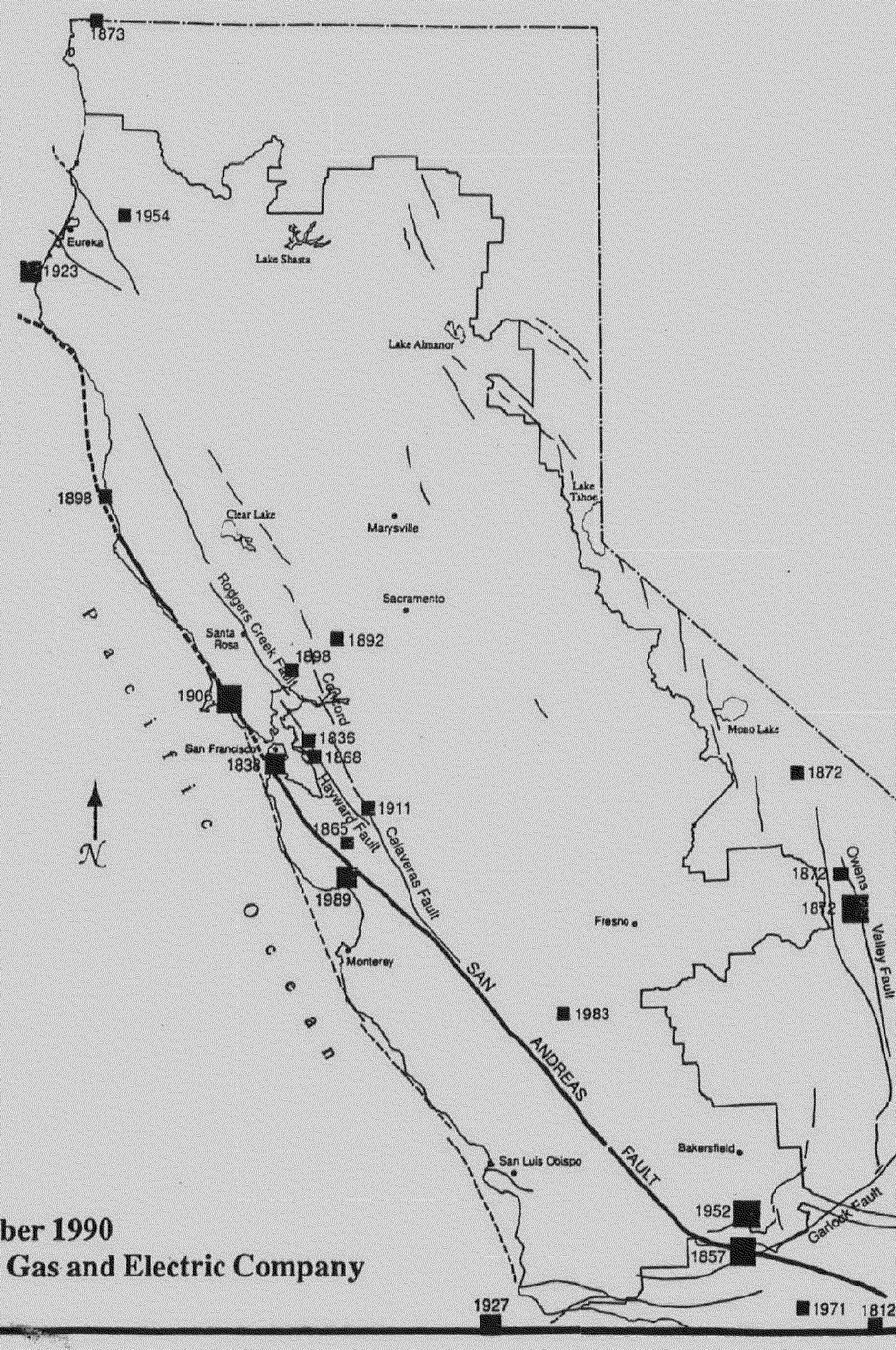
PROGRAM FOR REDUCING EARTHQUAKE VULNERABILITY OF GAS AND ELECTRIC SYSTEMS BY THE YEAR 2000



December 1990
Pacific Gas and Electric Company

Pacific Gas and Electric Company
77 Beale Street
San Francisco, CA 94106
415/972-6842

Leslie H Everett
Manager
Regulatory Relations

January 11, 1991

PG&E

Mr. Russell W. Copeland, Chief
Safety Division - Utilities Branch
California Public Utilities Commission
505 Van Ness Avenue, Room 2005
San Francisco, CA 94102

Dear Mr. Copeland:

Re: **Pacific Gas and Electric Company Program for Reducing Earthquake Vulnerability of Gas and Electric Systems by the Year 2000**

We are pleased to present PG&E's multiple-element, action-based program to reduce the impact of damaging earthquakes on our gas and electric systems and our customer service. The report was prepared by many contributing departments in PG&E and coordinated by the Geosciences Department.

PG&E is committed to meeting the objective of the California Earthquake Hazards Reduction Act of 1986 to significantly reduce seismic vulnerability by the year 2000. We concur with the Seismic Safety Commission's statement in *California at Risk* that, "Utility systems should be reviewed, and if necessary their design and construction improved so that they can withstand strong earthquake ground motion with minimal damage, and be brought back into operation quickly after a damaging earthquake." Our long-standing dedication to providing customer service includes protecting our utility systems, employees, and service to customers from the effects of earthquakes. Our commitment was evidenced in our September 20, 1989 response to your letter of July 28, 1989, wherein we described the earthquake preparedness programs that we had in place at that time.

Following the October 17, 1989, Loma Prieta earthquake, we received several additional requests from your office concerning our earthquake programs. We understand that the objective of these requests is to implement the recommendations of the Seismic Safety Commission to review seismic hazards, to mitigate the hazards where possible, and to develop emergency response and recovery plans so damaged systems can be brought back into operation quickly. We address the CPUC's requests in the accompanying report by considering the earthquakes having the highest likelihood of occurrence in the near future, and estimating the response of our gas and electric utility systems to such occurrences. By evaluating our utility systems' performance in response to high-probability, large-magnitude "scenario" earthquakes, we provide a realistic picture of the seismic resiliency of our utility service systems.

The Loma Prieta earthquake provided important lessons about preparing for and responding to the impacts of a significant earthquake on utility systems. At PG&E, we met the challenge of the Loma Prieta earthquake by activating our earthquake emergency response plan, which had been developed and practiced, but never before tested in a real earthquake. Although we experienced significant system damage, we had previously recognized the vulnerabilities of certain facilities and already had mitigation programs under way. We were successful in effecting emergency repairs and restoring most customer service quickly. Even so, we know that the 1989 earthquake was a stern warning to prepare for expected large earthquakes closer to the San Francisco Bay Area, where many more of our facilities and customers will be affected. The Loma Prieta earthquake has reinforced our commitment to our corporate-wide program for reducing earthquake vulnerabilities in our gas and electric systems.

We believe this vigorous program will significantly reduce the seismic vulnerability of our utility systems by the year 2000. This report is the first in a series of annual reports over the next ten years describing our progress in meeting this goal.

Further correspondence and questions on this matter should be directed to Eric Montizambert at 972-6859. Technical questions should be directed to Lloyd Cluff, Manager of the Geosciences Department, at 973-2791.

Sincerely,

Leslie H. Everett

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Enclosure

PACIFIC GAS AND ELECTRIC COMPANY

PROGRAM FOR REDUCING EARTHQUAKE VULNERABILITY OF GAS AND ELECTRIC SYSTEMS BY THE YEAR 2000

December 1990

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SUMMARY

Pacific Gas and Electric Company (PG&E) is committed to meeting the objective of the California Earthquake Hazards Reduction Act of 1986 to significantly improve California's earthquake safety by the year 2000. The principle objectives of our broad program are to increase the seismic resiliency of our gas and electric systems, and to improve our ability to rapidly restore service to customers after damaging earthquakes. This is the first annual report on our activities to identify seismic hazards and to reduce their effects on our gas and electric systems and services during the coming decade. Reports describing our progress in meeting our objectives will be prepared annually over the next ten years.

We have evaluated the likely effects of high-probability, large-magnitude "scenario" earthquakes in PG&E's service territory. This has allowed us to assess their impacts and set priorities for the mitigation of seismic hazards. Eight scenario earthquakes on the San Andreas, Hayward/Rodgers Creek, and Calaveras/Concord fault zones were analyzed for potential impacts on our gas and electric systems. These scenario earthquakes all have magnitudes of 6.5 or greater, have at least a 10 percent likelihood of occurrence in the next 30 to 50 years, and are located such that they could adversely affect many elements of our systems and many customers.

The impacts of the scenario earthquakes on PG&E's gas system have been evaluated by conducting site reviews of above-ground facilities, and by assessing pipelines in areas subject to soil liquefaction and slope instability and where they cross surface faults. PG&E's gas system is seismically rugged and has generally performed well during past earthquakes. The system's greatest vulnerability is the potential for leakage in portions of the distribution system that contain brittle pipe, weak pipe joints or welds, or corroded pipe, particularly in areas of soft soil conditions. The 25-year Gas Pipeline Replacement Program, which is 20 percent complete, includes these vulnerable pipe elements and is being modified to place higher priority on pipe within the impact areas of the scenario earthquakes subject to soft-soil effects. Pipeline fault-crossings have been analyzed for near-future replacement of the gas transmission lines that cross the San Andreas fault on the San Francisco Peninsula, and fault crossings of the Hayward and Calaveras fault are being evaluated.

The scenario-based assessment of PG&E's electric system has included field inspections of major facilities, and consideration of the redundancy in power sources and in transmission and distribution paths. Power generation facilities are seismically rugged, and we expect only minor damage due to earthquakes. Distribution lines may be damaged locally; however, these are readily repairable, and experienced crews are prepared with inventories of spare parts. High-voltage substations are the most vulnerable element of the electric system, due to fragile circuit breakers, transformers, switches, and other equipment. We have evaluated the impact of the scenario earthquakes on 22 of our most important substations. Results of the early phases of this study were beneficial in the October 17, 1989, Loma Prieta earthquake in reducing earthquake damage and accelerating restoration of service. Among our current hazard mitigation activities, replacing selected high-voltage circuit breakers and

bracing radiators on transformers are particularly important in reducing the seismic vulnerability of the electric system.

PG&E's corporate-wide program also includes emergency response and recovery planning and other important activities. We have established an Emergency Operating Center (EOC) in the General Office complex in San Francisco, and an Alternate EOC in San Ramon, and we conduct annual emergency response exercises to train personnel in using these centers. We have mutual aid agreements with the Western Systems Coordinating Council and nearby utilities to provide equipment and personnel as needed to restore service. Planning for recovery from damaging earthquakes, including provisions for adequate funding, is an integral part of our emergency planning. We consider seismic safety in planning, design, and construction of every new facility or component. Our education and public information efforts include programs focused on our customers, our employees, other organizations, and the general public. We also support research programs in engineering and geosciences that further earthquake safety.

PG&E's program to reduce the seismic vulnerability of our gas and electric systems includes realistically assessing seismic hazards; evaluating the response of our systems; identifying, prioritizing, and mitigating the vulnerabilities; and preparing for effective emergency response and recovery. The 1991 Action Plan that follows summarizes our current activities and those budgeted for 1991.

1991 ACTION PLAN

ACTIVITY	SCHEDULE	RESPONSIBLE PG&E UNIT
ASSESSING SEISMIC HAZARDS		
Continue data compilation for scenario earthquake and seismic hazard studies	Continuous program	Geosciences
Continue seismic and volcanic hazards studies in northeastern California and the Sierra Nevada	3-year study to be completed in 1991	Geosciences
Continue strong-motion instrumentation and ground-motion analyses at substation sites	Ongoing program to continue through 1991	Geosciences
REDUCING THE VULNERABILITY OF THE GAS SYSTEM		
Continue assessment of seismic vulnerabilities of the gas transmission, storage, and distribution facilities	Ongoing program to continue through 1991	Gas and Electric Project Engineering, and Gas Engineering and Construction
Continue Gas Pipeline Replacement Program and modify earthquake hazards priorities	25-year program; 20% complete. Priorities to be modified in 1991	Gas and Electric Distribution
Replace transmission pipelines 109 and 132 on the San Francisco Peninsula	Evaluation complete; replacement to begin in 1991	Gas and Electric Distribution
Attend Inter-Utility Seismic Working Group meetings	Continuous program	Geosciences, Civil Engineering, Gas and Electric Project Engineering, and Gas Engineering and Construction
Maintain awareness of improvements in seismic resistance of pipelines and related equipment	Continuous program	Geosciences, Civil Engineering
Update Gas Control Department contingency plans	New program to be completed in 1991	Gas Control
REDUCING THE VULNERABILITY OF THE ELECTRIC SYSTEM		
Develop and implement performance-based seismic evaluation criteria for the high-voltage system	Criteria to be developed in 1991. Implementation to continue through 1991	High-Voltage Transmission and Substations
Install transformer radiator bracing	Ongoing program to continue through 1991	High-Voltage Transmission and Substations
Replace selected circuit breakers at 500-kilovolt intertie substations	Multi-year program to begin in 1991	High-Voltage Transmission and Substations
Participate in dynamic testing of high-voltage components	Continuous program	Civil Engineering
Attend Inter-Utility Seismic Working Group meetings	Continuous program	Geosciences and Civil Engineering
Participate in EPRI research on earthquake ruggedness of substations	Complete in 1991	Civil Engineering
Perform seismic review of additional substations	Ongoing program to continue through 1991	High-Voltage Transmission and Substations, and Transmission and Substations
Maintain awareness of improvements in seismic resistance of electric transmission equipment	Continuous program	Civil Engineering, High-Voltage Transmission and Substations, and Transmission and Substations
EMERGENCY PLANNING AND OTHER ACTIVITIES		
Conduct annual earthquake exercise	Continuous program	Security
Evaluate post-earthquake functionality of the Energy and Gas Control Centers	1-year program to be completed in 1991	Power Control, and Gas Control
Review seismic performance of the General Office complex	1-year program to be completed in 1991	Building and Land Services

INTRODUCTION

Throughout California, state and local governments, corporations, organizations, and individual citizens are taking constructive actions to lessen the impacts of future earthquakes. Pacific Gas and Electric Company (PG&E) shares this commitment to earthquake hazard mitigation and preparedness. We are dedicated to protecting our utility systems, our employees, and our service to customers from the effects of earthquakes by continuing to improve our programs to realistically assess earthquake hazards, to assess our facilities and their capacity to accommodate these hazards, to prioritize and mitigate the vulnerabilities, and to prepare for effective emergency response and recovery.

Earthquakes have long been recognized as an inevitable aspect of the California environment. However, a variety of factors have contributed to an intensified mobilization of institutions and individuals to mitigate earthquake hazards. Since the 1906 San Francisco earthquake, several generations of population, construction, and business growth have occurred without significant damage and disruption due to earthquakes. Recently, however, damaging California earthquakes, including San Fernando (1971), Coalinga (1983), Whittier (1987), and especially Loma Prieta (1989), have heightened our awareness of seismic hazards. Catastrophic foreign earthquakes in Mexico (1985), Armenia (1988), and the Philippines (1990), have provided further evidence of the destructive power of very strong earthquakes.

During the past 15 or so years, new organizations have been created to focus on earthquake safety, including the California Seismic Safety Commission, the Bay Area Earthquake Preparedness Project, the Southern California Earthquake Preparedness Project, and the State Legislature's Committee on Earthquake Preparedness and Natural Disasters. In addition, many existing organizations have made earthquake safety a more important part of their endeavors. The growing acceptance of earthquakes as a continuing part of life in California has been accompanied by an increasing understanding that we can do much to lessen the impacts of earthquakes on people and property.

PG&E's ongoing program for reducing earthquake vulnerability meets the objectives of the California Earthquake Hazards Reduction Act of 1986, which:

> directs the Seismic Safety Commission to prepare and administer the California Earthquake Hazards Reduction Program to develop and implement new and expanded activities to reduce the earthquake threat to the citizens of the state significantly by the year 2000. . . The purpose of the program is to identify the hazards from earthquakes and determine ways to reduce their effects through hazards reduction, enhanced emergency responses, and improved recovery capabilities, using clearly defined and achievable initiatives. (California Seismic Safety Commission, 1989)

California at Risk, an annually updated publication of the California Seismic Safety Commission, provides an overall policy and action-oriented framework for identifying and mitigating earthquake hazards throughout the state. Initially, this publication was used primarily to define objectives, set priorities, coordinate programs, and evaluate the progress of the efforts of state agencies. Now, the activities of organizations, groups, and individuals in the private sector are being emphasized. Implementation of seismic safety clearly requires the commitment of the private sector as well as all levels of government.

Specifically regarding utilities, *California at Risk* (California Seismic Safety Commission, 1989) states that:

> Utility systems should be reviewed, and if necessary their design and construction improved so that they can withstand strong earthquake ground motion with minimal damage, and be brought back into operation quickly after a damaging earthquake.

An objective of PG&E's program of seismic preparedness is to enable the utility to restore service to most customers within a few days or less, through a combination of seismically resistant facilities, redundant networks for service and control, and strategic inventories and response plans to replace or temporarily bypass damaged facilities as promptly as conditions in the affected areas permit.

PG&E includes seismic consideration in all of our engineering decisions. Our century-long history of addressing and mitigating seismic hazards has included applying successive generations of building and equipment codes and regulations, augmented by the available knowledge at the time. In the past decade, our efforts have been intensified to assess and apply updated knowledge to our in-place systems, many elements of which were built 20 to more than 70 years ago. We have initiated major upgrades of parts of our systems, including a 25-year program of gas pipeline replacement of the older underground pipes, and circuit-breaker replacements for high-voltage substations. We have established an Emergency Operations Center to improve emergency response and recovery following earthquakes. In our current company-wide program to mitigate seismic hazards, we have considered all six of the major categories outlined in *California at Risk*: existing development, emergency planning and response, future development, recovery, education and public information, and research.

In this report, our analysis of the performance of PG&E's gas and electric systems during earthquakes is organized into four main sections. We first summarize our approach to understanding and prioritizing earthquake hazards, which considers high-probability, large-magnitude (scenario) earthquakes and their ground-motion, soil-stability, and surface-faulting effects. Second, the performance of our gas utility system during the likely earthquakes is evaluated, and mitigation plans are described. Third, the performance of our electric utility system during the likely earthquakes is evaluated, and mitigation plans are described. Fourth, our corporate planning and operations efforts are reviewed, with emphasis on emergency planning, future development, recovery, education and public information, and research. In the last chapter, our seismic hazard mitigation efforts are compiled into a detailed action plan for assessing seismic hazards and mitigating these hazards substantially by the year 2000. This report is the first in a decade of annual reports of our progress in meeting this goal.

PERFORMANCE OF PG&E'S GAS AND ELECTRIC SYSTEMS DURING EARTHQUAKES

The impact of a strong, nearby earthquake on PG&E's gas and electric systems will undoubtedly cause some interruption of customer service. Reducing these interruptions and rapidly restoring service are goals of PG&E's efforts to reduce earthquake vulnerabilities and to make our systems more earthquake-resistant. Our overall approach to improving the seismic performance of our gas and electric systems involves four aspects:

1) *Improving our understanding of earthquake hazards and how they may affect PG&E systems.* This knowledge of seismic hazards is based on locating faults and evaluating their activity, including assessing the probability of occurrence of various magnitude earthquakes on each fault. The potential effects of such earthquakes are characterized in detail by considering the potential for surface fault rupture, characterizing potential strong ground motions, assessing the susceptibility of a site to liquefaction, and evaluating the potential for slope failure.

2) *Improving our understanding of the ability of equipment, buildings, and other facilities to withstand strong seismic shaking.* Experience gained from earthquake damage (or lack of damage) around the world is the primary means of evaluating and improving our knowledge of earthquake performance. Testing and analysis also provide an improved basis for assessing the potential for earthquake damage.

3) *Developing seismic design criteria for new systems and structures, and seismic evaluation guidelines for existing ones.* Criteria and guidelines are developed to achieve a desired level of seismic performance, considering the redundancy of the system and the system's ability to deliver service even though it has some earthquake damage. They are based on the Uniform Building Code criteria as a minimum, and recognize the inherent seismic ruggedness of many parts of the gas and electric systems.

4) *Prioritizing and implementing earthquake mitigation activities.* High-priority components and facilities are those whose performance during earthquakes means the most to the most customers. Hazard mitigation involves a combination of reducing the potential for damage to components and facilities, relying on system redundancies to circumvent damaged areas, and preparing for rapid repair or temporary bypasses to restore service.

The use of "scenario" earthquakes as an impetus for coordinated regional planning within California has been beneficially applied by the California Division of Mines and Geology in four studies of large earthquakes postulated for the northern and southern San Andreas faults, the Hayward fault, and the Newport-Inglewood fault (Davis and others, 1982a; Davis and others, 1982b; Steinbrugge and others, 1987; Toppozada and others, 1988). We have adopted this technique and are using evaluations of the credible consequences of realistic earthquake occurrences anticipated within the PG&E service territory as a basis for identifying seismic vulnerabilities of our systems, for planning to mitigate these vulnerabilities, and for refining our emergency response planning. For the purposes of selecting scenario earthquakes for gas and electric systems analysis, we have used three selection criteria:

1) *Magnitude 6.5 or greater.* We selected this magnitude level because experience with the effects of earthquakes on modern utility systems in California and elsewhere during the past several decades indicates that events of magnitude 6.5 or greater have the potential to produce significant and relatively widespread damage, particularly in densely urbanized areas. Smaller earthquakes, such as the magnitude 6.2, 1984 Morgan Hill and the magnitude 5.7, 1987 Whittier Narrows events, have generally produced lesser, localized damage that, for a spatially distributed utility system, causes only local and temporary customer service disruption.

2) *High probability of occurrence.* We focused on earthquakes that have a high probability of occurrence during the design lifetimes of our gas and electric facilities, which generally are in the range of 30 to 50 years. Because the Uniform Building Code is associated with an earthquake probability of occurrence of 10 percent or greater in 50 years, we have used this probability level as a guide when selecting our scenario earthquakes. We also considered the results of the Working Group on California Earthquake Probabilities (U. S. Geological Survey, 1988, 1990).

3) *Potential significant impact on customers.* We focused our efforts to reduce seismic vulnerabilities on those earthquakes whose effects could interrupt service to large numbers of customers, disrupting business operations and residential life-styles within wide areas.

After selecting the scenario earthquakes using the above criteria, we are following a logical and consistent sequence of steps to assess and evaluate the seismic vulnerabilities of the gas and electric systems affected by the scenario events. We are estimating the extent of each scenario event's effects, and identifying the affected system components. Those components, facilities, or subsystems that are relatively vulnerable to seismic effects and that are important to maintaining or rapidly restoring service are selected for further evaluation. Site-specific earthquake hazard investigations, on-site engineering reviews, static and dynamic analyses, operational contingencies, or other evaluations may be required to refine the vulnerability assessments. Finally, we are developing alternatives for reducing the identified earthquake vulnerabilities, establishing priorities for strengthening or replacing vulnerable facilities, and mitigating the earthquake effects.

In the following sections, we discuss the application of the scenario earthquake method to the gas and electric systems and emergency response planning. The results of this work through 1990 are summarized in the 1991 Action Plan that concludes this report.

ASSESSMENT OF EARTHQUAKE HAZARDS

Significant historical earthquake activity within PG&E's service territory of northern and central California has been documented since the Spanish explorations and settlements of the eighteenth century. As illustrated in Figure 1, this activity has been concentrated in northwest California, near the greater San Francisco and Monterey Bay areas, and along the southern and southeastern margins of the service territory. Geologic and seismologic studies conducted with increasing sophistication during the past century have demonstrated that displacement along the San Andreas and related faults is the primary cause of this pattern of earthquake activity. During the past several decades, the improving scientific understanding of the occurrence of past earthquakes along the San Andreas fault system has reached the level that the potential for future earthquake activity can be estimated with relative confidence. Although earthquakes cannot be reliably predicted in terms of their exact time of occurrence, the technology to identify future locations of potentially damaging earthquakes and to assess the probabilities of their occurrence has entered scientific and engineering practice.

Selection of Scenario Earthquakes

Recent earth sciences research has identified the fault segments in California that are most likely to produce large earthquakes in the near future. A national Working Group on California Earthquake Probabilities, first chaired by Lloyd Cluff of PG&E, used this research to assess the probabilities of earthquake occurrence along the major faults of the San Andreas fault system (U. S. Geological Survey, 1988, 1990). This group chose a time interval of 30 years for their probability calculations, and they considered specific fault segments that had the potential for magnitude 7 or larger earthquakes. The 30-year interval used by the Working Group is within the typical lifetime of utility facilities and the 30- to 50-year time frame considered by PG&E for this report. The results of the Working Group's study are therefore appropriate for identifying high-probability, large-magnitude earthquakes that may affect PG&E's service territory.

Prior to the recent conclusions developed by the Working Group, PG&E had incorporated generic and site-specific seismic standards in their systems, as appropriate. Now, this new information can be applied to identify specific seismic hazards associated with specific fault segments and postulated events. The fault segments in PG&E's service territory associated with high-probability earthquakes of magnitude 7 or greater are along the San Andreas, Hayward, and Rodgers Creek faults (Figure 1). In addition to these faults, we also considered the potential for magnitude 6.5 earthquakes within the next several decades along two segments of the Calaveras fault zone and along the Concord fault.

During the next 30 to 50 years, additional strong earthquakes (magnitude 6.5 or greater), other than those identified as high-likelihood events, may well take place on other faults within the PG&E service territory. Continuing studies of earthquake potential will be used to identify additional scenario events for evaluation of utility system performance in the next several years; however, the scenario earthquakes chosen, due to their probability, magnitude, and location, clearly have the greatest

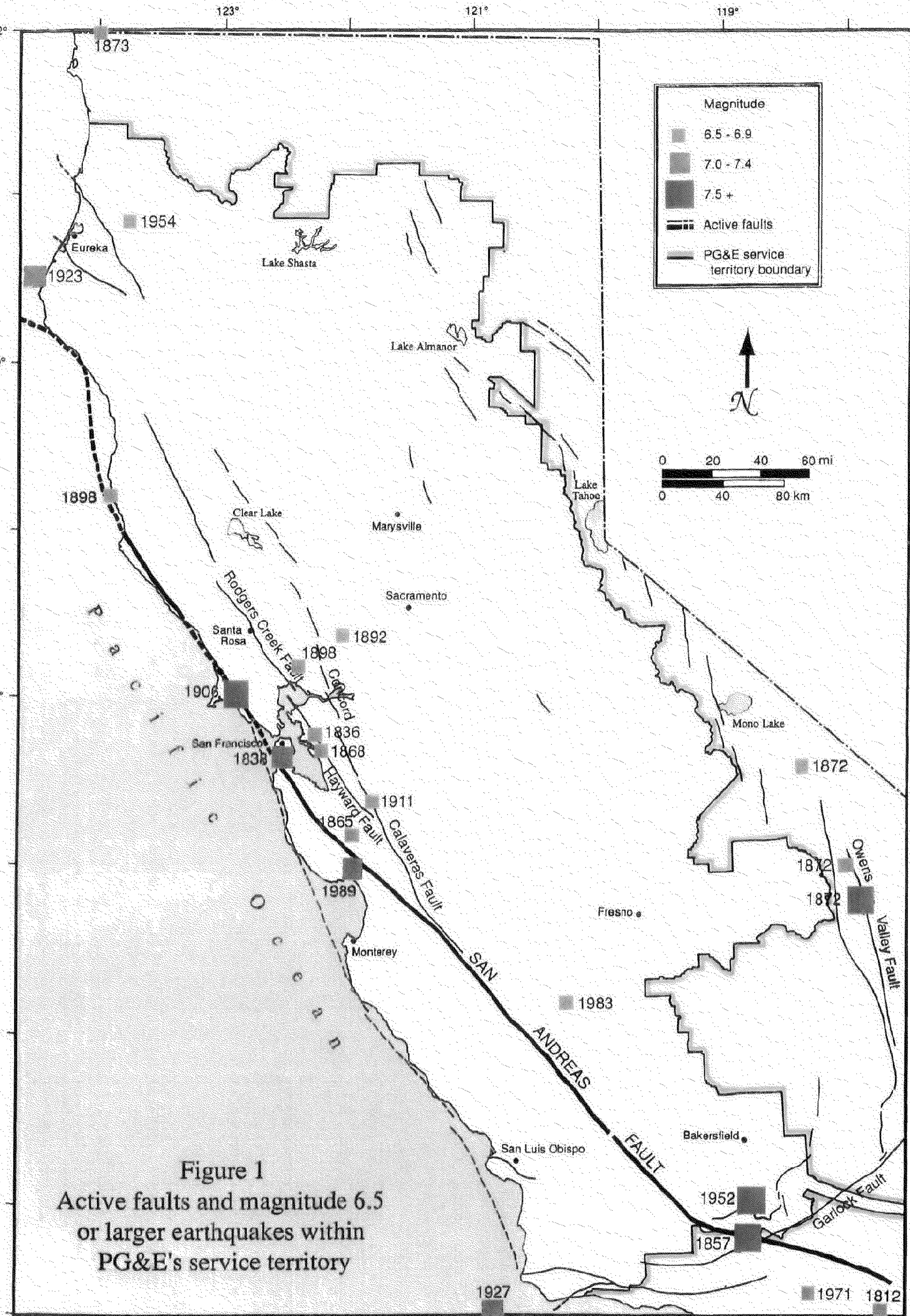

Figure 1
Active faults and magnitude 6.5 or larger earthquakes within PG&E's service territory

potential to impact PG&E's systems. Comparable earthquakes elsewhere in the service territory are not only lower in probability but also would have more localized and easily managed impacts.

Eight potential earthquakes (Table 1) meet the size and probability criteria described previously for selection as scenario earthquakes. Four of these earthquakes (the

Table 1

CHARACTERISTICS OF SCENARIO EARTHQUAKES

	Likelihood of Occurrence in Next 30 Years (percent)	Magnitude	Potential PG&E Customer Impact
Northern Segment of Hayward Fault	28	7	high
San Francisco Peninsula Segment of San Andreas Fault	23	7	high
Southern Segment of Hayward Fault	23	7	high
Rodgers Creek Fault	22	7	high
South-central San Andreas Fault	10 to 30	8	moderate
Northern Segment of Calaveras Fault	10	6.5	moderate
Central Segment of Calaveras Fault	10	6.5	moderate
Concord Fault	10	6.5	moderate

peninsular San Andreas event, the northern and southern Hayward fault events, and the event on the Rodgers Creek fault) would occur within the immediate San Francisco Bay Area and would directly impact the most densely urbanized portion of PG&E's service territory (Figure 2). Many transmission, distribution, and electric power generation facilities would be strongly affected by these scenario earthquakes. The south-central San Andreas event will be far from the majority of PG&E customers and facilities, but it may affect the 500-kilovolt intertie, which transmits power to or from PG&E and other electric utilities, and the southern gas transmission corridor. The occurrence of this event could also involve PG&E in assisting the Southern California utilities in their emergency response and recovery efforts. The northern and central Calaveras events and the Concord event are relatively less significant because they would be smaller in magnitude and would occur somewhat east of the urbanized core. Additional information about the scenario earthquakes is provided in the following paragraphs.

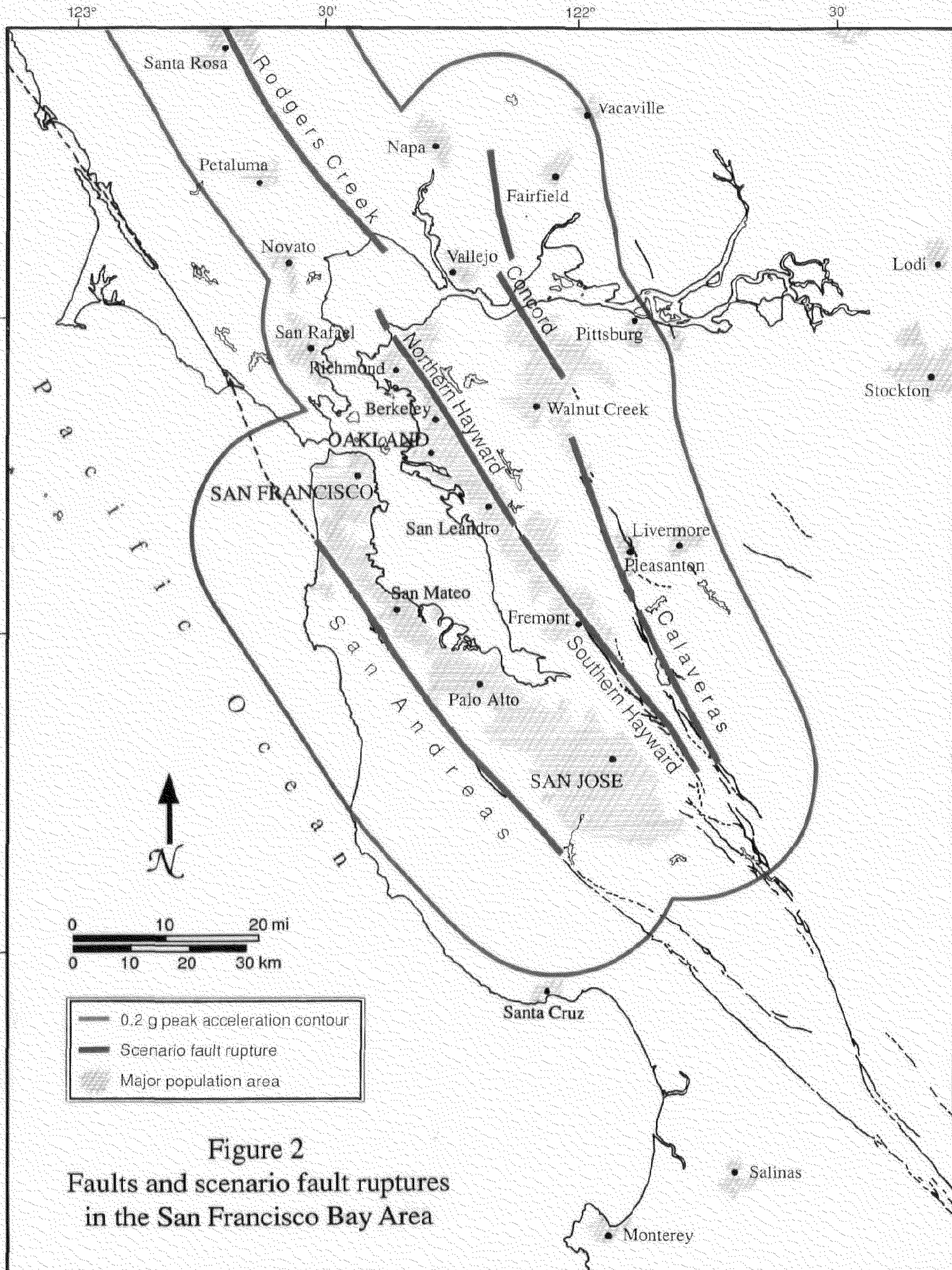

Figure 2
Faults and scenario fault ruptures
in the San Francisco Bay Area

Hayward Fault Segments and Rodgers Creek Fault. The Working Group (U. S. Geological Survey, 1990) identified two Hayward fault segments that ruptured in earthquakes having magnitudes near 7 in 1836 and 1868. They considered these events to be characteristic earthquakes for these segments, and calculated probabilities of 0.28 and 0.23 for the northern and southern segments, respectively, rupturing within the next 30 years. Magnitude 7 earthquakes on these segments are the maximum events expected on the Hayward fault. The California Division of Mines and Geology (Steinbrugge and others, 1987) considered an earthquake of magnitude 7.5 on the Hayward fault for their scenario, but the recent evaluation by the Working Group suggests that this magnitude value is too high. The Working Group also identified the Rodgers Creek segment of the Hayward fault as a potential source of a magnitude 7 earthquake, and calculated a probability of 0.22 for that event in the next 30 years.

San Francisco Peninsula Segment of the San Andreas Fault. The characterization of this segment is based primarily on evidence from large historical earthquakes, as discussed by the Working Group (U. S. Geological Survey, 1988, 1990). An earthquake of about magnitude 7 centered in the southern San Francisco Peninsula occurred in 1838, and is believed to have been associated with rupture of the peninsula segment. The San Francisco earthquake of 1906 also was caused by rupture on this segment, along with other segments for more than 350 kilometers to the north along the San Andreas fault. However, the amount of slip along the peninsula segment was relatively low compared with the total displacement observed along the fault from approximately Daly City northward. This observation suggests that the peninsula segment has a higher likelihood of rupturing in a magnitude 7 earthquake in the next few decades, whereas the recurrence of the 1906 earthquake of magnitude 8+ is not expected until after the middle of the next century. The Working Group (U. S. Geological Survey, 1990) concluded that the probability of a magnitude 7 earthquake on the San Francisco Peninsula segment of the San Andreas fault during the next 30 years is 0.23. Their study identified the San Francisco Peninsula segment as extending from mid-peninsula southeast to the northern end of the 1989 Loma Prieta earthquake rupture. In consideration of the uncertainties in accurately locating the endpoints of this segment, we have considered that the peninsula segment may extend as far north as Daly City, where the 1906 fault slip markedly increased to the north.

South-central San Andreas Fault. This portion of the San Andreas fault ruptured in a magnitude 8 earthquake in 1857; this is considered a maximum event for this part of the San Andreas fault. The rupture extended from about Cholame Valley south to Cajon Pass, just north of the city of San Bernardino, a distance of about 300 kilometers. The Working Group (U. S. Geological Survey, 1988) identified several segments along this zone that had ambiguous interpretations ranging from a probability of 0.1 to 0.3 of a magnitude 8 earthquake in the next 30 years. We have included this earthquake scenario in this study because the northern end of the associated fault rupture lies within the PG&E service territory.

Calaveras Fault Segments and Concord Fault. In the past decade, a series of earthquakes in the magnitude range from 5 to 6 1/4 has occurred along the southern Calaveras fault. This earthquake activity began in 1979 with the Coyote Lake earthquake (magnitude 5.9), continued with the Morgan Hill earthquake (magnitude 6.2) in 1984, and has most recently included several magnitude 5 earthquakes east of

San Jose near Alum Rock. The fault appears to be highly segmented and is probably not capable of earthquakes as large as magnitude 7. The Working Group (U. S. Geological Survey, 1988) concluded that there is little reason for assessing the probability of large earthquakes (magnitude 7 or greater), due to the occurrence of aseismic slip (fault creep) along the length of the fault, and the small size and infrequent occurrence of historical earthquakes. In consideration of the progressively northward seismic rupture of the Calaveras fault, we have included the central and northern segments of the fault as sources of high-likelihood earthquakes of magnitude 6.5 during the next 30 years. We have also included the northern extension of the Calaveras fault, called the Concord fault, as an equivalently likely source. Our scenario for the Concord fault includes rupture extending north across Suisun Bay and along the closely related Green Valley fault. The probability of occurrence of events along the Calaveras and Concord faults is considered to be less than that of the events on the San Andreas and Hayward faults; we have used a probability of 0.1 in 30 years.

Geologic and Ground-Shaking Effects of the Scenario Earthquakes

There are four basic hazards associated with the occurrence of a large earthquake such as the scenario earthquakes described above: 1) surface faulting, 2) strong ground motions, 3) ground failure, including liquefaction and slope failure, and 4) tsunami. These effects are discussed briefly below. We have prepared seismic hazard zonation maps that discriminate areas based on susceptibility to earthquake-induced liquefaction, slope failure, and, locally, tsunami for the entire PG&E service territory. Also included on these maps are the known traces of Quaternary faults and identified scenario-earthquake fault rupture segments. These maps have been compiled at a scale of 1:100,000 for the more urbanized part of the service territory, and 1:250,000 for the less densely developed areas.

Surface Fault Rupture. Surface fault rupture generally is expected to be associated with the scenario earthquakes listed in Table 1. The displacement of the ground surface is expected to be primarily horizontal shearing concentrated in a zone as wide as about 10 feet, with additional distributed displacement within about 500 feet of the primary surface fault trace. The amount and sense of fault displacement at the ground surface is strongly influenced by the local geologic conditions and by the depth of the earthquake. For example, the Loma Prieta earthquake was certainly large enough (magnitude 7.1) to be associated with surface faulting, but the location of the event along a relatively deep portion of the San Andreas fault did not permit the rupture plane to reach the ground surface. Based on statistics from numerous shallow crustal earthquakes worldwide compiled by Zhang and others (1989), we expect the following amounts of surface fault displacement to be associated with the scenario events:

Earthquake Magnitude	Average Amount of Surface Fault Displacement
6.5	1 to 2 feet
7	4 to 5 feet
8	15 to 20 feet

Ground Motions. For each scenario earthquake, we estimated the spatial distribution of expected ground motions. The peak ground acceleration was estimated using recently developed peak-acceleration attenuation relationships (PG&E, 1988) derived from statistical analyses of recordings of strong ground motions at rock sites for the magnitude range of 5.0 to 8.0. The strong-motion data base that was used is appropriate for strike-slip earthquake sources, the faulting mechanism of the San Andreas, Hayward, and Calaveras fault segments considered. The acceleration value was estimated as a function of the horizontal distance between the nearest point on the causative fault and the site, and as a function of earthquake magnitude. For each scenario, acceleration contours illustrate the area of 0.2 g or greater peak accelerations within the affected parts of the service territory (Figure 2). The acceleration values are medians of the distribution, and are treated as best estimates of peak ground accelerations expected to occur at rock sites during the scenario earthquakes.

Many of PG&E's facility sites within the greater Bay Area do not have rock or rock-like site conditions. Soft soil deposits and artificial fill are prevalent around the margin of San Francisco Bay and in river and creek drainages. These materials are known to modify site ground motions, causing motions different from those that would occur if the site consisted of exposed bedrock. Various soil site conditions change both the peak acceleration value and the frequency content of the ground motion, compared with those of a rock site. These changes can be significant in assessing the reaction of a given piece of equipment or a specific structure, each of which has its own frequency of greatest response, to the site-specific ground motion.

Liquefaction Potential. For water-saturated flat or shallow-slope conditions, some soils are subject to the phenomenon of liquefaction. If a sandy, water-saturated soil is shaken at a high enough acceleration level (generally about 0.20 g or greater) for multiple cycles of motion, the sand can densify enough to cause an increase in pore-water pressure adequate to cause the soil/water mixture to lose shear strength and temporarily behave as a liquid. Depending on the location and depth of the soil deposit, the liquefied material can erupt to the ground surface, producing local settlement. Objects on or within the liquefied material can tilt and sink; or, if there is a slope adjacent to the liquefied material, the upper soil layers can spread or slide laterally as much as tens or hundreds of feet. In the greater San Francisco Bay Area, there are numerous localities of historical liquefaction where significant damage to engineered structures has occurred. Geotechnical research has been conducted at such sites, both locally and internationally. As a result, the phenomenon of liquefaction is reasonably well understood, and accepted empirical methods of analysis have been developed to assess liquefaction potential at specific sites. We have applied this experience to assist us in assessing the vulnerability of our facilities and systems to liquefaction.

Slope-Failure Potential. Slope failures are masses of rock and soil that gravitationally move downslope. In this assessment, we considered the susceptibility to slope failure via deep-seated landslides such as rotational slumps, block slides, and earth flows. Susceptibility of hillslopes to fail is generally a function of rock type (lithology), slope, and moisture content. Because moisture content varies seasonally and is difficult to assess without detailed site investigation, our assessment of slope-failure potential was based chiefly on lithology and slope. Bedrock lithologies most likely to host slope failure are uncemented, clay-rich sedimentary rocks. In addition, oversteepened slopes along river canyons and in mountainous areas also are susceptible to slope failure, regardless of the underlying lithology. The geologic hazard associated with slope failure was classified on the basis of the degree to which an area possesses these characteristics, as well as documented cases of geologic and historical slope failure.

Tsunami. Tsunami, or seismically induced sea waves, are generally of concern only to coastal facilities adjacent to the open ocean. They are not a significant hazard from the scenario earthquakes we have considered. Tsunami caused by distant earthquakes in Alaska, Japan, and South American have ample warning times in which to prepare for and mitigate the effects.

PERFORMANCE OF THE GAS SYSTEM

A typical gas utility system has three major elements: a transmission system, storage facilities, and a distribution system. The transmission system consists of high-pressure gas lines that transport gas from gas production or storage fields. A transmission system may include compressor stations, terminals, and pressure-limiting stations. Storage facilities may include underground natural rock formations used for storage of gas, and above-ground equipment, including gas processing facilities and compressors. The distribution system consists of a network of pipelines and control facilities that distributes gas from transmission pipelines to individual customer services.

Gas transmission, storage, and distribution systems have performed well in past earthquakes in the United States and abroad. The inherent ruggedness provided by the design criteria for high-pressure pipelines and the related gas-handling equipment provides substantial strength and ductility reserves to resist earthquake forces and displacements. Low-pressure distribution systems are somewhat more vulnerable, because they may contain older steel pipe or cast-iron pipe that can leak when joints or corroded pipe sections are subjected to deformation due to strong seismic shaking, or to earth movements triggered by shaking or surface faulting. Above-ground portions of a gas system may be more susceptible to earthquake damage than the underground portions, because they lack the inherent bracing and motion-damping provided by burial. Above-ground components also may be damaged due to earthquake damage to the structures to which the components may be attached, such as meters attached to buildings or pipelines attached to bridges.

PG&E's gas system (Figure 3), like many others, has considerable seismic resistance. Historically, PG&E's gas facilities have performed well during past earthquakes, including the magnitude 6.7, 1983 Coalinga earthquake and the magnitude 7.1, 1989

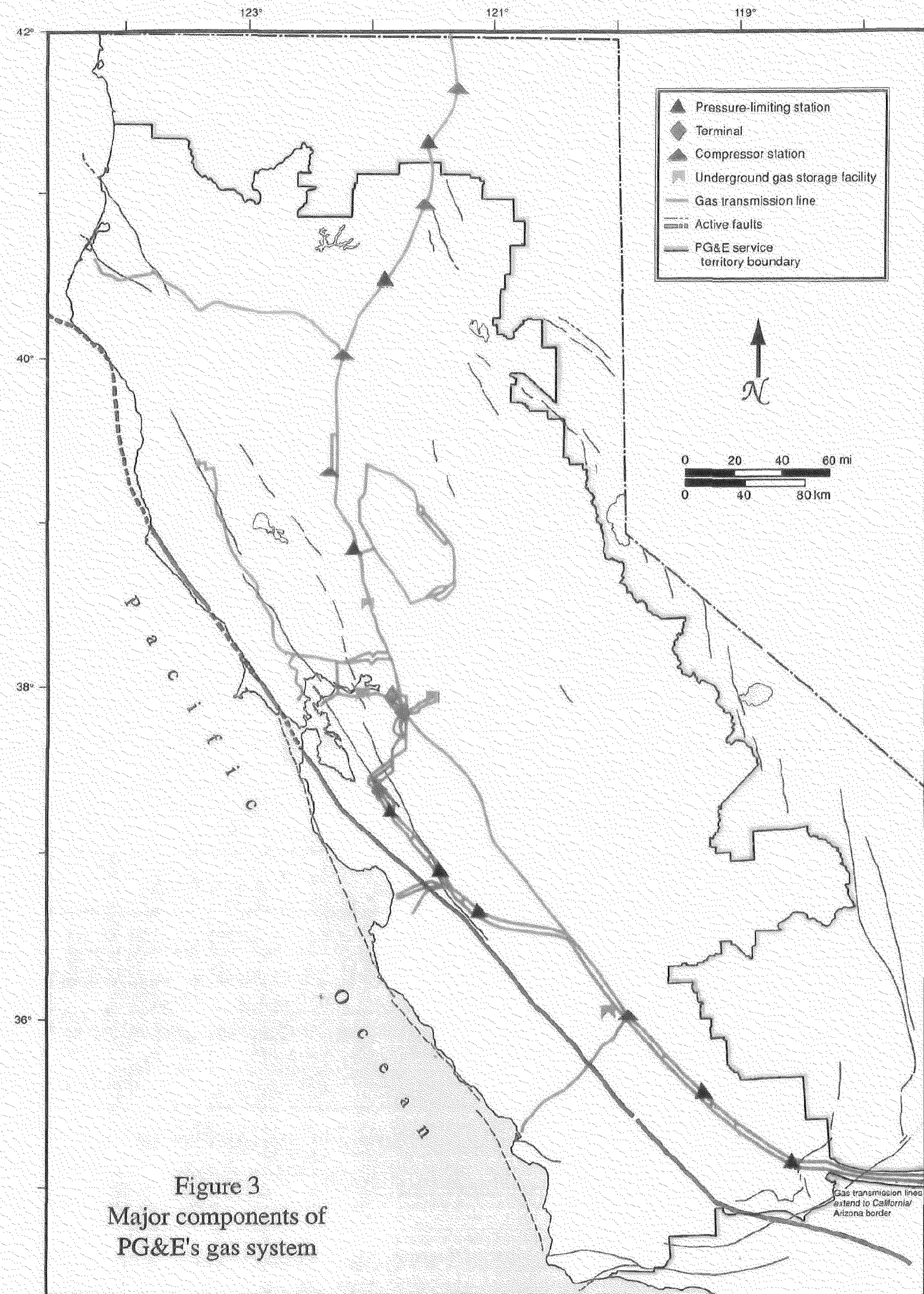

Figure 3
Major components of PG&E's gas system

Loma Prieta earthquake. The peak ground acceleration during the Coalinga earthquake is estimated to have been 0.25 g to 0.3 g at the nearby Kettleman compressor station, one of PG&E's largest. The Kettleman station did not experience any structural damage, and service was unaffected.

Our gas transmission and distribution components have considerable redundancy, which substantially reduces vulnerability to disruption. In addition, gas storage capacity within the system provides a supply, so customer service need not be interrupted even when transmission lines carrying imported gas are temporarily unavailable due to routine maintenance or earthquake damage. All operating systems are controlled by ten decentralized terminal/load centers, and coordinated centrally in San Francisco. Communication systems for the San Francisco Gas Control Center are being evaluated in detail as part of a seismic study to evaluate post-earthquake functionality of the Gas Control Center, which will be completed in 1991.

The evaluation of our system when subjected to the scenario earthquakes emphasized the identification of the least-resistant links in the gas system that have high importance due to lack of redundancy. In the following, we first describe the main functional elements of the system. We then assess likely impacts of the scenario earthquakes and identify efforts to mitigate expected damage or disruption.

Gas System Components

Gas Transmission System. PG&E's gas transmission system is a modern, sophisticated network of large-diameter pipelines providing gas to our distribution networks from out-of-state sources, as well as from gas production and storage fields within our service territory. This system consists of high-pressure pipelines, compressor stations, terminals, and pressure-limiting stations. These are fully "engineered" facilities, built to engineering and construction standards applicable at the time of construction. Most of these facilities have also had recent upgrades to include state-of-the-art, computer-assisted controls and telecommunications systems.

Gas is imported to our service territory in three main pipelines, which are routed almost entirely underground. One carries Canadian gas from the Oregon border, the other two carry Texas gas from the Arizona border. Other transmission lines tap into these main pipelines to provide service to large local customers, and to distribution systems. Most of the transmission lines fed by these three main pipelines are in the San Francisco Bay Area, where our largest residential and industrial gas demand exists. The two transmission lines carrying imported gas from Texas have an integral rupture-control system.

PG&E's transmission system also includes a gas gathering system. The gas gathering system is a network of small- and medium-diameter welded steel pipe, and associated compressors and gas treatment equipment. These pipes connect individual California producing wells and, after aggregation and processing, deliver the gas into the transmission system.

Compressor stations typically contain massive equipment such as compressors and generators, cooling towers, water tanks and other types of vessels for storage of liquids and compressed air, and large, open, steel-frame, one-story buildings. The compressor stations also contain extensive gas piping components. The stations have a computer-assisted Supervisory Control And Data Acquisition (SCADA) system, which assists in the control of the system during both normal and emergency operations. Backup electrical power is always provided at these stations to run the computer and telecommunications systems. Stations have additional backup power to operate the entire station, or are powered by multiple natural-gas-fueled generators that have redundant capacity to provide full-station power even if one of the generators is off-line.

Transmission system terminals control and meter gas flow at junctions of major transmission pipelines. Terminals have large-diameter piping underground and typically have a one-story control building. The control system provides for continuous 24-hour monitoring. Modern telecommunications systems link the terminals via the system-wide SCADA system. Unstaffed terminals can be operated remotely by staffed terminals. Battery and generator backup power systems provide redundant electrical power supply for each of these terminals.

Pressure-limiting stations are located at regular intervals on our transmission lines, and control safe line pressure. These stations generally have small yards, and one or more small buildings that house gas instrumentation equipment and, in some cases, SCADA and telecommunications equipment for remote monitoring and control. Stations having SCADA and telecommunications equipment have battery backup power. Piping normally is routed underground; valve operators are above-ground and sometimes in underground, concrete, valve vaults. Pressure control is assured in the event of an electrical power loss.

Gas Storage Facilities. PG&E's underground gas storage facilities supplement the system's imported gas at times when our customers' gas demands exceed supplies. This storage system also can provide redundancy in the event of service disruption in one or more of the transmission lines. The storage facilities vary in size, the largest of which, McDonald Island, has several elevated platforms for large equipment and vessels such as compressors and dehydrator towers, and computer-assisted control rooms that provide continuous monitoring and control of the station. Individual well pads are usually placed away from the central station, and generally consist of above-ground sections of pipe and valves, some above-ground vessels, and a control shed.

Gas Distribution System. PG&E's gas distribution system is a comprehensive network of high- and low-pressure piping, automatic and manual valves, regulators, controls, and meters. The system is characterized by predominately underground pipelines that reduce in size and pressure as they deliver gas to individual residential and commercial customers. These distribution pipelines are constructed of plastic, arc-welded steel, some older gas-welded steel, and a comparatively small amount of cast iron in our older, low-pressure systems. The gas distribution system is generally highly redundant, allowing a variety of choices to route gas to most customers affected by loss of service in a single pipeline.

Each of PG&E's six regions has one or more gas load centers. These are modern facilities having computer-assisted monitor and control systems, much like those at our transmission system terminals, that provide around-the-clock monitoring of the local gas distribution system. Many key remote facilities are controlled directly from the load centers. As with the transmission system terminals, the load centers are also tied into the SCADA system, allowing operators to monitor their individual system and the overall system status. In the event of a loss of telecommunication links with SCADA or with individual remote sites, the system can be operated manually. Pressure control systems will function automatically using on-site control systems.

Within the distribution system, regulator and metering stations are provided to distribute, control pressure, and measure the flow of gas. Although some are located below grade in street vaults, most of these stations have generally small yards with one or more small buildings or sheds. They may have above-ground sections of pipe and valves, or all underground piping with above-ground valve operators and some underground, concrete, valve vaults. Meters are provided at individual customer locations. SCADA and the telecommunications systems provide data exchange between some locations within the distribution system and the regional load center.

Assessment of Impacts of Scenario Earthquakes

We have focussed our gas system performance assessments on the scenario earthquakes listed in Table 1, seven of which are in the heart of PG&E's most concentrated gas distribution system, and near the delivery points of the gas transmission system (Figure 3). These scenario earthquakes are shown in Figure 4 in terms of the anticipated length of fault rupture for each event. The expected area of strong ground shaking has been estimated for each event, and is shown on Figure 4 by the zone within which ground accelerations are expected to be 0.2 g or greater. Outside this 0.2 g contour for each event, the acceleration level may exceed 0.2 g at soft- or deep-soil sites. As may be seen from Figure 4, any one of these events strongly affects only a portion of the gas system.

For each scenario, we have initiated three earthquake impact evaluations: field reviews of above-ground facilities subject to strong shaking and associated soil or slope failures; assessments of high-pressure transmission pipeline crossings of surface fault ruptures; and mapping of areas within which gas distribution piping (cast iron or older gas-welded steel) may be subjected to liquefaction or shaking-related soft-soil deformation. These evaluations are discussed below.

Above-ground Facilities. The on-site engineering review of above-ground facilities and pipelines will be completed in 1991. More than 100 facilities have been reviewed so far. At each facility, an engineering team inspects the facility to identify those components critical to the facility's post-earthquake operation. Each of these components, including lateral support systems and anchorages, is then individually inspected to assess vulnerabilities. Where vulnerabilities are readily identified, such as the need for increased bracing or anchorage, those modifications are given immediate attention. Potential hazards to the telecommunications system, such as anchorage

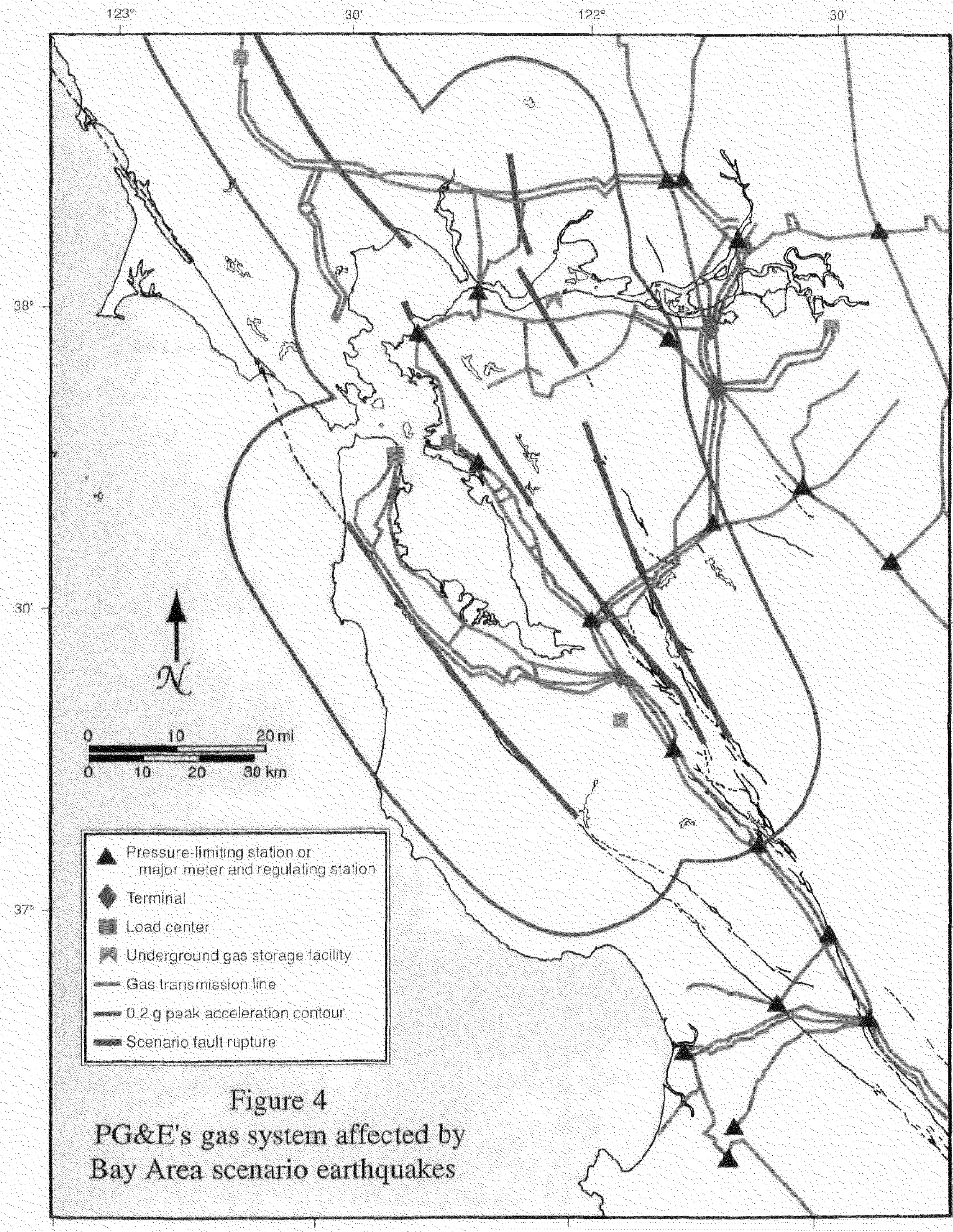

Figure 4
PG&E's gas system affected by Bay Area scenario earthquakes

failures or falling adjacent equipment, also are addressed. Components whose vulnerability requires further investigation or analysis are noted and addressed subsequently. Geotechnical reviews are performed at each facility site to compile information about its geologic and foundation conditions and their potential contribution to earthquake damage. Above-ground pipelines are similarly inspected, with special attention given to the method of pipeline support, possible interaction between a supporting bridge structure and our pipeline, the potential for embankment failure, and the potential for amplification of ground motions due to site geologic conditions.

Pipeline Fault Crossings. Field reviews are being conducted for transmission pipeline crossings of scenario earthquake fault ruptures to assess the potential for damage due to surface fault displacement. For each locality, the available detailed geologic mapping of the fault trace is reviewed and the location of the pipeline corridor with respect to the fault is verified on site. For the expected amounts of fault displacement and the geologic and geotechnical conditions at the pipeline fault crossing, the potential for pipeline deformation is estimated.

Liquefaction and Other Soil Effects. For each of the scenario-earthquake areas, we are compiling maps of the primary high-pressure pipelines and of the areas of the cast-iron and other pipe types. We then superpose these gas system data on the maps of areas having the potential for soil liquefaction and areas susceptible to slope instability. This process identifies transmission pipelines that may be stressed or damaged by soil movement, and the areas of distribution piping that may be particularly vulnerable to post-earthquake leaks.

Results of Vulnerability Assessment

The scenario-based assessment of the gas transmission, storage, and distribution systems is in progress. The results of the field reviews, fault-crossing assessments, and assessments of where the weak piping material can cause leaks will be used to estimate the physical damage to the gas system following each of the scenario earthquakes. From estimated damage to the gas system, we will estimate the effects on operations, and mitigation steps will be determined and prioritized. However, the work already completed has focused attention on several vulnerabilities, and we have initiated some mitigation programs.

The gas system's greatest earthquake vulnerability is the potential for extensive leakage in portions of the distribution system that are relatively weak because of brittle pipe, weak pipe joints or welds, or corroded pipe. Seismic effects are expected to be particularly damaging to these leak-prone pipes in areas of poor soil where *in situ* pipe deformations may be large due to liquefaction or amplification of ground-motion. The least-resistant elements of the gas system have been the focus of the CPUC-approved Gas Pipeline Replacement Program, which was implemented in 1985 to replace aging gas pipe throughout the PG&E system. The pipelines in the replacement program range in age from 43 to more than 100 years. Although they met the construction standards at the time of installation, they do not meet present-day standards. The review of our gas system completed in 1984 identified 800 miles of remaining cast-iron pipe, 1100 miles of pre-1931 gas-welded steel pipe, and 460 miles of transmission pipeline to be included in the program. Table 2 summarizes the locations and amounts of pipe in the replacement program, and the status of replacement at the start of 1990. The pipelines selected for the program vary in condition as they approach the upper range of their service lives, and replacement was evaluated based on age, pipe type, corrosion and pressure factors, weld and joint type, leak history, and location. The remaining 30,000 miles of pipe in the PG&E system are one-third ductile plastic pipe and two-thirds modern steel pipe, both of which perform well in earthquakes.

The Gas Pipeline Replacement Program is a 25-year program having a total cost of more than $2 billion. Through 1990, we have replaced approximately 550 miles of pipe at a cost of approximately $440 million. By incrementally replacing the aging pipe, including all of the cast-iron pipe in the system, the earthquake resistance of the system will be substantially increased. Pipeline replacement priorities have been based largely on evaluations of the condition of pipelines, which implicitly resulted in high priorities for pipelines vulnerable to damage in earthquakes. We are augmenting the seismic component of the prioritization process by emphasizing replacement of pipe in service areas subject to soft-soil effects within the impact areas of the scenario earthquakes, thus accelerating the upgrade in safety and reliability in those areas most likely to be affected by large earthquakes in the future.

Approximately 360 miles of the gas transmission system pipeline are included in the Gas Pipeline Replacement Program. The rest of the transmission system is well-constructed of modern, arc-welded steel pipe that is expected to withstand the effects of seismic shaking. Very few sections of these pipeline corridors exist in soils vulnerable to failure, but even under soil-failure conditions, these large-diameter pipelines are expected to withstand these effects without significant damage.

Pipeline fault-crossings are vulnerable to large, highly localized pipeline displacements that can damage or rupture the affected pipeline. Pipeline fault-crossing analyses have been completed for the two transmission pipelines (109 and 132) that cross the San Andreas fault between the Milpitas terminal and the Potrero load center in San Francisco, in preparation for mitigation of these crossing hazards during replacement of these pipelines. Evaluations are being made of the pipeline crossings of the Hayward and Calaveras fault zones (Figure 4). Because in general it is not possible to avoid a fault crossing, mitigation measures considered include both pipeline design to accommodate the expected displacement, and rapid isolation and repair in the event that damage does occur.

The transmission system's large compressor stations are in areas not highly affected by the scenario events. Some minor damage could occur and have a possible short-duration impact on individual station operations, but significant system damage or curtailment of our gas service is not expected.

Our transmission system terminals are generally rugged. Field engineering reviews have identified some minor modifications, such as increased anchorage or support

Table 2

STATUS OF GAS PIPELINE REPLACEMENT PROGRAM
January 1990

Geographic Area	Subprogram	Total Miles	Miles Replaced (1985-1989)	Miles Remaining*
San Francisco	Cast Iron	484	62	422
	Steel	113	12	101
	Transmission	8	6	1
	Total	605	80	524
San Jose	Cast Iron	59	16	43
	Steel	82	9	73
	Transmission	14	4	10
	Total	155	29	126
Oakland/ Berkeley/ Alameda/ Richmond	Cast Iron	74	26	48
	Steel	245	73	172
	Transmission	18	11	7
	Total	337	110	227
Rest of System	Cast Iron	203	51	152
	Steel	661	90	571
	Transmission	423	83	340
	Total	1,287	224	1,063
Whole System Totals	Cast Iron	819	155	664
	Steel	1,102	184	917
	Transmission	463	104	359
	Total	2,384	443	1,940

* Totals may be off 1 due to rounding.

bracing, that will reduce the likelihood of damage. The Milpitas terminal is located on soil that may be vulnerable to liquefaction. This condition is being studied to evaluate whether mitigation steps are appropriate.

Our transmission system pressure-limiting stations have no structures that are particularly vulnerable to earthquake damage, and should perform well in our scenario events. Some equipment anchorage enhancements have been identified in our field engineering reviews and will be implemented.

The largest of our underground storage facilities, McDonald Island, in the Sacramento Delta, is a modern, well-constructed facility. It is geographically located such that rock-site peak ground accelerations are expected to be low. Soft-soil conditions at the site, however, may amplify ground motions, and this facility is being reviewed to assess whether this amplification is likely to have significant effects. The Los Medanos facility, located near the Calaveras fault, is expected to be subjected to strong seismic shaking. It, too, is a modern, well-constructed facility, and is not expected to be subjected to soil-failure conditions. This facility is currently under engineering review in our study program. The other two of our four underground storage facilities are located far enough away from our scenario events so as not to be significantly impacted.

PERFORMANCE OF THE ELECTRIC SYSTEM

A typical electric utility system has three major elements: power generation facilities, a power transmission system, and a distribution system. Power generation facilities are the primary sources of electricity. They rely on a variety of power plant resources, such as fossil fuels, nuclear, hydro, geothermal, and other sources. The power transmission system consists of high-voltage transmission lines, along with substations that transport and distribute the energy. The distribution system consists of a network of lower-voltage lines and control facilities, which distribute power from substations to individual customer services. Most components of PG&E's electric system (Figure 5) have considerable inherent seismic resistance and redundancy, which substantially reduce their vulnerability to disruptions.

The electric system is regulated from the Energy Control Center in San Francisco. The center meets load demand with the least expensive energy available while maintaining the integrity of the electric system. We have a back-up Energy Control Center in Fresno. Both facilities are staffed 24 hours a day.

PG&E uses the company's highly redundant microwave communications network to gather electric system data, and to control generation and power transfers to match supply to demand. Communication through the microwave system is not expected to be impacted significantly during earthquakes, based on the good performance of microwave systems during past earthquakes, and because of the redundancy in the network. Communication systems for the San Francisco Energy Control Center are being evaluated in detail as part of a seismic study to evaluate post-earthquake functionality of the Energy Control Center, which will be completed in 1991. Besides

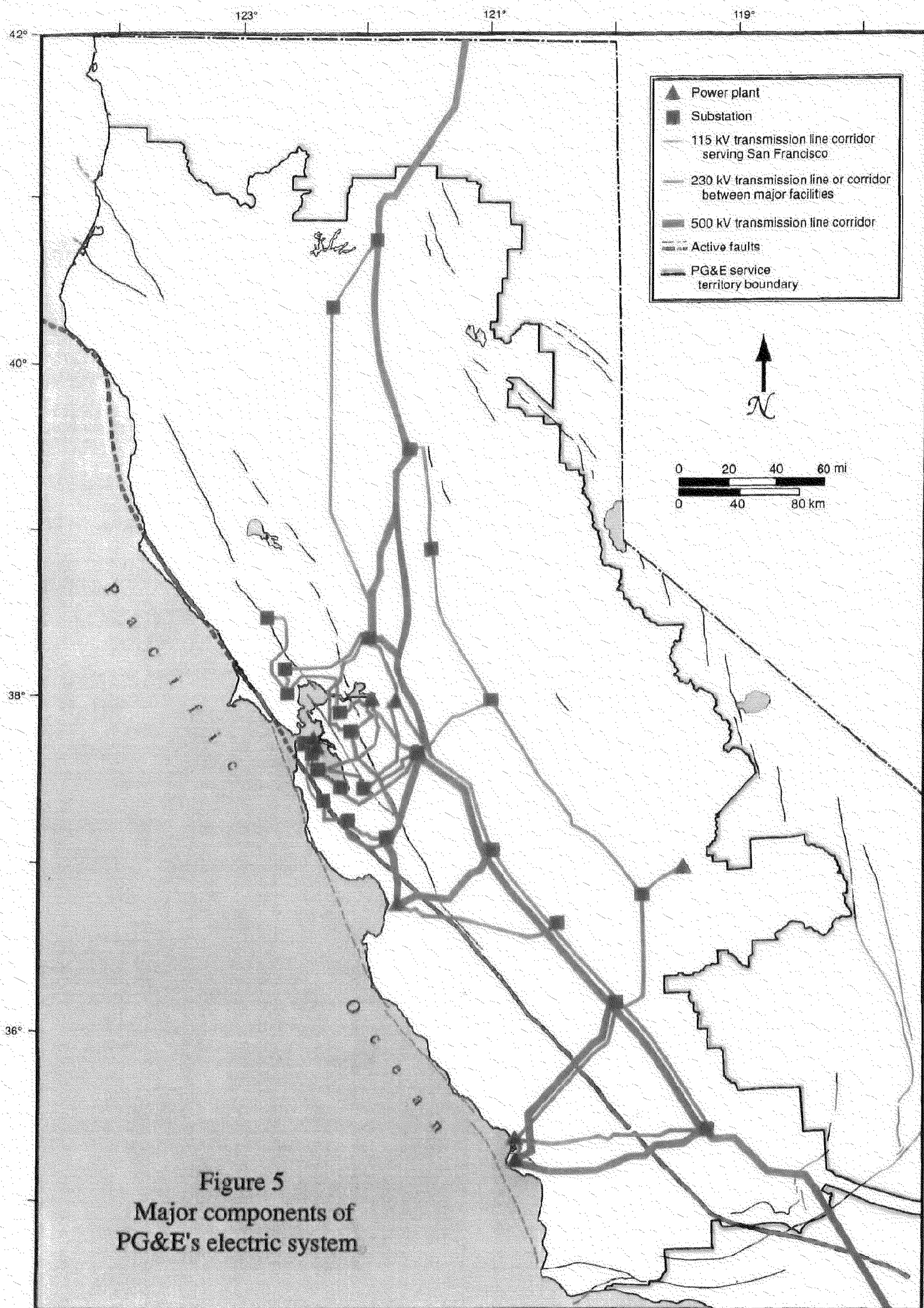

Figure 5
Major components of
PG&E's electric system

the microwave system, other means of communication are available, such as dedicated Pacific Bell lines, mobile radios, and cellular telephones. Some substations and power plants can also communicate through an electronic coupling system using power transmission lines.

Our evaluation of the performance of the electric system during the scenario earthquakes emphasized the identification of the least-resistant links that have high importance. In the following, we first describe the main functional elements of the electric system. We then assess likely impacts of the scenario earthquakes and identify efforts to mitigate expected damage or disruption.

Electric System Components

Power Generation Facilities. PG&E's power generation facilities are diverse, geographically dispersed, and use several different power generation technologies. The locations of major power generation facilities are shown in Figure 5. Hydroelectric dams and nuclear plants are built to appropriately high standards; these components have been extensively reviewed by the California Division of Safety of Dams, the Federal Energy Regulatory Commission, and the U. S. Nuclear Regulatory Commission, and therefore are not considered in this report. PG&E's electric system has major fossil fuel (oil and natural gas) and geothermal power plants that contribute more than 50 percent of PG&E's total generating capacity.

PG&E has designed its power plants to requirements that met or exceeded the building code levels. Experience from numerous earthquakes in California and worldwide indicates that power plants designed to building code levels are seismically rugged and suffer little damage during earthquakes. In most cases, power plants have operated through the earthquake or have been restored to operation within a day or so. We also recognize the importance of adequate anchorage for equipment in power plants and have conducted inspections and modification programs to ensure proper anchorage. PG&E expects its power plants to suffer relatively minor damage in future earthquakes, and service to be restored within hours to days.

No single power plant of PG&E's system contributes more than 10 percent of our total generating capacity, and none of the individual generating units contributes more than 5 percent of total capacity. This multiplicity of power sources, the wide geographic distribution of power sources, the seismic resiliency of individual power units, the availability of additional power through interties with other utilities, and lower customer demands anticipated during the post-earthquake period combine to indicate there will be an adequate supply of power to meet post-earthquake demands.

Power Transmission System. The power transmission system consists of high-voltage transmission lines, along with substations that switch, regulate, and control power. PG&E's major transmission lines and important substations are shown in Figure 5. Historical performance during earthquakes indicates that transmission towers and lines are resistant to damage from ground motions. Moreover, PG&E's transmission-tower design loads for wind, in combination with broken-wire loading, are more stringent than earthquake design loads. Although transmission towers and lines are unlikely to be damaged by ground motions, they can be locally vulnerable to damage from slope failures; however, slack in the wires allows significant lateral movement or settlement of the towers without disruption of service, and this type of damage will be highly localized and readily repairable.

As is the case with the gas system, PG&E has installed a Supervisory Control and Data Acquisition (SCADA) system to provide remote status interrogation of many substations in the electric system, and we are reviewing the need to expand SCADA to others. Each substation has batteries as a back-up source of power for the SCADA system and telecommunications equipment. Major substations also have emergency generators.

High-voltage substations in the transmission system contain a host of electrical equipment, including circuit breakers, various transformers, switches, and other equipment. Experience in previous earthquakes indicates that some of this equipment, particularly high-voltage circuit breakers, is vulnerable to seismic shaking. In general, high-voltage substations are widely recognized as the least seismically resistant element in electric utility systems.

Electric Power Distribution System. The electric power distribution system is a comprehensive network of distribution lines of various voltages lower than the high-voltage transmission lines, along with substations to control the distribution of electric power. The distribution system is generally highly redundant, allowing a variety of choices to route power to most customers affected by damage in a single distribution line.

The 1952 Kern County earthquake inflicted considerable damage to PG&E's distribution system by destroying thousands of pole-mounted transformers. Since then, all of our new pole-mounted transformers have been secured rigidly, using bolted connections to support-brackets and to the poles themselves. After the 1989 Loma Prieta earthquake, 225 pole-mounted transformers were replaced, primarily in the Santa Cruz area. Most of these repairs were associated with transformer damage due to conductors hitting transformer casings, line surges, and pole foundation failures; no transformer fell off its pole.

Although there may be damage to electric power distribution lines due to ground motions, slope failures, or failures of buildings and other structures adjacent to the distribution lines, such damage will be localized and generally readily repairable. PG&E's operating divisions have considerable inventories of spare parts; the necessary components are standard off-the-shelf items. Additionally, repair crews are well-experienced in repairing distribution system damage due to winter storms and other causes.

Distribution system substations operate at much lower voltages than transmission system substations, and have higher levels of redundancy. Furthermore, the electrical components of distribution system substations are much more seismically resistant than are analogous components for high-voltage transmission system substations. The performance of low-voltage substations in previous earthquakes has been very good;

therefore, major earthquake damage to distribution system substation equipment is not expected. Damage that may occur is likely to be relatively local and to be readily repairable. Each substation has batteries as a back-up source of power for the SCADA system and telecommunications equipment. Major substations also have emergency generators.

Assessment of Impacts of Scenario Earthquakes

In 1986, PG&E initiated a major study of the seismic vulnerability of substations, using the scenario-earthquake approach. Seven of the eight scenario earthquakes used for our current evaluations (excluding only the Rodgers Creek fault) were used in the 1986-90 study. A multiple-discipline study team, consisting of civil engineers, electrical engineers, geoscientists, and electrical operations experts, considered the effects of the earthquakes on high-voltage equipment and facilities. PG&E's electric system contains approximately 1000 substations, and there are a great number and variety of equipment and structures within these substations. The vulnerability and importance of the substations vary greatly, depending on their location and role in the electric power system. A preliminary screening of substations, which included all 500-kilovolt substations and other substations within the 0.2 g acceleration ground-motion contours for the scenario earthquakes (Figure 6), resulted in selection of 206 substations for further study. Using historical seismic performance of equipment of different types and voltages, the customer-service function of the substation in the system, and its seismic exposure, 22 of the most important, most vulnerable substations were chosen for detailed study.

The impacts of the scenario earthquakes on PG&E substations were evaluated by (1) identifying the principal components in substations and switchyards, including all components required for emergency operation, (2) estimating the seismic level that will damage these components, (3) estimating the seismic hazard and level of damage at each facility, and (4) estimating the condition of the electric system following the scenario earthquake. The components considered are summarized in Table 3.

The estimated seismic damage levels for yard equipment were based primarily on performance records from past earthquakes. Among different models of equipment of the same type and voltage, the damage level can vary greatly. For example, the various 230- and 500-kilovolt circuit breakers in PG&E's system have damage threshold levels that vary from 0.05 g to much higher than 0.5 g. For equipment that has not been subjected to past earthquakes, damage threshold levels were based on original design criteria, seismic tests, dynamic calculations, discussions with other utilities, and engineering judgment. The reasonableness of damage threshold levels was confirmed through discussions with other electric utilities.

Control and protection equipment has performed well in earthquakes when anchored and braced to Uniform Building Code load levels. Newer equipment is anchored and braced to withstand loads generally higher than required by the Uniform Building Code. Older equipment has been inspected during site reviews, and anchorage and bracing added or modified where found to be inadequate.

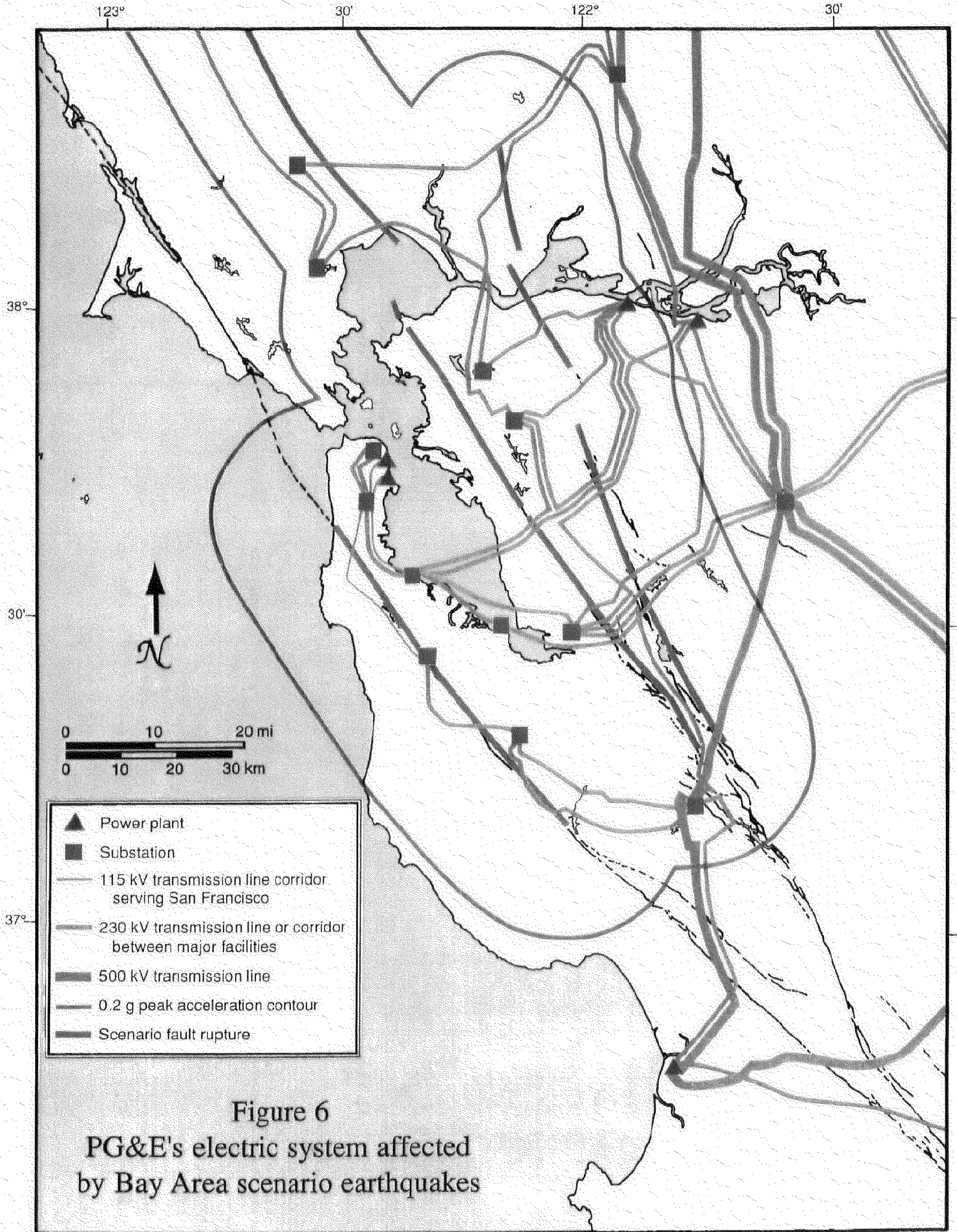

Figure 6
PG&E's electric system affected by Bay Area scenario earthquakes

Table 3

HIGH-VOLTAGE SUBSTATION AND SWITCHYARD COMPONENTS EVALUATED IN SCENARIO EARTHQUAKES

YARD EQUIPMENT

- High Voltage Circuit Breakers
- Transformers
- Current Transformers
- Air Switches
- Circuit Switchers
- Surge Arresters
- Wave Traps
- Coupling Capacitor Voltage Transformers (CCVT)
- Rigid Busses

CONTROL AND PROTECTION EQUIPMENT

- Switchboards
- Station Batteries
- Emergency Generators

BUILDINGS

- Main Control Buildings
- Spare Parts Storage Buildings
- Other Buildings Adjacent to Yard Equipment

Each substation building was individually evaluated because of the wide variation in structural systems, the type of materials used in construction, the age, and the condition of the buildings. Existing drawings and calculations were used for evaluations when available; otherwise, field reviews and calculations were made.

Damage to the substations affected by a given scenario was evaluated using the predicted site-specific ground motions and geotechnical factors. Geotechnical factors considered include differential foundation settlement due to liquefaction or poor soil conditions, differential movement of equipment foundations due to lateral spreading, the influence of landslides, possible changes in the frequency content and amplitude of the ground acceleration due to soft soils.

The damage to each type of evaluated equipment at each substation was estimated. As circuit breakers have significantly different fragility values depending on model and manufacturer, the model and manufacturer for each breaker were listed for each substation, and the position of each breaker was shown on a single-line diagram. The amount and type of damage was estimated for each model and type of breaker, as well as for other types of equipment. The type of damage will have a significant effect on restoration time and on system operation. For example, one style of 230-kilovolt circuit breaker is likely to have gasket leaks at 0.15 g and broken porcelain bushings at 0.25 g. Leaking gaskets can probably be repaired within days, whereas it may take weeks to repair or replace a breaker that has broken bushings. In cases where it was judged that not all the equipment of a certain type would be damaged, damaged equipment was generally assumed at locations within the facility that would most severely impact the facility's operability.

For each building reviewed, the level and type of damage and the effect on occupancy were estimated for each scenario. Using these descriptions of the estimated damage at each substation for a given scenario, we estimated the effects of the earthquake on the operation of the individual facilities. This information was assembled on a single-line diagram of the electrical system, and enabled us to estimate the post-earthquake condition of the system.

Results of Vulnerability Assessment

The system elements most critical to the transmission of power through a substation are circuit breakers and transformers. Among the circuit breakers and transformers in the substation system, we identified live-tank circuit breakers and transformer radiator systems as particularly vulnerable to seismic damage. Several new programs at PG&E are directed toward mitigating these hazards. They include programs to replace selected 500-kilovolt circuit breakers, and to brace radiators on critical transformer banks. In addition, geotechnical and equipment fragility information compiled in the substation seismic study will be incorporated in long-term plans to define seismic evaluation criteria for specific equipment currently in the high-voltage system. Coupled with PG&E's commitment to perform dynamic tests on important new high-voltage equipment, such as circuit breakers, and with efforts to improve the seismic resistance of electric transmission equipment, these programs will significantly enhance the structural strength of PG&E's electric system.

In addition to identifying substation components that are vulnerable to seismic damage, the study team noted that in an emergency, many damaged facilities can be returned to service within a short period by bypassing many of these components. Several important elements of a substation, such as air switches, switch and bus equipment, surge arresters, and wave traps, can be circumvented temporarily to restore emergency power. In these cases, it is the type of substation damage, rather than the amount of damage, that will dictate the pace of service restoration and the effective impact of an earthquake.

Geotechnical aspects play an important role in determining the extent of seismic damage at particular sites. Some of PG&E's substations are on sites that are particularly sensitive to ground motions. In some cases, these sites may amplify ground motions. At others, ground failures, due to liquefaction, lateral spreading, or landslides, may be hazards in specific areas of a substation yard. In all of these cases, we are compiling accurate, current geotechnical information to assess the seismic hazard at the specific site. In addition, we are installing strong-motion instruments to expand our knowledge of the geotechnical and ground response characteristics at five key substation sites.

The substation study was nearly complete when the October 17, 1989, Loma Prieta earthquake occurred. Notably, the earthquake confirmed many of the predictions of the study. For example, the four 230-kilovolt live-tank circuit breakers that were damaged at the San Mateo substation were identified as vulnerable by the study. The 230-kilovolt bulk-oil circuit breakers at San Mateo, which were not damaged, were properly identified as resistant to seismic damage. Likewise, specific types of 500-kilovolt circuit breakers at the Metcalf and Moss Landing substations failed, while other types were not damaged, as expected from the study. The study also predicted that little or no damage would occur in substation equipment operating at 115 kilovolts or lower, or to control and protection equipment; these important conclusions were confirmed by the experience of the Loma Prieta earthquake. In addition, the substation study proved helpful in the rapid restoration of service after the Loma Prieta earthquake. Results of the early phases of the study helped PG&E respond to the earthquake quickly by identifying which facilities would have damage, what types of damage to expect, and how to restore the system.

CORPORATE EMERGENCY PLAN AND OTHER ACTIVITIES

Emergency Planning and Response

PG&E has long-standing, comprehensive plans for the restoration of gas and electric service following emergencies. We deal with emergencies somewhere in our utility system almost on a daily basis. Violent storms, fires, gas leaks, equipment damage or failure, and other problems occur with enough regularity that basic electric and gas emergency plans are frequently exercised. The response to small-scale emergencies is handled locally, at the operating division level. Our operating divisions have highly trained crews, stockpiles of necessary supplies, and well-established procedures for quickly restoring services following small-scale emergencies. An earthquake that caused only local damage also would be handled locally by our operating divisions.

PG&E recognizes, however, that moderate to severe earthquakes have the potential to cause damage over large portions of our utility system and that such large-scale disruption clearly requires a centrally coordinated, corporate-wide response. Our overall corporate response to emergencies was formalized as a Standard Practice in 1986 (revised in 1989), and established guidelines for emergency planning activities throughout our company.

Between 1980 and 1985, PG&E developed an effective Life Safety Program for our General Office complex in San Francisco. The program provides for the support of the headquarters staff for 72 hours after an earthquake capable of isolating the buildings from outside support. The PG&E Emergency Operations Center (EOC) was established in 1987 in the General Office complex as the central location for policy direction and overall management of emergency operations. The EOC is equipped for both voice and data communications using both company and dedicated Pacific Bell telephone capability, as well as cellular and satellite telephone equipment.

The EOC and our emergency management planning are designed to provide five key functions in an emergency: (1) obtain an overall assessment of the extent of the disaster and its impact on our facilities, (2) develop an overall strategy for dealing with the disaster, (3) support recovery efforts through procurement and allocation of personnel and other resources, particularly those from unaffected regions and outside sources, (4) provide for centralized dissemination of essential information to company management and employees, and (5) provide for centralized dissemination of information to the public through major media, and to local, state, and federal agencies. In an emergency, company personnel are trained to observe the following priorities: (1) protecting life, (2) protecting property and maintaining service to customers, (3) restoring gas and electric services, (4) restoring critical company functions, and (5) restoring other normal operating functions.

In addition to the EOC in San Francisco, PG&E has established an Alternate EOC at our San Ramon Learning Center, which can be used if the primary EOC is inaccessible. To provide additional redundancy in managing our electric and gas systems during an emergency, PG&E has established full backup facilities at remote locations for our electric and gas control centers and for data processing.

The EOC and other backup facilities provide the necessary communications hardware for responding to an emergency. However, a truly effective response to a major emergency requires not only the hardware but also fully trained personnel. PG&E conducts ongoing training to prepare key personnel for effective emergency response. In June 1989, we conducted our first functional emergency response exercise at the EOC. This exercise involved over 100 key people and proved very effective at testing and refining our emergency response plans. The report analyzing the emergency response exercise was delivered to the General Manager of the Distribution Business Unit on the afternoon of October 17, 1989, a few hours before the Loma Prieta earthquake.

The training exercise conducted a few months before the earthquake proved invaluable in helping personnel perform their essential functions during the very real task of responding to the Loma Prieta earthquake. PG&E's emergency response to the earthquake was coordinated from the EOC from approximately 6:00 p.m. on October 17th until 2:00 p.m. on October 19th. Subsequent to the Loma Prieta earthquake, the EOC was augmented by upgrading computer and telecommunications capacity and by further streamlining emergency management procedures. In April 1990, we held another functional emergency response exercise at the EOC. This exercise, which involved more than 150 key personnel from the General Office and the four Bay Area Regions, incorporated lessons learned from the first exercise and from the Loma Prieta earthquake, and helped to further prepare personnel to respond as effectively as possible in future earthquakes. In addition, earthquake response exercises are conducted several times a year within local PG&E organizations, and our backup power control facility is activated weekly.

Effective emergency response also requires the marshalling of personnel, supplies, and replacements for damaged equipment. All of PG&E's operating divisions maintain stockpiles of supplies to restore local gas and electric service. In an emergency, extensive assistance with personnel, supplies, and equipment would be quickly available from other PG&E regions that, due to their distance from the particular earthquake, would not have sustained damage. In some cases, it is possible to transfer redundant or less essential equipment at unaffected locations to repair the most essential damaged equipment. Critical equipment also can be obtained from other utilities under mutual aid agreements; for example, the Western Systems Coordinating Council (WSCC) maintains a listing of spare power transformers and mobile transformers to aid WSCC members in an emergency. We have also arranged for alternative transportation means to circumvent possible earthquake damage to road and rail systems. Mutual aid agreements also provide for personnel support to augment PG&E crews in restoring utility service.

PG&E's corporate-wide commitment to effective emergency planning and response was rewarded in the Loma Prieta earthquake. Our emergency planning prepared key personnel to respond quickly, the EOC effectively managed the response and recovery efforts, and our crews (along with crews provided by other utilities) had the skills, supplies, and equipment necessary to quickly restore gas and electric service to our customers.

Future Development

PG&E considers seismic safety in the planning, design, and construction of every new facility or component in our utility systems. We use the Uniform Building Code for California as our *minimum* seismic criteria; more conservative criteria often are used to ensure increased seismic safety and reliability of the facility or component. PG&E's gas and electric utility systems are mature and fully operational now. We do not expect to make major new additions to our generating capacity, and we expect to make only a few major additions to our bulk power and gas transmission systems between now and the year 2000. One of these additions for which seismic safety is being considered is the Pipeline Expansion Project, in which a new transmission pipeline is planned by PG&E and Pacific Gas Transmission Company. The pipeline will transport Canadian gas into the state along a route generally paralleling the existing transmission corridor (Figure 3) and terminating at the transmission pipeline junction 80 miles east of Monterey.

Our electric and gas distribution systems will be expanded gradually as development continues in California. Generally, distribution system components are relatively rugged with respect to earthquake survivability and are readily repaired in the event of damage. Nevertheless, we will include seismic considerations in the planning, design, and construction of new distribution systems.

Recovery

Planning for recovery from damaging earthquakes is an integral part of our corporate-wide emergency planning. Recovery operations begin as soon as immediate emergency actions to protect lives, to protect facilities, and to maintain service to our gas and electric customers are completed.

Personnel resources for recovery efforts are available from within PG&E. To supplement crews within affected regions, crews from regions not affected by an earthquake can be marshalled quickly to help with recovery operations. In addition, mutual aid agreements with other utilities provide additional personnel resources. For example, after the Loma Prieta earthquake, 160,000 customers were without gas service (mostly because customers had turned off their own gas supply). Relighting all of these customers was an extremely labor-intensive effort; 340 of the more than 1100 servicepersons working to restore service were from other utilities. As discussed previously, supplies and spare parts are available from within the PG&E system, as well as from other utilities through mutual aid agreements.

Recovery from a major earthquake also requires financial resources. In addition to its own financial resources, PG&E maintains working relationships with the four largest California banks and with sixteen other major banks. Therefore, we have access to the financial resources necessary to recover quickly from a damaging earthquake.

Education and Public Information

Education and public information are essential, high-priority components of our corporate-wide earthquake preparedness program. Our education effort includes programs focused on our customers, employees, other organizations, and the general public. The objective of these education programs is to ensure that as many people as possible are fully informed about proper steps to follow before, during, and after an earthquake to protect lives and to minimize the impact of earthquakes on property and on our utility systems.

We take advantage of numerous ongoing opportunities to provide information to the general public about earthquake safety aspects of gas and electric service. PG&E publishes articles on earthquake safety in *PG&E Progress*, which is sent to four million residential customers. The April 1989 issue addressed "How to Survive the Big One," and informed the public that most experts agree a major earthquake will probably hit the Bay Area in the next 30 years. The December 1989 issue contained a clip-and-save list of earthquake planning items. Information used by Pacific Bell in its telephone directory section on pre- and post-earthquake actions is provided in part by PG&E. We also cooperate with state and local agencies to provide earthquake safety information during the annual Earthquake Preparedness Month. PG&E also was a financial supporter of the U. S. Geological Survey's informative and educational newspaper supplement, "The Next Big Earthquake in the Bay Area May Come Sooner than You Think" (September 9, 1990), and helped with its Chinese translation.

Communication with the public is particularly important after a damaging earthquake has occurred. PG&E is well-practiced in providing emergency information to the public from our News Department, which functions around the clock, 365 days a year. We have taken steps to better prepare the news media with post-earthquake response information regarding customer service and safety. For example, we have prepared two videotapes, "Earthquake Gas and Electric Safety: When to Shut It Off and How" and "Earthquake Safety for Natural Gas: When to Shut It Off and How." In April 1990, these videos were distributed to all television stations within PG&E's service territory; audio versions were sent to all the radio stations. Spanish-language versions were sent to all Spanish-speaking television and radio stations in our service territory. PG&E also maintains close liaisons with the California Office of Emergency Services, the Red Cross, and other emergency service groups to provide public information and coordinate emergency planning.

Research

Mitigating seismic hazards requires not only the application of current knowledge, but also research into new and better techniques. Although generally not defined as academic research, our technical and professional employees throughout our company are constantly evaluating and testing new materials, products, and procedures, and collecting performance data. This research often leads to substantial improvements in practice and procurement specifications. PG&E has been consistently funding research programs in engineering and geosciences that further earthquake safety. Within the company, the Research and Development Department funds earthquake research in dam safety, probabilistic seismic hazard analysis, insulator design, and other topics.

PG&E also supports external research through our financial and staff support of the Electric Power Research Institute and Gas Research Institute. PG&E is a sponsor of the Pipeline Fault Crossing Field Experiment at Parkfield, California, which is being conducted by the National Center for Earthquake Engineering Research. We also financially support and have staff participation in academic programs at California universities, including the University of California at Berkeley and Stanford University, that are involved in earthquake engineering and earth sciences research. The ongoing gas and electric Seismic Working Group meetings among PG&E and other California utilities serve to establish research needs and share the dissemination of research results.

PG&E will continue to enthusiastically support research concerned with reducing seismic hazards. We believe that such research will continue to produce tangible results -- a better understanding of earthquakes and their effects, and a utility system that is safer and more resilient during earthquakes.

1991 ACTION PLAN

The 1991 Action Plan that follows summarizes our current activities and those budgeted for 1991. The process of identifying and then mitigating seismic hazards has several key stages. The first stage is information-gathering to assess seismic hazards and vulnerabilities. The second stage is analysis and planning to identify and prioritize mitigation activities. The third stage is implementation of the decisions reached in the first two stages. The action plans presented below and summarized in Table 4 identify efforts in each of the four major areas discussed previously in this report: (1) assessing seismic hazards, (2) reducing the vulnerability of the gas system, (3) reducing the vulnerability of the electric system, and (4) corporate emergency planning and other activities. In each of these four areas, some of our earthquake countermeasures are at the information-gathering stage, some are at the analysis and planning stage, and some are at the implementation stage. The action plans in future annual reports in this decade will incorporate the progress made in these four areas and will have increasing emphasis on implementation.

ASSESSING SEISMIC HAZARDS

Continue data compilation for scenario earthquake and seismic hazard studies. The Geosciences Department of PG&E has become a repository for current geologic, seismologic, and geotechnical information pertaining to earthquake hazards and earthquake effects in California and other relevant seismically active areas. Additional information is gathered during project studies and through participation by PG&E personnel in professional meetings and other activities. This broad-based data-gathering will continue in 1991 and future years, and the impacts of additional scenario earthquakes will be evaluated, as appropriate.

Continue seismic and volcanic hazards studies in northeastern California and the Sierra Nevada. A three-year study of potential earthquake and volcanic hazards in the Sierra Nevada and adjacent parts of the Modoc Plateau of central and northern California will be completed in 1991. The objective of this study (supported by PG&E's Research and Development Department) is to provide an up-to-date geologic and seismologic data base to be used in evaluating earthquake and volcanic hazards for dams, power plants, and gas and electric facilities in the region.

Continue strong-motion instrumentation and ground-motion analyses at substation sites. A program of detailed geotechnical and site response studies has begun for the San Mateo, Metcalf, Newark, Ravenswood, and Monte Vista substations. This multi-year study (supported by PG&E's Research and Development Department) will continue in 1991 with the installation of strong-motion instruments to record future strong shaking at the sites. Geotechnical borings and tests will be performed to enable the analysis of site amplifications. These data will be combined with existing nearby strong-motion records and on-site ground noise studies to evaluate past damage or lack of damage to substation equipment to refine techniques for minimizing future damage to substation equipment in earthquakes.

Table 4

1991 ACTION PLAN

ACTIVITY	SCHEDULE	RESPONSIBLE PG&E UNIT
ASSESSING SEISMIC HAZARDS		
Continue data compilation for scenario earthquake and seismic hazard studies	Continuous program	Geosciences
Continue seismic and volcanic hazards studies in northeastern California and the Sierra Nevada	3-year study to be completed in 1991	Geosciences
Continue strong-motion instrumentation and ground-motion analyses at substation sites	Ongoing program to continue through 1991	Geosciences
REDUCING THE VULNERABILITY OF THE GAS SYSTEM		
Continue assessment of seismic vulnerabilities of the gas transmission, storage, and distribution facilities	Ongoing program to continue through 1991	Gas and Electric Project Engineering, and Gas Engineering and Construction
Continue Gas Pipeline Replacement Program and modify earthquake hazards priorities	25-year program; 20% complete. Priorities to be modified in 1991	Gas and Electric Distribution
Replace transmission pipelines 109 and 132 on the San Francisco Peninsula	Evaluation complete; replacement to begin in 1991	Gas and Electric Distribution
Attend Inter-Utility Seismic Working Group meetings	Continuous program	Geosciences, and Civil Engineering
Maintain awareness of improvements in seismic resistance of pipelines and related equipment	Continuous program	Geosciences, Civil Engineering, Gas and Electric Project Engineering, and Gas Engineering and Construction
Update Gas Control Department contingency plans	New program to be completed in 1991	Gas Control
REDUCING THE VULNERABILITY OF THE ELECTRIC SYSTEM		
Develop and implement performance-based seismic evaluation criteria for the high-voltage system	Criteria to be developed in 1991. Implementation to continue through 1991	High-Voltage Transmission and Substations
Install transformer radiator bracing	Ongoing program to continue through 1991	High-Voltage Transmission and Substations
Replace selected circuit breakers at 500-kilovolt intertie substations	Multi-year program to begin in 1991	High-Voltage Transmission and Substations

Table 4

1991 ACTION PLAN
(Continued)

ACTIVITY	SCHEDULE	RESPONSIBLE PG&E UNIT
REDUCING THE VULNERABILITY OF THE ELECTRIC SYSTEM (Continued)		
Participate in dynamic testing of high-voltage components	Continuous program	Civil Engineering
Attend Inter-Utility Seismic Working Group meetings	Continuous program	Geosciences and Civil Engineering
Participate in EPRI research on earthquake ruggedness of substations	Complete in 1991	Civil Engineering
Perform seismic review of additional substations	Ongoing program to continue through 1991	High-Voltage Transmission and Substations, and Transmission and Substations
Maintain awareness of improvements in seismic resistance of electric transmission equipment	Continuous program	Civil Engineering, High-Voltage Transmission and Substations, and Transmission and Substations
EMERGENCY PLANNING AND OTHER ACTIVITIES		
Conduct annual earthquake exercise	Continuous program	Security
Evaluate post-earthquake functionality of the Energy and Gas Control Centers	1-year program to be completed in 1991	Power Control, and Gas Control
Review seismic performance of the General Office complex	1-year program to be completed in 1991	Building and Land Services

REDUCING THE VULNERABILITY OF THE GAS SYSTEM

Continue assessment of seismic vulnerabilities of components of the gas transmission, storage, and distribution facilities. Seismic engineering inspections, compilation of geologic and geotechnical conditions, and evaluations of post-earthquake operational alternatives are in progress and will be completed in 1991 for the gas facilities and pipelines that may be affected by high-probability scenario earthquakes. Potential vulnerabilities will be identified for further investigation, evaluation, and mitigation as appropriate. During the course of this work, opportunities to reduce earthquake vulnerabilities using simple, rapidly performed modifications are being identified and implemented. These include providing additional anchorage and bracing where needed, and restraining telecommunications equipment.

Continue Gas Pipeline Replacement Program and modify earthquake hazards priorities. The priorities for replacement of the gas transmission pipelines and distribution mains that are included within the Gas Pipeline Replacement Program will be modified to take into account the relative probability of exposure to earthquake hazards. For each pipeline element, a priority factor will be computed that incorporates the probability of occurrence of surface faulting or strong ground shaking at the element, and the presence or absence of hazardous geologic conditions such as liquefaction or slope instability. This priority factor will cause the early replacement of the more vulnerable portions of the gas pipeline system that are close to the scenario earthquakes.

Replace transmission pipelines 109 and 132 on the San Francisco Peninsula. Under the Gas Pipeline Replacement Program, the transmission lines 109 and 132, which connect the Milpitas terminal with the Potrero load center in San Francisco, are being replaced. Studies of geologic hazards along the pipeline corridor have identified four crossings of the San Andreas fault and localities having a potential for liquefaction or landsliding. Each of these hazards will be mitigated during the course of design and construction activities to be carried out during the next several years.

Attend Inter-Utility Seismic Working Group meetings. During 1990, a group of representatives from PG&E, Southern California Gas, Southwest Gas, and San Diego Gas and Electric met periodically to exchange information and ideas regarding earthquake hazard mitigations for gas systems. The group plans to continue such exchanges in 1991. Areas of particular attention for the group are code enhancements, defining mutual seismic hazard mitigation research needs, and cooperating to set seismic equipment standards for vendors. One of the key goals of this group is to share results from seismic investigations and earthquake mitigation information.

Maintain awareness of improvements in seismic resistance of pipelines and related equipment. PG&E personnel will continue to attend industry and professional meetings to bring new ideas and practices to PG&E for improving gas system performance in earthquakes.

Update Gas Control Department contingency plans. The results of the scenario earthquake assessments will be used to update and refine the earthquake contingency plans maintained by the Gas Control group within PG&E. The new information about expected system conditions produced by the scenario events will improve the realism of emergency response planning for the gas system.

REDUCING THE VULNERABILITY OF THE ELECTRIC SYSTEM

Develop and implement performance-based seismic evaluation criteria for the high-voltage system. The current information on earthquake hazards and the vulnerabilities of the high-voltage system will be used to estimate post-earthquake operational conditions and functionality requirements. Using these requirements, we will develop seismic evaluation criteria for the installed equipment (circuit breakers, transformers, air switches, line traps, and coupling capacitor voltage transformers) such that, if the installed equipment met the criteria, post-earthquake functionality would be preserved. The criteria can then be used to plan specific equipment upgrades for relatively vulnerable components.

Install transformer radiator bracing. Cooling radiators on certain high-voltage transformers have proven vulnerable to strong seismic shaking. Designs and drawings are being prepared for braces that will improve their seismic resistance. New braces will be installed initially on transformers at the Metcalf and San Mateo substations.

Replace selected circuit breakers at 500-kilovolt intertie substations. In 1990, we developed a multi-year plan to replace vulnerable 500-kilovolt circuit breakers in the southern portion of the service territory. With the objective of improving the capability to maintain the post-earthquake operability of transmission lines and transformer banks, we prioritized breakers for replacement on the basis of their relative importance and seismic exposure. The first breakers proposed to be replaced are at the Gates and Midway substations.

Participate in dynamic testing of high-voltage components. PG&E has been requesting vendors to perform dynamic tests on high-voltage equipment to ensure good structural and operational performance during earthquakes. In the past three years, we have participated with Southern California Edison and the Los Angeles Department of Water and Power in three shake-table tests on 500- and 230-kilovolt circuit breakers, and two such tests on current transformers. We also use such tests to study the performance of equipment constructed using more seismically resistant materials. In January 1991, we will participate in a test of a 500-kilovolt breaker that incorporates a non-porcelain bushing with improved structural characteristics. We expect to be involved in additional equipment tests sponsored by vendors who wish to respond to our preference for dynamic testing to meet our concerns about earthquake vulnerability.

Attend Inter-Utility Seismic Working Group meetings. Beginning in 1986, a group of representatives from PG&E, Southern California Edison, the Los Angeles Department of Water and Power, and San Diego Gas and Electric have been meeting periodically to exchange information and ideas regarding earthquake mitigations for electric systems. The group plans to continue such exchanges in 1991. Areas of particular attention for the group are seismic criteria for equipment, interactions with substation equipment vendors, inter-utility post-earthquake assistance, and joint research needs. We intend to jointly consider the impacts of the south-central San Andreas scenario earthquake to develop coordinated mitigation and response plans among the affected utilities. PG&E also meets periodically with Japanese utility representatives to discuss seismic criteria, concerns, recent equipment developments, and lessons learned from past earthquakes.

Participate in Electric Power Research Institute (EPRI) research on earthquake ruggedness of substations. PG&E engineering and operations personnel are participating with other California utilities in a multi-year EPRI project to mitigate earthquake damage to high-voltage substations. Their first tasks, which are in progress, involve the development of seismic fragility values for high-voltage equipment and preparation of a manual of practice for reducing seismic vulnerability in substations. The results of their project can be used by the utility industry to evaluate the earthquake vulnerability of substation equipment and systems.

Perform seismic reviews of additional substations. We are performing additional on-site inspections and assessing site-specific earthquake vulnerabilities to extend the recently completed high-voltage substation study to additional substations and for additional earthquake scenarios. The studies include consideration of geotechnical factors, site-specific ground motions, and transmission-line vulnerabilities. These results will be combined with the previously developed data to prioritize substation upgrades and assist in emergency response and recovery planning.

Maintain awareness of improvements in seismic resistance of electric transmission equipment. We will continue to participate and take leadership roles in professional activities that bring new ideas and practices to PG&E for improving the seismic performance of the electric system and that share our experience in mitigation efforts with other utilities and research engineers. PG&E personnel are active participants in lifeline engineering committees and conferences of the American Society of Civil Engineers and the Earthquake Engineering Research Institute.

EMERGENCY PLANNING AND OTHER ACTIVITIES

Conduct annual earthquake exercise. An earthquake exercise is in the planning stage for the spring of 1991. It will extend the earthquake training experience for PG&E personnel and test the recently upgraded Alternate Emergency Operations Center in San Ramon. In conjunction with the exercise, corporate recovery planning for critical utility functions will be expanded and refined. The emergency planning activities will also be expanded to provide plans for post-earthquake resources and improved communications for emergency operating centers located within PG&E's operating regions.

Evaluate post-earthquake functionality of the Energy and Gas Control Centers. The Energy and Gas Control Centers are located in PG&E's corporate center in San Francisco and encompass the facilities and the attendant telecommunications and data processing needed for centralized operation and control of the electric and gas systems. The seismic vulnerabilities of these systems to the identified scenario earthquakes are being evaluated by PG&E personnel and consultants. The study is due to be completed in 1991.

Review seismic performance of the General Office complex. A seismic evaluation task force has been studying PG&E's older buildings at 215 Market, 215 Market Annex, 245 Market, and 25 Beale in downtown San Francisco. The task force will complete its study and make its recommendations in 1991. The task force includes building management and civil engineering personnel from PG&E, and independent consulting structural engineering and architectural firms. One of the objectives of the task force is to assess the expected post-earthquake functionality of the buildings under seismic loading. Access to resources in these buildings, including files and drawings, would facilitate emergency response and earthquake recovery.

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