems associated with earthquake-triggered automatic gas shutoff valves.

Existing hybrid valve solutions on the market are expensive (upwards of $500) and require professional installation (at around the same cost). Additionally, there is little market for these devices—likely due to their higher cost. The City and County of San Francisco may consider a program to help industry develop a lower-cost hybrid valve (see Chapter 5).

Hybrid Valves: A Summary		
Benefits	Drawbacks	Cost
A highly customizable solution allows the property owner to specify under what exact conditions gas should be shut off. Hybrid valves can address some of the drawbacks associated with either earthquake-triggered valves or excess flow valves.	Current options are expensive and there is not much of a market around these hybrid devices.	**To Property Owner:** *Equipment:* $150-$500+ *Installation:* $100-$500+ **To City:** Would likely require a program to encourage industry research and development. Inspection and enforcement costs are also associated.

4.3 Reducing Post-Earthquake Ignitions Related to Electrical Systems

Arc Fault Circuit Interrupters

Arc-fault circuit interrupters (AFCIs) detect an unintended electrical arc and shut off electricity to the affected circuits before the arc starts a fire. In other words, AFCIs sense electricity "leaking" from damaged or decayed wiring and cut off electricity before overheating.[35] Arc faults are the leading cause of electrical fires in the U.S.[36]

This solution could be considered analogous to the excess flow valve approach to preventing gas fires; it passively shuts off electricity when it notices a potentially dangerous anomaly in the electric system.

Arc-fault circuit interrupters are today required in certain areas of new building. Currently the San Francisco version of the National Electric Code requires AFCIs on any new circuit with the exception of a circuit that is required by the code to be protected by a Ground Fault Circuit Interrupter (GFCI).

For the purposes of reducing post-earthquake fire risk, installing a GFCI is less effective. A GFCI protects from shocks; an AFCI protects from fires.

AFCIs can be installed on existing circuits, but there is evidence that AFCIs don't always work well on old wiring, though the Consumer Product Safety Commission estimates that AFCIs could prevent more than 50% of electrical fires.[37]

AFCIs can be purchases for approximately $35 each, with total installation costs ranging from $140-$350 depending on the number of AFCIs that need to be installed.[38] Installation should be performed by a licensed professional, not the property owner. More research, though, is needed to determine whether installation of AFCIs in all properties (not just new wiring) would be cost-effective in actually reducing electricity-related ignitions following an earthquake, especially given the concern of their effectiveness in older wiring systems.

Arc-Fault Circuit Interrupters: A Summary		
Benefits	Drawbacks	Cost
A passive, automatic solution that can reduce risk for electric fires from wiring damaged by building shaking. Targets the most common type of (non-earthquake-related) electrical fires. Estimated to prevent 50% of electrical fires (in non-earthquake situations).	Current codes require either AFCIs or GFCIs. GFCIs do not help mitigate post-earthquake electrical fire risk. More research is needed to determine if AFCIs are effective at reducing post-earthquake fire risk, especially with old wiring systems.	**To Property Owner:** *Equipment:* $35 per AFCI *Installation:* $100-$300 **To City:** Little additional inspection and enforcement costs.

Earthquake Sensing Breakers

A fairly new solution, not widely installed in the United States, is an earthquake-sensing breaker. This device can be considered analogous to the earthquake-triggered automatic gas shutoff valve; it detects shaking an electric power source and automatically cuts off electricity. Installed on a property's breaker box, these solutions can help prevent a common type of post-earthquake fire: when power goes out while the appliance is in use, an earthquake moves or damages the appliance, and then a fire starts from the appliance after the power is restored. With an earthquake-sensing breaker solution installed, power would not be restored to the property until the homeowner confirms it is safe. The widespread social impacts seen in large-scale gas outages associated with earthquake-triggered automatic gas shutoff valves are not as concerning here—property owners can restore their own electric service.

Three main types of breaker seismic safety designs are available in Japan:

- A weight attached to a breaker switch would drop during shaking, tripping it. This would shut off power to the entire house, which would disable lighting and in-home medical equipment.
- A built-in electronic circuit would detect shaking and cut off power for the entire house. Similar concerns exist.
- A shake-detecting sensor would transmit a signal to individual extension units and outlets, and electricity would be cut off only to those units. This allows a property owner to target the most vulnerable or dangerous appliance, and keep life-saving lighting or medical equipment active.

Japan's Central Disaster Management Council has pushed for the installation of these devices in Japan, however uptake has been slow.[39] These solutions are not widely available; even in Japan reports show that none of the types are commonly available directly to consumers. If availability was not a problem, at a cost of around $60, the most basic earthquake-sensing breaker technology would not require professional installation.

Earthquake-Sensing Breakers: A Summary		
Benefits	Drawbacks	Cost
Can help prevent a very common type of post-earthquake electrical fire. Basic technologies do not require professional installation and are inexpensive. Widespread social impacts are less of a concern because property owners can restore their own electric service.	As these solutions are only beginning to be deployed in Japan, their effects on reducing post-earthquake fires are unknown.	**To Property Owner:** *Equipment:* \$60-\$200+ *Installation:* \$100-\$300 **To City:** Would likely require a program to encourage industry research and development, in addition to associated inspection and enforcement costs.

4.4 Summary of Analysis

The following table presents a summary of each of the possible solutions as they relate to meeting the City's goals. Refer to the above discussion of each possible solution for further discussion on benefits and drawbacks.

	Policy Goals			
	Effectiveness	**Ease of Implementation**	**Social Impacts**	**Cost**
Solutions to Reduce Gas-Related Ignitions				
Earthquake-Triggered Automatic Gas Shutoff Valves	Highly effective at automatically reducing ignition risk due to gas when no one is present to take alternative action.	**To Property Owner:** Professional installation required. **To City:** A certification program already exists at the state level. Would require investment in inspection and enforcement programs.	Significant social impacts are possible with widespread gas outages that could last weeks to months. People forced to leave their homes because of a lack of utilities does not meet the City's shelter-in-place goals.	**To Property Owner:** *Equipment:* \$100-\$300 *Installation:* \$100-\$300+ **To City:** Requires investment in enforcement and inspection.
Excess Flow Valves (At Appliance and/or Meter)	A targeted solution that only activates when it senses a problem in the downstream gas line, but may not sense a slow, low-flow leak. Additionally, gas is never completely shut off.	**To Property Owner:** Professional installation required. **To City:** A certification program already exists at the state level. Would require investment in inspection and enforcement programs.	Because valves will automatically reopen when danger is no longer present, social concerns associated with earthquake-triggered shutoff valves are not applicable.	**To Property Owner:** *Equipment:* At Appliance: \$5-\$15 At Meter: \$100 *Installation:* \$100-\$300+ **To City:** Requires investment in enforcement and inspection.
Hybrid Valves	Because hybrid valves are customizable, they are highly effective at reducing risk of ignition taking into account property-specific vulnerabilities.	**To Property Owner:** Hybrid valves are expensive, tough to find, and require professional installation. **To City:** An industry would likely need to be incubated to bring hybrid valves to an acceptable cost. The state certification program could be leveraged. Would require	Widespread and unnecessary outages can be minimized by setting valves to only trigger in the presence of multiple factors.	**To Property Owner:** *Equipment:* \$200-\$500+ *Installation:* \$100-\$500+ **To City:** Would likely require investment in further developing the market. Requires investment in enforcement and inspection.

		investment in inspection and enforcement programs.		
Gas Appliance Bracing	Correct appliance bracing can reduce risk of ignition at the appliance by 80%, however much appliance bracing is done incorrectly, significantly impacting this effectiveness.	**To Property Owner:** Appliances can be braced by property owners with inexpensive, off-the-shelf solutions. **To City:** To be most effective, would require investment in public education, inspection, and enforcement programs.	No negative post-earthquake social impacts.	**To Property Owner:** *Equipment:* \$15-50 per appliance *Installation:* \$0-\$100 per appliance **To City:** Requires investment in public education and outreach, inspection, and enforcement.
Manual Shutoff	If property owners understand when and how to shut off their gas manually, and are home when danger is present, this option can be effective.	**To Property Owner:** Property owners need only a wrench and an understanding of how and when to shut off gas. **To City:** Expanded public education could improve effectiveness of this solution.	Widespread outages are possible if wide swaths of the population shut off gas as a precautionary measure. Significant demands will exist to restore service. Can be difficult for disabled, elderly, or injured residents.	**To Property Owner:** *Equipment:* \$5-\$20 *Installation:* N/A **To City:** Requires investment public education programs.
Solutions to Reduce Electricity-Related Ignitions				
Arc-Fault Circuit Interrupters	Targets the most common type of electric fire, but impacts on specifically reducing post-earthquake fire are unknown. May not be effective in systems with older wiring.	**To Property Owner:** Requires professional installation. **To City:** Little additional inspection and enforcement required.	Few social impacts exist.	**To Property Owner:** *Equipment:* \$35 per AFCI *Installation:* \$100-\$300 **To City:** Little additional inspection and enforcement costs.
Earthquake Sensing Breakers	Like an earthquake-triggered automatic gas shutoff valve, highly effective at reducing	Little data exist on earthquake-sensing breakers and more research is needed.	A property owner can restore their own electricity after an event, so social impacts are	**To Property Owner:** *Equipment:* \$60 to \$200+ *Installation:* \$100-\$300

	risk when no one is present to take action.	There is currently little to no market in the United States for these devices.	minimal. However, because power is automatically cut, the immediate loss of critical in-home medical devices is a concern.	**To City:** Inspection and enforcement costs if this solution is mandated through code.

Table 7. Summary of analysis against City's policy goals.

Chapter 5

Recommendations

There is no silver-bullet or one-policy-fits-all program to address post-earthquake fire risk in the City and County of San Francisco. The most effective post-earthquake fire mitigation program will likely include many facets of the above options. Additionally, significant tradeoffs exist given the various policy goals of the City. As such, the following actions are recommended:

1. Under the auspices of CAPPS and ESIP, convene a working group to specifically study post-earthquake fire (**both gas and electric**), acknowledge an acceptable level of risk, identify and prioritize goals, and advance recommendations for future City guidelines and regulations.

- Use this report to inform and frame discussion, and leverage the successful Private School Risk working group process as a model.
- As CAPPS and ESIP have learned, community-driven processes result in the most successful policy. Buy-in is more likely when the community itself confronts these tradeoffs.
- Include engineers, fire officials, building safety experts, vulnerable population advocates, and policy makers.

2. To inform the community working group or as part of the working group process, conduct further study on the following:

- A cost-benefit analysis of earthquake-triggered automatic gas shutoff valves and excess flow valves specifically.
- Barriers to market for hybrid gas valves and solutions to mitigate post-earthquake electric fire risk.
- Catalog and investigate possible solutions that reduce risk and damage at the other five steps of the fire-following earthquake process.

3. Through the newly launched EPICENTER, incubate an industry around hybrid-style gas shutoff systems and earthquake-caused electrical fire prevention solutions. This could take various forms:

- Design competition with small reward.
- Small research and development grants to existing gas valve manufacturers.
- City funding of research and development that would result in a City-owned patent.
- Partnering with university engineering departments.

4. In the interim, take advantage of existing (and inexpensive) opportunities for public education on fire risk, detecting gas leaks, and manually shutting off gas valves. This "low-hanging fruit" solution has potential to minimize risk under certain conditions.

Appendix A: Gas Valve Ordinances in the Bay Area

Cities

- City of Berkeley
- City of Brentwood
- City of Clayton
- City of Concord
- City of Hercules
- City of Lafayette
- City of Martinez
- City of Moraga
- City of Oakley
- City of Orinda
- City of Pinole
- City of Pittsburg
- City of Richmond

Counties

- Alameda County
- Contra Costa County
- Marin County

Appendix B: Gas Valve Manufacturers and Distributors

Manufacturer/Vendor	Contact Name	Contact Number	Contact E-Mail
Pacific Seismic Products, Inc.	Sharon Harper	661-942-4499	psp@thevine.net
Seismic Safety Products	Gary Lynden	509-669-7037	ssp@nwi.net
Earthquake Safety Systems Inc.	Owen Widdicombe	805-534-1582	info@eqsafetysys.com
Little Firefighter Corporation	Ezra King	714-834-0410	Info@LittleFirefighter.com
Affordable Safety Solutions	Fabian Padilla	310-674-7335	N/A

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