Geologic Hazard Evaluations For Gas Transmission Lines 109 And 132 In San Bruno

Prepared by the Geosciences Department

November 1, 1992

PG&E Pacific Gas and Electric Company

Pacific Gas and Electric Company

Geosciences Department, F22A
One California Street, Room 2200
P.O. Box 770000
San Francisco, CA 94177
415/973-2792
Fax 415/973-5778

March 5, 1993

Mr. George Foscardo
Planning Director
City of San Bruno
567 El Camino Real
San Bruno, CA 94066

Dear George:

On December 17, 1992, we had an informative meeting with you and your staff and consultants to discuss questions and concerns regarding seismic safety as it applies to the replacement of our gas transmission pipelines through the San Bruno portion of the San Francisco Peninsula pipeline corridor. This meeting followed the submittal to you of an extensive and detailed report, "Geologic Hazard Evaluations for Gas Transmission Lines 109 and 132 in San Bruno," prepared by PG&E's technical staff and dated November 1, 1992. The review of this report conducted by your staff and consultants, particularly Consulting Engineering Geologist Murray Levish, raised four questions, which were addressed during the meeting. In this letter, we summarize the questions raised at the meeting, and provide additional information to clarify and document the issues.

1. **Crossings of Additional Possible Secondary Faults.** The possible existence of additional secondary faults was raised by Mr. Levish. The studies documented in the 1992 PG&E report identified and evaluated the Serra fault and several subsidiary faults located in the zone between the Serra fault and the main traces of the San Andreas fault (1992 PG&E report, p. 16). Mr. Levish and the PG&E technical staff agreed during the meeting that possible yet-to-be-discovered faults would have no more potential for surface fault displacement than the Serra and other known faults in this zone. Thus, for example, a minor thrust fault near Crestmoor Drive, as postulated by Mr. Levish, could potentially experience surface displacement of a foot or less.

   In response to both the specific question about thrust faulting near Crestmoor Drive and the general issue of unidentified additional minor secondary faults, the 1992 PG&E report included a generic analysis of the potential for pipeline displacements due to concurrent surface faulting amounts of as much as 1 foot of thrust deformation and 3 feet of horizontal shear deformation. The results indicated that the standard design planned for the pipeline replacement incorporates more than adequate ruggedness to mitigate such minor fault displacements (1992 PG&E report, p. 32). In certain locations where there are several bends in the pipeline, added safety will be provided by using heavier-walled pipe and long-radius elbows. The planned replacement pipelines will adequately mitigate the largest potential secondary fault displacements anticipated by Mr. Levish, as discussed in the meeting of December 17, 1992.

2. **Conservative Analysis of Backfill.** The planned installation of the new pipelines involves excavating trenches about 6 feet deep, into which the pipe is placed. The pipe is surrounded by and the trench is backfilled with sandy material that has been well compacted so as to support the overlying pavement and traffic loads. In addition to supporting traffic loading, sandy backfill allows the pipeline to move within the trenchline during an earthquake. In the PG&E analysis of earthquake-caused stresses on the buried pipeline, we assumed the backfill material had the mechanical properties of the local sedimentary rock along the pipeline route (1992 PG&E report, p. 29-30), which is much stronger and more dense than the planned backfill. The results of the analysis indicated that the pipeline would perform well, even assuming rock-like backfill. Thus, using sandy backfill material provides an added margin of confidence in the safety of the design. As agreed at the meeting on December 17, no further analysis is needed.

3. **Subsidence of Deep Fill.** The planned pipeline routes traverse several areas of man-made filled ground in San Bruno, and differential settlement can be a potential hazard in such areas. Although no areas of potential significant differential settlement were identified along the routes (1992 PG&E report, page 19), an analysis was performed for possible failure of an artificial fill along the route. This analysis considered an extreme case in which the fill was assumed to experience slope failure such that the pipeline was allowed to deform under its own weight, unsupported by the fill. The results indicate that the strains in the pipeline would be less than one-fourth of the reasonable tensile strain limits for the pipe (page 32). Thus, the planned pipeline has a very large capacity to withstand settlements of filled ground.

   Mr. Levish raised a question about the potential for settlement of the deep fills emplaced at locations along the frontage road for Highway 280, with possible amounts of settlement of as much as one percent of the fill depth; for example, 1 foot of settlement for 100 feet of fill. The capacity of the pipeline is more than adequate to accommodate such minor displacements. As agreed at the meeting on December 17, 1992, no further analysis of this consideration is needed.

4. **Alquist-Priolo Special Study Zones.** In 1972, the State of California established the Alquist-Priolo Special Study Zone Act to prohibit the construction of structures for human occupancy across known active surface-fault rupture areas. As a result of this Act, detailed geologic maps have been prepared to identify the locations of known active surface faults, such as the San Andreas fault, and the zones within which detailed investigations of the locations of individual fault traces are required. High-pressure gas pipelines are not covered by the statement or intent of the Alquist-Priolo Act. Even so, PG&E, as a prudent owner and operator of such facilities, has conducted detailed fault location studies to identify the locations of the primary traces of the San Andreas fault and adjacent secondary faults to assure that we have accurately identified and characterized potential surface faulting hazards to the replacement pipelines. We have mitigated these hazards by relocating the pipelines to avoid crossing the main San Andreas fault traces, and by using a pipeline design that can accommodate minor or secondary faulting. Thus, PG&E has met the spirit of the Alquist-Priolo Act, both in using the Act's data base for fault evaluation, and in mitigating the potential hazards of surface faulting along the pipeline routes.

We appreciate the opportunity to work together with you to bring to closure the above four items identified in our review meeting on December 17, 1992. We believe that these discussions, in combination with the 1992 PG&E report, represent a sound and prudent basis for completing the design of the replacement of Pipelines 109 and 132 in the City of San Bruno. Please call me at (415) 973-3116, if you have any further questions.

Sincerely yours,

[redacted]

William U. Savage
Senior Seismologist

cc: Paul Beckendorf
Elizabeth Brokaw
Leslie Day
Jim Gamble
Dennis Guido
Harry Herrera
Chih-Hung Lee
Tim Hall - Geomatrix

PG&E

PUBLIC INFORMATION FACT SHEET
GAS LINES 109/132 REPLACEMENT PROJECT
DALY CITY, SOUTH SAN FRANCISCO AND SAN BRUNO

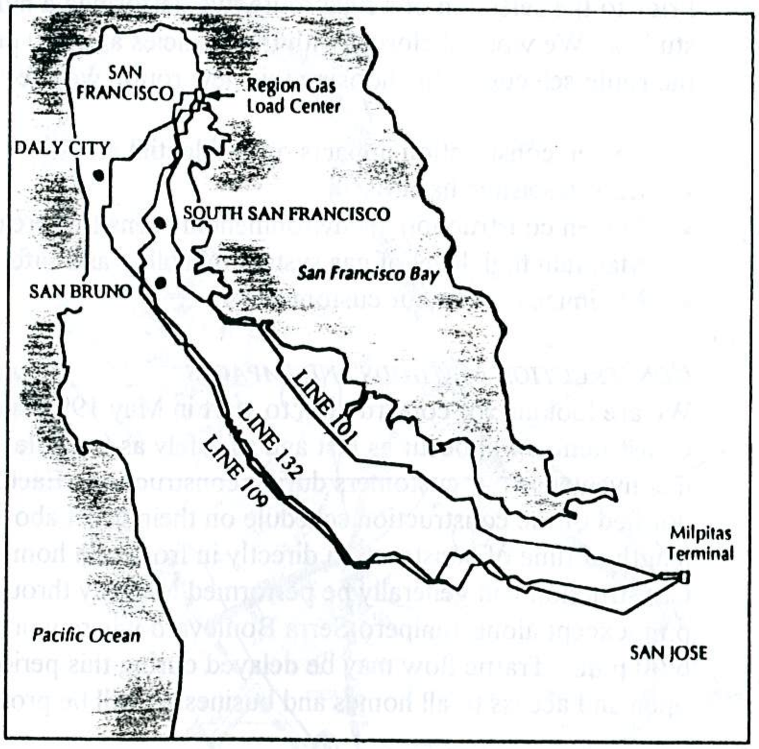
PURPOSE OF THIS FACT SHEET

This fact sheet provides information on a natural gas pipeline project that PG&E is starting in May. The following information will explain why this project is necessary, how we will keep you informed, and how we will try not to inconvenience you during construction. If you have any questions or concerns, please call the Line 109/132 Project Hotline at (415) 695-2640. For any other gas or electric service issues, please call the PG&E Customer Services office at (415)761-9103.

WHY DOES PG&E NEED TO DO THIS WORK?

In 1985, PG&E began the Gas Pipeline Replacement Program that will replace all aging natural gas pipelines in the system over a 25-year period. The purpose of this program is to maintain safe and reliable gas service to our customers. As part of this program, plans were made to replace the three natural gas pipelines that supply the Peninsula between San Francisco and Milpitas. We call these Lines 109, 132, and 101.

The old pipeline sections will be replaced with higher quality pipe using modern construction methods. The replacement of Line 101 was completed in 1989. The older portions of Lines 109 and 132 will be replaced by the year 2000. The current phase will be built from May 1993 to May 1994 in Daly City, South San Francisco and San Bruno.



EXISTING PIPELINES TO BE REPLACED IN 1993-1994

The section of Line 109 to be replaced in '93-'94 runs through Daly City, South San Francisco and San Bruno along Skyline Boulevard and in the San Francisco Watershed area. The short sections of Line 132 to be replaced in '93-'94 are located near Claremont Drive and along Skyline Drive and Skyline Boulevard in the City of San Bruno and in the San Francisco Watershed area. The existing lines cross the San Andreas fault in two locations along Skyline Boulevard, and also go through several residential back yards. We plan to replace these pipelines in new locations to reduce the seismic risk and environmental impacts along the lines. The maintenance access to the lines will also be greatly improved. All gas will be removed from the old pipelines and they will be sealed for safety and abandoned in the ground.

PUBLIC BENEFITS

The new lines will continue to provide safe, reliable gas to Daly City, South San Francisco and San Bruno, as well as the rest of the San Francisco Peninsula. The new lines should last for another 80 to 100 years.

NEW ROUTE DESCRIPTIONS

The new route for Line 109 starts at Hickey Boulevard and Saint Francis Boulevard in Daly City. It heads east on Hickey Boulevard and crosses under Interstate 280 to Junipero Serra Boulevard. It turns south on Junipero Serra Boulevard to Avalon Drive, which becomes Crestwood Drive as the street turns south. The pipeline continues on Crestwood past Sneath Lane, through the golf driving range, and onto the Interstate 280 frontage road until it reaches San Bruno Avenue. The pipeline will turn west on San Bruno Avenue to Skyline Drive and to Skyline Blvd. where it turns south and enters the San Francisco Watershed. The new route for Line 132 will run from San Bruno Avenue down Skyline Drive and the east shoulder of Skyline Boulevard, and will then turn south into the San Francisco Watershed. (Please see attached map.)

ROUTE SELECTION CRITERIA AND CONSIDERATIONS

Prior to the selection of a final route, we performed a number of environmental and geological studies. We worked closely with the agencies and city departments involved to get input into the route selection. In choosing this new route, we used the following items as criteria:

- Lessen construction impacts on residential areas.
- Lessen seismic hazards.
- Lessen construction in environmentally sensitive areas.
- Maintain high level of gas system reliability and safety.
- Minimize cost to our customers.

CONSTRUCTION METHODS AND IMPACTS

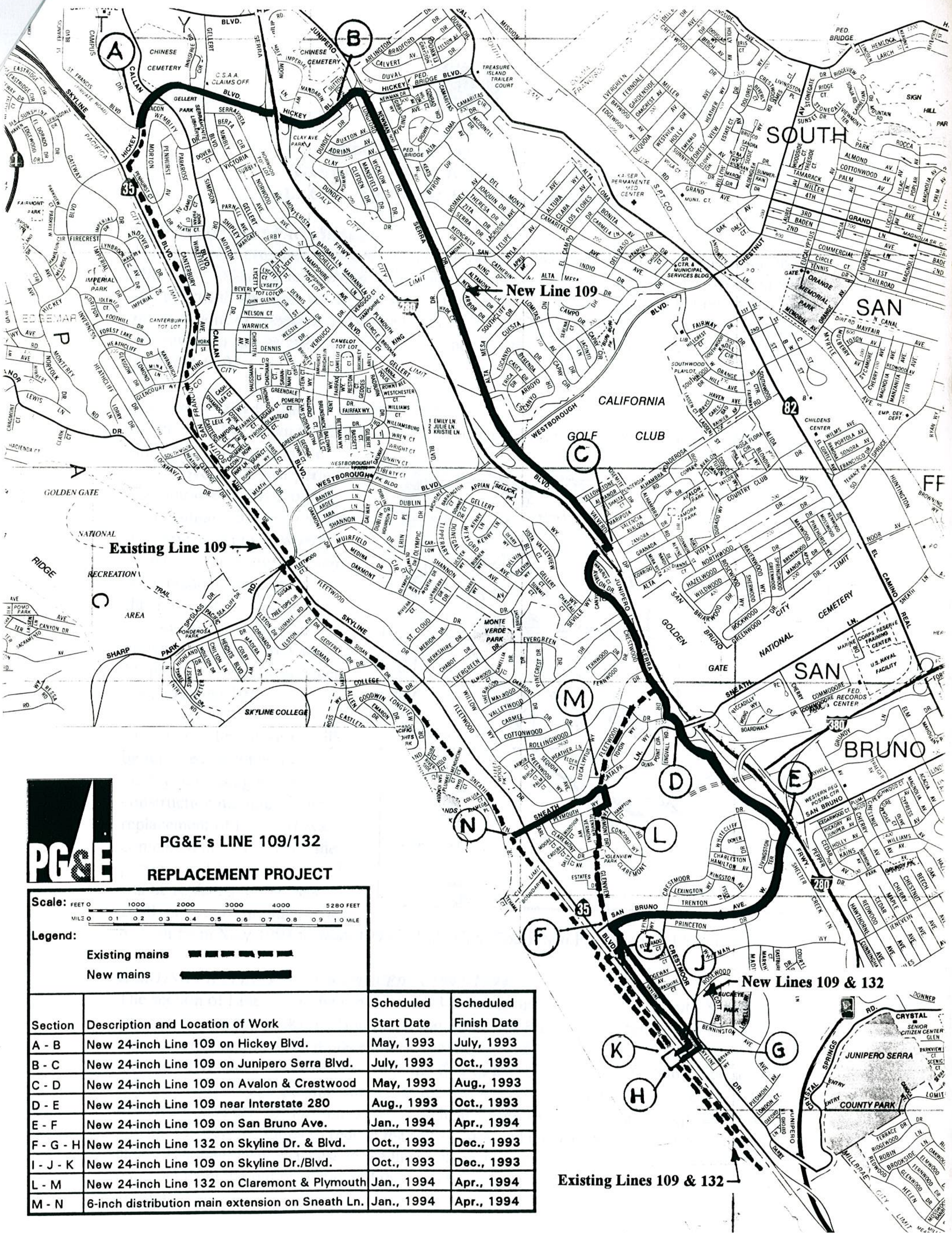
We are looking for construction to start in May 1993 and to last through May 1994. Construction will occur as fast and as safely as possible. We will do all we can not to inconvenience our customers during construction. Each home and business will be personally notified of the construction schedule on their street about one week in advance. The average length of time of construction directly in front of a home or business will be about one week. Construction will generally be performed Monday through Friday between 8:00 a.m. and 4:00 p.m. except along Junipero Serra Boulevard where work will take place from 7:00 a.m. to 6:00 p.m. Traffic flow may be delayed during this period, but at least one lane will be kept open and access to all homes and businesses will be provided.

The construction of Lines 109 and 132 will result in some noise, which is being limited by the daytime construction when fewer people will be affected. The trench will be filled or steel-plated at the end of each working day. All construction debris will be removed. In the event any landscaping is damaged by construction, it will be restored.

See the attached map for the schedules in specific areas. The project schedule may change due to weather, available manpower, and soil conditions.

FOR MORE INFORMATION, PLEASE CONTACT:

PG&E Line 109/132 Project Hotline..(415) 695-2640



PG&E's LINE 109/132

REPLACEMENT PROJECT

Scale: FEET 0 1000 2000 3000 4000 5280 FEET

MILE 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 MILE

Legend:

Existing mains ▬ ▬ ▬

New mains ▬▬▬

Section	Description and Location of Work	Scheduled Start Date	Scheduled Finish Date
A - B	New 24-inch Line 109 on Hickey Blvd.	May, 1993	July, 1993
B - C	New 24-inch Line 109 on Junipero Serra Blvd.	July, 1993	Oct., 1993
C - D	New 24-inch Line 109 on Avalon & Crestwood	May, 1993	Aug., 1993
D - E	New 24-inch Line 109 near Interstate 280	Aug., 1993	Oct., 1993
E - F	New 24-inch Line 109 on San Bruno Ave.	Jan., 1994	Apr., 1994
F - G - H	New 24-inch Line 132 on Skyline Dr. & Blvd.	Oct., 1993	Dec., 1993
I - J - K	New 24-inch Line 109 on Skyline Dr./Blvd.	Oct., 1993	Dec., 1993
L - M	New 24-inch Line 132 on Claremont & Plymouth	Jan., 1994	Apr., 1994
M - N	6-inch distribution main extension on Sneath Ln.	Jan., 1994	Apr., 1994

SUMMARY

PG&E is replacing portions of Gas Transmission Lines 109 and 132 on the San Francisco Peninsula. Although our older gas transmission facilities met the design and construction standards at the time they were installed, some do not meet present-day standards, and have been the recent subjects of review and replacement. Replacement priorities are based on age, construction factors, condition of the pipe, and exposure to seismic hazards. Sections of pipelines in seismically vulnerable areas are given the highest priority for replacement.

The greatest seismic hazard to our pipelines on the San Francisco Peninsula is the San Andreas fault. The effects of a scenario earthquake on the San Andreas fault, which for this study was taken to be a repeat of the 1906 earthquake, are likely to be strong ground shaking, surface fault rupture, ground distortion adjacent to the fault, seismically induced liquefaction, slope failure, and differential settlement.

To evaluate these effects, PG&E has conducted studies along the existing and preferred new routes for Lines 109 and 132 to ascertain the level of hazard. Investigations included aerial reconnaissances from helicopters, visual inspections from motor vehicles, and site visits on foot. We reviewed written eyewitness accounts and photographic records of the 1906 earthquake effects to assess the characteristics of surface faulting and ground deformation. We reviewed pertinent published and unpublished maps and the relevant literature, and conducted detailed geologic mapping of key sites. Records of exploratory soil borings and trenches in the vicinity of the pipeline routes were studied. Aerial photographs taken before and after urbanization were analyzed. We compared our independent interpretation of the landscape features indicative of active faulting with Alquist-Priolo Special Study Zone maps, and with the fault mapping by others.

The results of our studies in San Bruno indicate that the most vulnerable areas are pipeline crossings of the San Andreas fault, where future displacements could be as large as 10 feet. Lines 109 and 132 will be rerouted to avoid this hazard. In addition to surface faulting on the primary fault, it was recognized that, during a 1906-type earthquake, ground rupture also could occur on related subsidiary faults. For this study, we have assumed subsidiary strike-slip faults are capable of as much as 3 feet of right slip across a zone that is 10 to 70 feet wide. Thrust deformation of 1 foot at a dip angle of 20 to 40

degrees was postulated for the Serra fault, and 3 inches of reverse slip at a dip angle of 80 degrees was postulated for the faulted Franciscan/Merced contact. Distortion of the ground, or warping, occurred during the earthquake in 1906, decreasing with distance from the fault and becoming insignificant beyond 450 feet. For this study, we evaluated the effects of as much as 3.2 percent of warping parallel to the San Andreas fault, based on the amount of distortion observed in 1906. Two areas of possible slope instability were identified: an artificial fill area of low to moderate hazard on the north side of San Bruno Avenue between Glenwood and Alpine, and an area of low hazard near Glenview Drive south of its intersection with Earl Avenue. Liquefaction and ground settlement are not hazards to Line 109 and 132 through San Bruno.

Segments of the pipelines and the surrounding soil were modeled, and the pipelines were subjected to finite element analyses using the assumed parameters for faulting and ground distortion. The results of the engineering analysis found that the likely maximum compressive strain along the new sections of Lines 109 and 132 is less than 1.6 percent. This is well below the strain limits recommended to ensure the integrity of the pipeline.

The inherent ruggedness provided by the design specifications for new high-pressure pipelines is adequate to mitigate the potential hazards to Line 109 identified during these studies. Existing Line 132 was found to have similar levels of inherent ruggedness, despite the fact it was originally installed using no special seismic design considerations. By building to existing codes, minor fault displacements, minor slope failures, and differential settlement are not significant hazards to buried welded steel pipe.

Existing pipeline design and construction standards provide for adequate safety; however, PG&E has elected to provide extra safety at selected locations. We will avoid the potential for slope instability on the north side of San Bruno Avenue by placing the pipe on the south side of the street. We plan to use pipe having a 0.5-inch wall thickness at the potential locations of high strain along the new segments of Lines 109 and 132, and also along existing Line 132 where we will replace a small segment of the pipeline at the intersection of Plymouth Way and Glenview Drive. Additionally, we plan to install long-radius bends at selected turn points. These measures will mitigate the potential high compressive strain on a small segment of existing Line 132, and will help to ensure that a maximum strain level of 1.6 percent is well within the capacity of the new 24-inch, X-60 grade pipe.

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1 - INTRODUCTION

PG&E's gas transmission system is a 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. The system consists of high-pressure pipelines, compressor stations, terminals, and pressure-limiting stations; all are fully "engineered" facilities, built to engineering and construction standards applicable at the time of construction. Most of these facilities also have had recent upgrades to include state-of-the art, computer-assisted controls and telecommunications systems.

Although our older gas transmission facilities met the design and construction standards at the time of their installation, some do not meet present-day standards, and have been the recent subjects of review and replacement. In 1984, pipeline replacement priorities were established based on age, pipe type, corrosion and pressure factors, weld and joint type, leak history, and location. We identified 463 miles of transmission pipe, in addition to cast-iron and gas-welded steel pipe in the distribution system ranging in age from 45 to more than 100 years old, to be included in a 25-year Gas Pipeline Replacement Program.

PG&E's Gas Pipeline Replacement Program has been reviewed and authorized by the California Public Utilities Commission in General Rate Cases. Each year, we prepare progress reports for the Safety Branch of the Commission. Although our pipeline replacement priorities were based on evaluations of the condition of pipelines, implicitly resulting in high priorities for pipelines vulnerable to damage in earthquakes, following the Loma Prieta earthquake in 1989, the Commission requested we augment the seismic component of the prioritization process. In response to this request, we now emphasize the replacement of pipe in service areas subject to seismic hazards, thus accelerating the upgrade in safety and reliability in seismically vulnerable areas.

The greatest seismic hazard to our pipelines on the San Francisco Peninsula is the San Andreas fault. Because the San Andreas fault is capable of producing surface displacements of several feet and strong ground shaking within the next few years to tens of years, pipeline crossings of this recognized hazard are locations of significant concern. Accordingly, evaluations of Lines 109 and 132, which traverse the San Francisco Peninsula from downtown San Francisco to Milpitas, were initiated in 1989. In 1991, specific mitigative measures for crossings of the San Andreas fault and related subsidiary faults were investigated, including possible rerouting to reduce the exposure to surface fault displacement.

Approximately 15,450 feet of the planned gas transmission pipelines (12,450 feet of Line 109 and 3000 feet of Line 132) traverse the City of San Bruno. Three of the four pipeline crossings of the San Andreas fault currently are located in San Bruno. These potentially hazardous crossings precluded replacement of the pipeline in place. It was considered prudent to select alternative corridors for rerouting the pipes to eliminate the high seismic hazards. A seismic hazard evaluation of proposed alternative routes was completed in January 1992; additions to that study have been ongoing to address concerns and alternative routes brought up in meetings with the City of San Bruno. In addition, information on possible maximum fault displacements was provided to EQE Engineering, Inc. for finite element analyses of the pipeline along the planned routes.

On September 22, 1992, a meeting was held with the City of San Bruno to share the results of PG&E's geologic and seismic studies and to present preferred routes. George Foscardo, Director of Planning for the City of San Bruno, asked that PG&E provide the City information to assist them in answering questions about the safety and design of the pipeline. Murray Levish, the City's geologic consultant, stated that it was important for him to review our background information and the displacements PG&E assumed in our analysis and design. The purpose of this report is to address these requests.

The following report presents the evaluations leading to the selection of the preferred pipeline routes for Lines 109 and 132. It discusses the technical bases for the siting and design of the replacement pipelines. All of our hazard information pertinent to the preferred routes through San Bruno is presented.

2 - APPROACH TO HAZARD EVALUATION

PG&E has an ongoing commitment to reduce the earthquake vulnerability of all of its facilities. We focus our attention and resources on the most effective mitigation actions by realistically assessing the seismic hazards in an area through the identification of high-probability scenario earthquakes. The various effects of the scenario earthquakes, including strong ground shaking, surface faulting, and ground failure, are analyzed. We then evaluate the likely response of our facilities, components, and operations to these earthquake effects. From these data, we can assess the need for mitigative measures, select appropriate design parameters, or conduct further studies, as necessary.

Using the information from scenario earthquake analyses, we identified earthquake vulnerabilities along Gas Transmission Lines 109 and 132, which extend from San Francisco to Milpitas. A Phase I assessment in 1989 found that surface rupture on the San Andreas fault, seismically induced liquefaction and related phenomena, and landsliding and other slope failures were potential hazards along portions of the existing pipeline corridor. A matrix was developed to compare the relative severity of the various hazards (Table 1). The matrix was based on three variables: the amount and geometry of likely ground displacement, the width of the zone over which the displacement is likely to

Table 1

MATRIX FOR CLASSIFICATION OF LEVEL OF HAZARD TO THE PIPELINE

	Expected Occurrence of Hazardous Process[1]					
	Within 50 years		**50 to 500 years**		**>500 years**	
Distribution of Displacement[2]	**C**	**D**	**C**	**D**	**C**	**D**
>5 feet	Very high	High	High	Moderate	Moderate	Low
>1 foot to ≤5 feet	High	Moderate	Moderate	Low	Low	Very low
6 inches to ≤1 foot	Moderate	Low	Low	Very low	Very low	Very low

[1] The time categories reflect the following parameters:
≤50 years = anticipated useful life of the replaced pipeline
≤500 years = conceptual life of the pipeline/utility corridor
>500 years = greater than the foreseeable life of the pipeline/utility corridor

[2] Displacements are considered concentrated (C) if the ratio of the displacement to the width of the displacement zone is ≥0.5, and diffuse (D) if this ratio is <0.5.

be distributed, and the period of time during which the displacement is likely to occur. We selected a ground displacement of 6 inches as the threshold of concern, because smaller displacements are not likely to induce adverse strains on buried welded steel pipes. The hazard level and the risk of damage to the existing pipelines due to surface faulting at the crossings of the San Andreas fault were found to be high. Mitigation of the hazard along those sections of Lines 109 and 132 was given high priority.

Phase II investigations were performed for each segment of Lines 109 and 132 identified during Phase I as having adverse or uncertain geologic conditions. The Phase II level of effort included the interpretation of aerial photographs, site reconnaissances, detailed geologic mapping of key sites, compilation and analysis of available borehole data, and compilation and evaluation of historical earthquake data, especially regarding the local effects of the 1906 earthquake. The goal of these studies was to characterize the hazards and provide design information for the replacement of the pipelines. The results of these studies are presented herein.

ASSESSING THE SURFACE FAULTING HAZARD

Quantifying the surface faulting hazard for design purposes requires assessment of where future fault ruptures are likely to occur, their likelihood of occurrence, and how much displacement is likely on the fault traces and distributed across the entire fault zone. Numerous geologic studies substantiate that surface rupture usually is confined to a narrow zone along a preexisting fault trace, and that the type, amount, and location of future displacement typically is similar to that which occurred on the fault in the recent geologic past. The most likely locations for future surface rupture on the northern San Andreas fault zone are along the primary and subsidiary fault traces that ruptured in 1906. The timing of future earthquakes is based primarily on an assessment of fault slip rate, and is expressed either as an average recurrence time or as a probability of occurrence within a specified time interval. Recurrence times for future earthquakes on the northern San Andreas fault zone have been calculated by the Working Group on California Earthquake Probabilities (1988, 1990), which states there is a 23-percent chance of a magnitude 7 earthquake on the San Francisco Peninsula segment of the San Andreas fault within the next 30 years. A repeat of the 1906 earthquake, which is considered to be the maximum northern San Andreas event, is given a 2-percent chance within the next 30 years. The amount of displacement in a given event may be estimated from empirical relationships and from observations of displacements in 1906.

Because the anticipated useful life of the replaced pipeline is at least 50 years (up to 100 years), and the useful life of a pipeline/utility corridor can be as long as 500 years, a 1906-equivalent scenario earthquake has been considered for this project. We accurately located the San Andreas fault using aerial photographs taken both recently and before urbanization. We studied recent geologic mapping (for example, Brabb and Pampeyan, 1972a; 1983), including Alquist-Priolo Special Study Zone maps of the area prepared by the California Division of Mines and Geology, and performed detailed geologic mapping of selected sites. We compared our independent interpretation of landscape features indicative of active faulting with the Special Study Zone maps, with published fault mapping by Bonilla (1971), Brown (1972), and Brabb and Olson (1986), and with published and unpublished mapping by Pampeyan (1975; 1981; 1983).

We reviewed both written eyewitness accounts and photographic records of the 1906 earthquake effects to assess the characteristics of surface faulting likely during future earthquakes along the San Andreas fault, including the location, amount, and style of slip on primary and subsidiary fault traces, as well as on zones of distributed shear. We reviewed very useful observations by Herman Schussler, chief engineer for the Spring Valley Water Company (Schussler, 1906), and by a team of geologists consisting of Robert Anderson, Henry O. Wood, and Andrew C. Lawson, whose notes are compiled in the Report of the State Earthquake Investigation Commission (Lawson, 1908).

The deformation associated with the San Andreas fault in 1906 consisted of fault slip and ground distortion that extended some distance from the fault. This distributed shear occurred in a relatively wide zone adjacent to the narrow zone of concentrated faulting. We analyzed fence lines that were bent and offset by the primary fault and subsidiary faults to understand the pattern and amount of ground distortion.

We also have assessed the hazard associated with the Serra fault zone, which is parallel to and 0.5 to 1 mile east of the San Andreas fault zone in the San Bruno area. The fault initially was interpreted as meeting the provisions of the Alquist-Priolo Act and was included in a Special Studies Zone by the State Geologist in 1974, based on observations that the fault cuts the Merced Formation of Pleistocene age, and the overlying Colma Formation of late Pleistocene age (Brabb and Pampeyan, 1972a; Bonilla, 1971).

ASSESSING THE LIQUEFACTION HAZARD

To assess the potential for earthquake-induced liquefaction and liquefaction-related ground failure along Lines 109 and 132, we reviewed information regarding historical occurrences of earthquake-induced ground failure along the pipeline corridors. We studied available geologic and geotechnical data, such as records of exploratory soil borings in the vicinity of the pipeline routes, to identify locations having ground conditions susceptible to liquefaction and ground failure.

ASSESSING THE SLOPE INSTABILITY HAZARD

Slope stability investigations began with visual inspections of the pipeline corridors from motor vehicles and from helicopters. We reviewed pertinent published maps, including those of Brabb and Pampeyan (1972a; 1972b; 1983), Brabb and others (1972), Wright and Nilsen (1974), and Wieczorek and others (1985). Field reconnaissances were conducted of selected sites to assess existing and potential significant slope failures in densely vegetated areas near the pipelines, and in areas where slope failures were reported by Brabb and Pampeyan (1972b). We also reviewed accounts of ground failures during the 1906 earthquake (Lawson, 1908), the magnitude 5.3 Daly City earthquake near Mussel Rock in 1957 (Bonilla, 1959), and the 1989 Loma Prieta earthquake (EERI, 1990).

Aerial photographs along the pipeline corridors in the hilly regions between Daly City and Woodside were reviewed and analyzed. The photographs included frames from U. S. Geological Survey series GS-CP, taken July 29, 1946 (scale 1:21,500); U. S. Geological Survey series GS-VACY, taken August 15, 1960 (scale 1:20,000); U. S. Geological Survey series GS-VBZK (scale 1:18,750); and Pacific Aerial Survey series AV-3556, taken June 19, 1989 (scale 1:12,000).

OTHER IDENTIFIED HAZARDS

Differential Settlement

Local differential settlement has been reported within the pipeline relocation area. Settlements of several inches to several feet have been observed in certain neighborhoods following grading and development of the hillsides. We reviewed reported cases of settlement and related phenomena to better understand the potential hazard to the pipelines. We also discussed settlement issues with appropriate city officials.

Strong Ground Motion

Strong ground motion is not a hazard to underground welded steel pipe. However, strong ground motion can cause damage to above-ground facilities due to vulnerabilities involving inadequate anchorage and bracing of components. This exposure will be mitigated by engineering design and construction, and by the inherent ruggedness provided by the design specifications for high-pressure pipelines and related gas-handling equipment. These specifications provide substantial strength and ductility reserves to resist earthquake forces.

3 - RESULTS OF HAZARD EVALUATION

GEOLOGIC SETTING OF SAN BRUNO

The City of San Bruno, California, straddles the San Andreas fault, one of the major active tectonic features of North America. Recurrent slip across this fault zone has controlled the development of the local topography and has strongly influenced the nature and distribution of earth materials in the San Bruno area. With the exception of some local ground movement that may be a consequence of hillside grading and development, the geologic and geotechnical conditions within San Bruno that might affect gas transmission lines are largely related in one way or another to activity on the San Andreas fault.

Within San Bruno, there are four ages of earth materials that are traversed by the preferred routes for Pipelines 109 and 132. From oldest to youngest, these are Franciscan Complex bedrock, the Merced Formation, the Colma Formation, and a series of younger, largely unconsolidated terrestrial deposits such as alluvium, slope wash, and artificial fill. The aerial distribution and characteristics of each of these geologic units are described below.

The Franciscan Complex consists of a heterogeneous assemblage of deep-sea sediments and related oceanic crustal rocks of Mesozoic age (65 to 200 million years old). These rocks bear the imprint of ancient tectonic subduction; consequently, the Franciscan Complex now is highly disrupted, much of it having been reduced to a tectonic "paste" called melange (Wahrhaftig and Sloan, 1989). The Franciscan Complex consists predominantly of graywacke sandstone and interbedded shale, with lesser amounts of submarine basalt (greenstone), chert, serpentinite, and rare high-pressure metamorphic rocks known collectively as blueschist.

Franciscan rock materials crop out in the San Bruno area west of the San Andreas fault, locally in a 1000-foot-wide belt east of the fault, and in a narrow slice in the hanging wall block of the Serra fault just west of the Interstate 280 corridor (Bonilla, 1971; Pampeyan, 1981). Franciscan sheared rock, the melange unit, is found east of the fault and underlies portions of the pipeline replacement routes. The sheared rock consists predominantly of graywacke sandstone, siltstone, and shale, substantial portions of which have been pervasively sheared, but also includes hard blocks ("tectonic knockers") of other Franciscan rock types such as greenstone and highly cemented sandstone. A significant part of this unit consists of firm to soft, dense, clayey fault gouge, an unstable material, particularly when saturated.

Unconformably overlying the rocks of the Franciscan Complex are the moderately consolidated and locally fossiliferous fine-grained sandstone and siltstone beds of the Merced Formation (Brabb and Pampeyan, 1972a). Fossiliferous horizons tend to be cemented with calcium carbonate and hard. Minor clayey and pebbly horizons are also present locally. The Merced Formation, a unit of Pliocene(?) and Pleistocene age (less than 2 million years old), accumulated under shallow marine and intertidal conditions within an elongate and possibly fault-bounded trough located primarily on the eastern side of the San Andreas fault.

The Merced Formation underlies the terraced hillsides in San Bruno between Skyline Boulevard on the west and Interstate 280 on the east. These beds accumulated approximately at sea level to a few tens of feet below sea level, and now crop out at elevations ranging from about 200 feet to 600 feet above sea level. East of Interstate 280, the Merced Formation/ Franciscan bedrock contact is found in boreholes at depths of 400 to 500 feet below sea level (Bonilla, 1964). Beds of the Merced Formation have been deformed by folding and faulting associated with slip on the San Andreas fault, and now dip primarily to the northeast at moderate to steep angles. Several landslides involving Merced sediments were mapped in the steep canyon walls of the San Bruno area prior to development on the hillsides (Brabb and Pampeyan, 1972b). Shallow debris-flow scars also are common features on aerial photographs taken before the hillsides were modified. Most of these slope failures are either no longer present or not visible due to extensive grading.

The Merced Formation is moderately folded and cut by both high-angle strike-slip faults, including the 1906 trace of the San Andreas fault and its subsidiary traces, and by the Serra fault, a southwest-dipping thrust fault that probably merges with the San Andreas at depth. This geologically young deformation is probably directly related to a change in relative motion between the American and Pacific plates that occurred about 3 million years ago (Harbert and Cox, 1989) and that introduced a component of compression across the local plate boundary. The western limit of the Merced Formation in the San Bruno area is either the main (1906) trace of the San Andreas fault, or an unconformable depositional contact about 1000 feet to the east (Bonilla, 1971; Pampeyan, 1981). Pampeyan (1981) depicts this contact as being locally faulted where it crosses San Bruno and Glenview avenues near Skyline Boulevard. In this area the contact crosses the steep slopes of San Bruno Creek canyon, a topographic setting in which downhill creep may have enabled Franciscan materials to move on top of the younger Merced sediments, giving the contact the appearance of a reverse or thrust fault.

The Merced Formation is unconformably overlain on the northeast by the Colma Formation, typically a soft and friable to loose sand, with minor amounts of gravel, silt, and clay. Colma beds accumulated under shallow marine to subaerial dune conditions during a major highstand of sea level during the late Pleistocene, between 70,000 and 130,000 years ago (Clifton and Hunter, 1989), and may be more than 100 feet thick (Pampeyan, 1981). The Colma Formation is only slightly deformed in the San Bruno area, but has been cut locally by the Serra fault and is in thrust contact with Franciscan sheared rocks west of Interstate 280 between Sneath Lane and San Bruno Avenue (Pampeyan, 1981).

The Franciscan, Merced, and Colma formations are locally overlain by a variety of unconsolidated to weakly consolidated terrestrial materials of latest Pleistocene age to Holocene age (past 11,000 years): (1) Alluvium occurs in well-defined stream valleys and in fans at the bases of slopes, and typically consists of loose to soft and friable gravel, sand, silt, and clay in variable proportions. These materials are usually sorted by running water into distinct layers and lens-shaped deposits. (2) Slope wash, ravine fill, and colluvium (including landslide deposits), are unconsolidated to moderately consolidated deposits of sand, silt, clay, and rock fragments that have accumulated by the downslope movement of soil and weathered rock debris. These materials are typically unsorted and are unbedded or indistinctly bedded.
(3) Artificial fill consists of a wide variety of natural and man-made materials ranging from engineered freeway fills to refuse dumps. The thickness and geotechnical properties of artificial fill are highly variable, and must be assessed on a site-by-site basis.

The topography of the San Bruno area reflects both the active tectonic processes that are deforming the earth materials along the plate boundary, and the ongoing modification of the deformed ground by erosion and deposition. The hilly terrain of San Bruno rises abruptly from the flat plain surrounding San Francisco Bay across a pronounced northeast-facing step just west of Interstate 280 that marks a surface trace of the Serra fault. Deformed Merced and Colma beds east of this trace clearly indicate that a deeper "blind" thrust fault is also present and probably active. These thrusts and the folded beds in their hanging walls form part of a "positive flower structure" that represents the local crustal response to a component of compression across the San Andreas fault. Thrusting along the Serra fault has elevated the block to the west, enabling streams to carve deep canyons into the relatively soft beds of the Merced Formation. The steep slopes of the canyon walls have promoted the development of landslides, debris flows, and related slope failures. Sediment eroded from the elevated hillsides has been deposited in alluvial fans on the bay plain east of the Serra fault (Lajoie and others, 1974).

Topography in the western part of San Bruno is dominated by the San Andreas fault, which truncates the uplifted surface developed across the folded Merced Formation beds and the Franciscan sheared rocks. The San Andreas fault zone is marked by a prominent "rift" valley formed due to erosion of the rocks weakened by recurrent shearing along the zone of strike-slip faulting by tributaries of San Mateo Creek. The higher topography west of the fault, for example, Sweeney Ridge, is due to the relatively resistant rocks of the Franciscan Complex.

GEOLOGIC HAZARDS IMPORTANT TO PIPELINES IN SAN BRUNO

Surface Faulting

San Andreas Fault **-** The total amount of deformation associated with the 1906 earthquake on the San Andreas fault on the San Francisco Peninsula ranges from 9 feet of right slip on a single fault trace to a total of 17 feet of combined fault slip and ground distortion. Pipeline crossings of this fault are the only geologic conditions along Lines 109 and 132 that were assessed as having a high level of hazard. Lines 109 and 132 will be rerouted when they are replaced, thus avoiding this hazard where the pipelines cross the fault.

The Alquist-Priolo Special Studies Zone Act of 1972 designated areas within 500 feet of active faults as special study zones. This legislation requires that buildings for human occupancy be located at least 50 feet from the actual fault, and that geologic studies be done to ensure that structures are not placed directly on top of ground likely to rupture during major earthquakes. Although pipelines are not covered by the Act, we have met these provisions by conducting special studies within the zone, and relocating the lines that now cross the San Andreas fault to new corridors more than 50 feet from the fault.

In addition to surface faulting on the primary fault, subsidiary faulting, drag during rapid fault displacement, and the elastic rebound that may follow can produce significant horizontal distortion over a wide zone. The horizontal distortion that might occur away from the primary trace of the San Andreas fault is important because it may be sufficient to induce significant stresses in the ground surrounding a pipeline. The width of the zone of faulting and ground distortion associated with a strike-slip fault such as the San Andreas also may be influenced by several variables, including the underlying geology, the geometry of primary and subsidiary fault traces within the fault zone, and the relationship of fault traces.

During the 1906 earthquake, deformation due to elastic rebound and drag diminished with distance from the primary fault trace. The best strain gauges were fences that crossed the fault zone. The distributed deformation/distance data plotted on Figure 1 indicate that all significant lateral ground deformation occurred within approximately 450 feet of the 1906 trace of the San Andreas fault. For this project, the threshold of deformation that we considered to be significant was at least 0.5 foot of shear distributed over a distance of 50 feet laterally (equivalent to 1 percent distortion). Amounts of distortion less than 1 percent were not considered to be significant to the performance of a welded steel pipe.

In addition to evaluating the total amount of distributed shear across the fault zone and the width of the zone of deformation, it is important to calculate the percent of distortion with distance from the primary fault trace. The percent of distortion is the ratio of the amount of distortion versus the distance over which the distortion occurred. The ratio, or percent distortion, for each linear fence line segment was calculated by dividing the amount of distortion along each segment by the length of the segment. Ratios of segment lengths ranged from 0.002 to 0.043 (0.2 percent to 4.3 percent distortion); ratios for all segments that have more than 0.1 percent distortion are plotted on Figure 1. The length of each line segment indicates the distance over which the distortion was measured. Specifically, the highest deformation/distance ratio at distances greater than 450 feet is 0.002 (0.2 percent distortion); this amount of distortion is significantly less than the amount considered significant (1 percent). Typical ratios observed within 450 feet of the San Andreas fault are 0.015 to 0.027 (1.5 percent to 2.7 percent distortion), which represent potential distributed deformation of 1.5 foot to 2.7 feet within 100 feet, laterally. Only one fence line segment has a high distortion ratio (4.3 percent); this segment has been correlated with a mapped lineament, and is considered to be a subsidiary fault.

To provide a conservative estimate of the amount of distortion that may occur in the vicinity of the San Andreas fault zone, we have identified a relationship between total shear deformation and distance that is based on the maximum measured ratio, rather than on the median value of the ratios. Although data from only four sites were used to make a quantitative analysis of the pattern of secondary deformation, qualitative observations of secondary deformation at several other sites support the limits of distortion defined in Figure 1. The deformation/distance relationship also is conservative, because the 1906 earthquake is considered to represent the maximum event for the northern San Andreas fault. Thus, future displacements along this segment of the fault are not likely to exceed those that occurred in 1906.

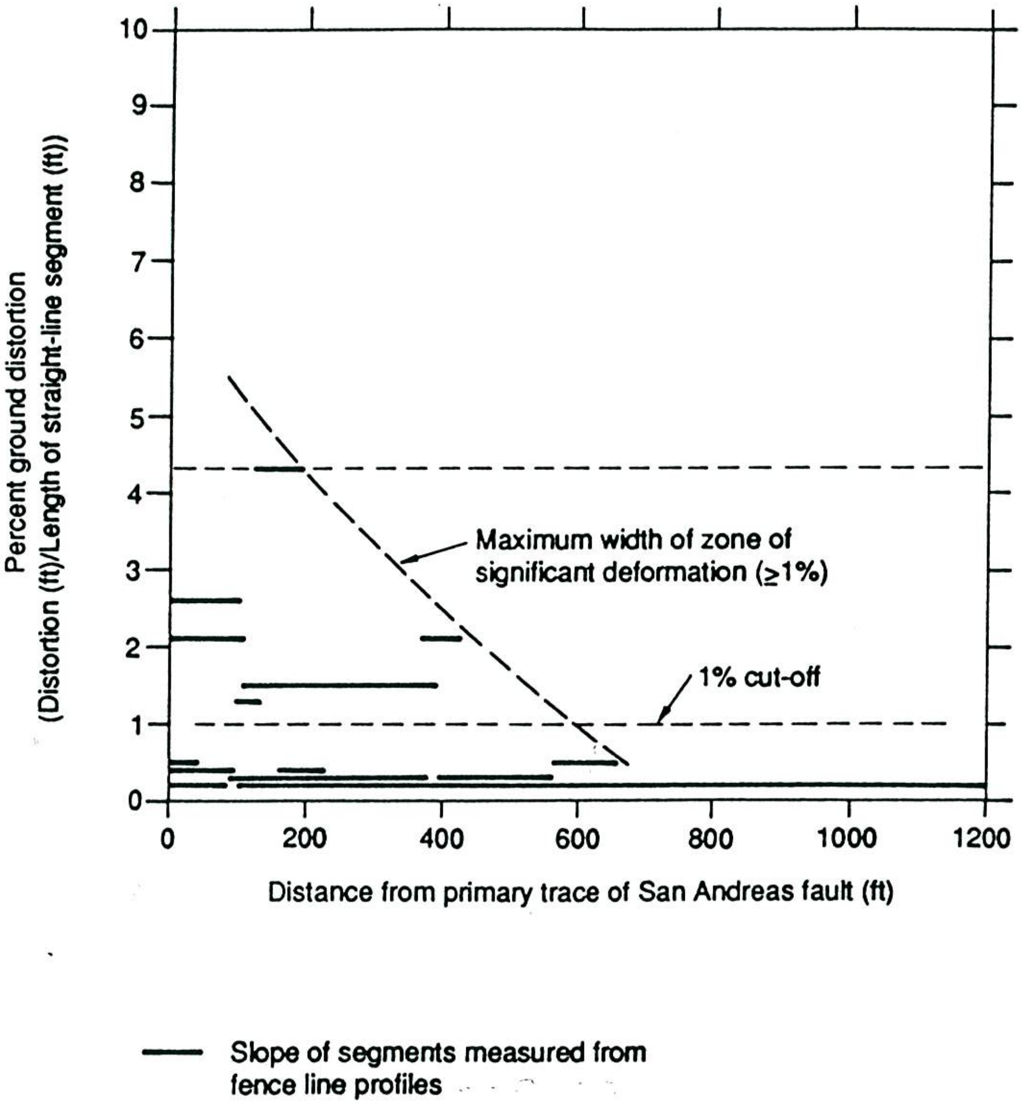


Figure 1. Percent of ground distortion versus distance from the primary trace of the 1906 rupture on the San Andreas fault. The length of the line indicates the length of fence segment for which deformation was measured. Distortion of less than 1 percent is considered insignificant for welded steel pipe. Distortion greater than 4 to 5 percent is likely to be recognized as a distinct fault.

Serra Fault Zone - The Serra fault zone is parallel to and 0.5 to 1 mile east of the San Andreas fault zone in the San Bruno area (Plate 1). The Serra fault initially was shown on geologic maps of the San Francisco South and Montara Mountain quadrangles by Bonilla (1971) and by Pampeyan (1981), respectively. Brabb and Olson (1986) diagrammatically depict the Serra fault as a series of northwest-trending, southwest-dipping thrust faults exposed over an area as wide as 0.6 mile. The fault is not marked by geomorphic features considered diagnostic of geologically recent slip, making the fault difficult to locate accurately, particularly after development has occurred and obscured the stratigraphic relationships that would indicate thrusting. The low topographic relief across the traces indicates the fault is characterized by low slip rates and small (less than 1 foot) surface displacements.

The most recent slip on strands of the Serra fault zone is at least as young as latest Pleistocene (past 120,000 years). In several places, Franciscan Complex bedrock is thrust over the Merced Formation on shears that dip 20 to 40 degrees to the southwest. Smith (1981) observed about 16 feet of apparent dip slip on one of the shears within the Serra fault zone, but noted that because no detailed stratigraphic investigations had been made along this imbricate thrust zone, he could not estimate the amount of cumulative displacement. After reviewing available consulting reports, interpreting aerial photographs, and conducting a field investigation of the Serra fault zone, Smith (1981) recommended the fault not be a Special Studies Zone, because there was no conclusive evidence of faulting during the Holocene (the past 11,000 years). The California Division of Mines and Geology reconsidered the Serra fault and removed it from the Alquist-Priolo Special Studies Zone.

The thrust faults appear to be a manifestation of local strain partitioning (contemporaneous strike slip and dip slip) along the San Andreas fault. Based on a structural analysis of the San Bruno area, we interpret that the Serra fault intersects the San Andreas fault at depths between 0.5 and 1 mile, too shallow for the thrust faults to act as independent seismic sources. However, based on its probable structural connection with the San Andreas fault, we assume, for the conservative purposes of this study, that the Serra fault zone is capable of coseismic ground rupture given a large earthquake on the nearby San Andreas fault.

In light of the compressional coseismic ground ruptures observed along the northeastern flank of the Santa Cruz Mountains in the communities of Los Gatos, Cupertino, Los Altos Hills, and Palo Alto after the 1989 Loma Prieta earthquake, future slip on the San Andreas fault might be accompanied by minor displacements on one or more strands within the Serra fault zone. After the Loma Prieta earthquake, the observed net slip on individual compressional coseismic breaks was small, ranging from fractions of an inch to a few inches. The maximum observed total shortening of 8 to 10 inches occurred across three discrete breaks in the concrete channel walls of Los Gatos Creek. Ground cracking near the Chinese Cemetery in Colma, reported by Lawson (1908), also may represent coseismic thrusting, although the line of cracks does not correspond to any of the mapped traces of the Serra fault zone (Brabb and Olson, 1986). Judging from the compressional displacements observed during the Loma Prieta earthquake, and from eyewitness accounts of the deformation northwest of the Chinese Cemetery in 1906 and again in 1957, a maximum of 1 foot of shortening may occur across the Serra fault zone during future large earthquakes on the San Andreas fault. Historical observations indicate the shortening is likely to be distributed across a surface zone several feet wide.

An alternate approach to assessing the ground rupture potential of the Serra fault zone is to estimate the tectonic shortening rate across the zone, and to assume this shortening rate is manifest as slip on thrust faults in the zone, rather than as folding. This shortening rate may be estimated from a synthesis of fault-normal convergence rates across the San Andreas plate boundary system implied by plate motion studies, geodetic studies in the Bay Area, VLBI (very long baseline interferometry)-derived strain data for the Pacific/North America plate boundary, and geologic studies of fault-normal convergence in northern California. Models for the relative motion of the Pacific and North American plates predict fault-normal convergence rates of approximately 4 mm/yr to 13 mm/yr (Cox and Engebretson, 1985; deMets and others, 1987; Harbert, 1991). Geodetically derived data and confidence limits for the strain field in the San Francisco Bay region establish an upper limit to San Andreas fault-normal convergence rates of about 5 mm/yr (Lisowski and others, 1991). The velocity field for the eastern Pacific and western North American plates derived from VLBI data suggests convergence east of the San Andreas fault is approximately 3.4 ±1.0 mm/yr (Ward, 1990).

On the basis of these data, we assume an approximate average convergence rate of 5 mm/yr across the entire San Andreas fault system at the latitude of the Bay Area. Of this 5 mm/yr, 2 to 3 mm/yr are accounted for by convergence across the San Gregorio and San Andreas faults, leaving about 2.5 mm/yr for distribution on faults east of San Francisco Bay, such as the Hayward, Calaveras, and Concord faults. Based upon the subdued topographic expression of the San Gregorio fault, we assume that no more than 0.5 to 1 mm/yr of convergence occurs west of the San Francisco Peninsula across the fault, and that 2 mm/yr occurs across the San Andreas fault proper, 1 mm/yr on each side. Given an estimated return period of 221 ±40 years for major earthquakes on the northern San Andreas fault (Niemi and Hall, 1992), and given the very conservative assumption that ALL of this shortening occurs on the trace of the

Serra fault that cuts the earth's surface, we estimate maximum slip on this trace of 7 to 10 inches per major 1906-type earthquake on the San Andreas fault. This estimate does not include the strain accommodated on the blind component of the Serra fault and on other faults that might be present, and the strain consumed in folding the Franciscan, Merced, and Colma formations east of the San Andreas fault. Our estimated maximum dip slip of 1 foot per event across the Serra fault zone based on crustal strain data corresponds well with our other independent estimate and represents a very conservative value for assessing the ground rupture potential of this feature.

Other Faults in San Bruno - We also assessed the likelihood of significant faulting occurring between the San Andreas fault on the west and the Serra fault on the east. Potential faults in this area could be right-slip faults subsidiary to the San Andreas, thrust or reverse faults that cut the hanging wall block of the Serra fault and merge with this feature at depth, or oblique-slip faults that manifest both slip characteristics.

Fortunately for this study, a fence that crossed the active fault trace and much of the San Andreas fault zone was surveyed after the earthquake by R. B. Symington, civil engineer. This fence, which was located near the upper end of San Andreas Lake, crossed the fault at nearly right angles. The location of this fence (fence C) and its pattern of deformation are shown on Figure 2. Unfortunately, the fence has since been torn down and can no longer be examined. The 1946 aerial photographs do, however, show the position of the fence line on the northeast side of Skyline Boulevard, so we were able to estimate its former location near the lake to within approximately ±25 feet. Symington recorded a total right-lateral displacement of 16.9 feet within a zone of deformation 1800 feet wide (Lawson, 1908). From his data, we interpret two zones of concentrated faulting: the primary 1906 trace and a subsidiary trace to the west, and a broad zone of warping to the northeast. Approximately 6.5 to 7 feet of right slip occurred on the primary trace over a narrow zone estimated to be less than 10 feet wide; 3 feet of right slip occurred within a 70-foot zone on the subsidiary trace. To the northeast, right bending (distributed shear) of 6 to 7 feet occurred within a zone 420+ feet wide.

The 3 feet of right slip is the largest displacement recorded in 1906 on a subsidiary fault within the San Andreas fault zone on the San Francisco Peninsula. For purposes of assessing the hazard to gas pipelines posed by slip on subsidiary faults near the San Andreas fault, we assume conservatively they are each capable of a maximum strike-slip displacement of 3 feet.

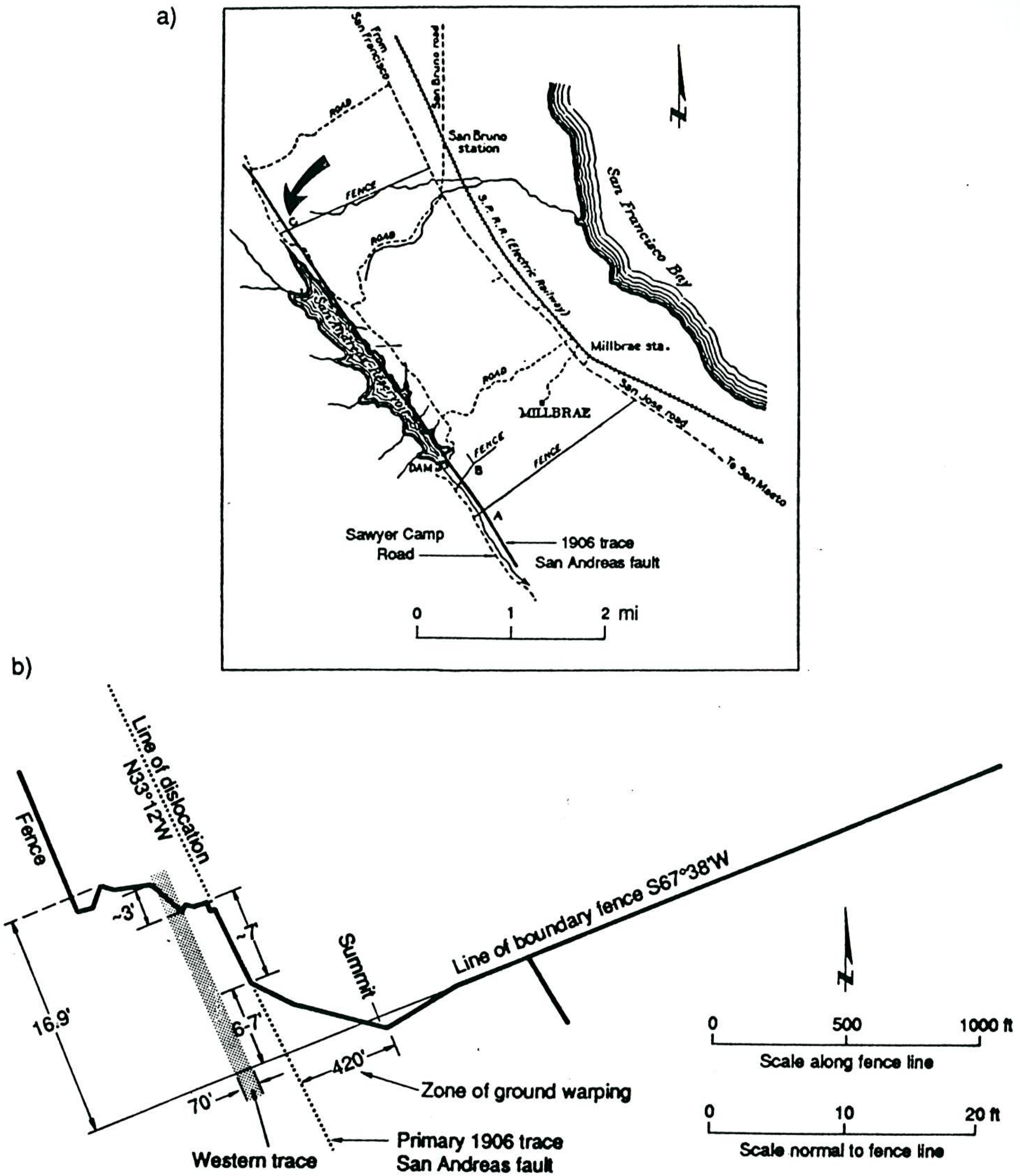


Figure 2. a) Index map showing the locations of fences near San Andreas Lake offset by the San Andreas fault in 1906. Note fence C (modified from Lawson, 1908, Figure 30).
b) Configuration of fence C following the 1906 earthquake showing a western trace, the primary 1906 trace of the San Andreas fault, and an eastern zone of ground warping (modified from Lawson, 1908, Figure 31).

Two north-trending subsidiary faults north of San Bruno Avenue and west of Glenview Drive (Plate 1) have been mapped by Pampeyan (1981) and are shown on the Alquist-Priolo Special Studies Zone map for Montara Mountain Quadrangle. Based upon our assessment of maximum displacements on subsidiary faults active in 1906, we have assumed that each of these faults is capable of a maximum of 3 feet of right slip across a zone that is 10 to 70 feet wide.

Pampeyan (1981) also shows a third fault in this area that trends subparallel to the San Andreas fault, east of Glenview Drive (Plate 1). According to Mr. Levish, San Bruno's geologic consultant, Franciscan bedrock overlies the younger Merced Formation across this feature, a structural relationship consistent with an interpretation of thrust faulting. Based on our assessment of field conditions, the relationships portrayed on Pampeyan's (1981) map, and a structural analysis of the block east of the San Andreas fault, we conclude that the Franciscan/ Merced contact is a depositional contact that has been locally modified by minor shearing and downslope creep. Pampeyan depicts the contact as a fault where it traverses the steep slopes of San Bruno Canyon; elsewhere, in gentle terrain, the contact shown is clearly depositional.

Assuming conservatively for the pipeline hazard analysis that this contact is a fault and that it has accommodated all the uplift of the Merced Formation exposed next to the San Andreas fault, we can estimate a maximum vertical slip across this feature. To do this, we assume the uplift of 500 feet on the Merced beds west of the contact has occurred within the last 500,000 years, a minimum age for the Merced Formation in this area. This yields a maximum uplift rate of 0.001 ft/yr (0.3 mm/yr). Given an estimated recurrence period of 221 ±40 years for great earthquakes on the northern San Andreas fault (Niemi and Hall, 1992), or estimates of a local San Andreas slip rate that varies from 12 mm/yr (Hall, 1984), to 19 mm/yr (Working Group, 1990), to 24 ±3 mm/yr (Niemi and Hall, 1992), we estimate a maximum slip of 3 inches per event on this faulted contact. This small amount of dip slip is below our threshold of concern, and poses essentially no hazard to the planned welded steel pipeline.

Liquefaction

Based upon our reviews of historical occurrences of liquefaction and liquefaction-related ground failure, and of reported geologic conditions along the pipeline routes, the conditions for liquefaction do not exist along San Bruno's existing or relocation routes. Liquefaction is not a hazard to Lines 109 and 132 through San Bruno.

Slope Instability

Steep slopes underlain by the poorly consolidated sediments of the Merced Formation experienced ground fracturing during the 1906 earthquake and during the magnitude 5.3 Daly City earthquake in 1957. There was little or no net displacement on the fractures, and the landslides generally were very shallow. Little deformation was observed in the adjacent, more competent bedrock. Failures are most likely in areas where the bedding is parallel to steep slopes or roadcuts, in areas where the sediments are saturated, and within artificially steepened slopes. Based upon the lack of reported major slides within San Bruno during the 1906 and 1957 earthquakes, and during the exceptionally wet winters of the early 1980s, the potential for hazards to buried pipelines due to slope failures is low, provided areas of known landsliding are avoided. Slope instability is not a significant hazard to Lines 109 and 132 through San Bruno.

Differential Settlement

Differential settlement within the proposed pipeline relocation area is the result of compaction of fill materials following development. It takes place soon after the placement of a fill, and it typically diminishes with time. Most neighborhoods within San Bruno are at least several years old, and the process of compaction is largely complete. Even if large-scale settlement were to occur, it would not be a significant hazard to gas transmission pipelines, because welded steel pipe can span several tens of feet without severe deformation. Differential settlement is not a hazard to Lines 109 and 132 through San Bruno.

PREFERRED ROUTES

Although avoiding adverse geologic conditions to enhance public safety and reduce the risks of pipeline failures and service disruptions was a primary goal in relocating Lines 109 and 132, the preferred pipeline routes are the result of many considerations, in addition to geologic hazards. PG&E also has addressed environmental, societal, right-of-way, cost, maintenance, operation, and construction factors in route selection, as described in PG&E's environmental analysis for this project. PG&E studied several alternative alignments, and consulted with the local agencies to reach the preferred routes. The routes described below (Plate 1) were suggested by the cities of Daly City, South San Francisco, and San Bruno. After studying the routing options, PG&E prefers these routes because they minimize potential impacts on residences, have fewer construction restrictions, and avoid crossing the San Andreas fault.

Preferred Route for Line 109

The preferred route for Line 109, called the Junipero Serra Route, begins at the intersection of Hickey Boulevard and Saint Francis Boulevard in Daly City. It continues east on Hickey Boulevard, and crosses under Interstate 280 to Junipero Serra Boulevard. (Line 109 was replaced down Hickey Boulevard between Gellert Boulevard and Imperial Way in the summer of 1992 to accommodate Daly City's scheduled road repaving in the fall of 1992.) It turns south on Junipero Serra to Avalon Drive, and heads west on Avalon.

As the pipeline route enters San Bruno, Avalon Drive becomes Crestwood Drive. Line 109 would continue south along Crestwood, past Sneath Lane, and onto the Interstate 280 frontage road until it reaches San Bruno Avenue. The pipeline route turns west on San Bruno Avenue to Crestmoor Drive. It continues south on Crestmoor to Cambridge Lane, where it heads west to Highway 35. PG&E will bore under Highway 35 and terminate the line approximately 100 feet south at a new valve lot on San Francisco Water Department property.

Alternate Route for Line 109

An alternative to the preferred route also has been considered for Line 109, because access to the Interstate 280 frontage road requires that the California Department of Transportation grant PG&E a longitudinal encroachment permit. The alternate route is the same as the Junipero Serra Route up to the intersection of Crestwood Drive and Fleetwood Drive. The route turns west onto Fleetwood to Rollingwood Drive, where it heads east a short distance to PG&E-owned property behind houses facing Fleetwood, where it heads south. (Line 132 is already located on this property.) When the route reaches Catalpa, it turns west and rejoins Fleetwood down to Sequoia Avenue. It continues south on Sequoia to Sneath Lane, and heads east to Claremont Drive. From here, it turns south on Claremont Drive, west on Plymouth Way, then south onto Glenview Drive. When it reaches San Bruno Avenue, the alternate route turns north to Crestmoor Drive. From the corner of Crestmoor Drive and San Bruno Avenue, it continues the same as the preferred route.

The alternate route will only become the preferred route if PG&E is unable to obtain a longitudinal encroachment permit from Caltrans along the Interstate 280 frontage road. This alternative affects more residences and is closer to the San Andreas fault than the Interstate 280 frontage road route. It has the potential for fewer impacts than other options considered, however.

Preferred Route for Line 132

Most of Line 132 in San Bruno does not need to be replaced at this time, as it was installed using welding methods that meet current standards. The line does, however, cross the San Andreas fault twice along Skyline Boulevard (Highway 35) between San Bruno Avenue and Cambridge Lane, and this section of pipe will be relocated. The preferred route will be south along Skyline Drive (a short street that parallels Highway 35) from San Bruno Avenue. Where Skyline Drive ends, the pipeline will continue in a California Department of Transportation right-of-way for Highway 35 to Cambridge Lane, where it will turn west and go under Highway 35. It will terminate approximately 100 feet south at a new valve lot on San Francisco Water Department property.

CHARACTERIZATION OF HAZARDS ALONG THE PREFERRED ROUTES

The following discussion of potential hazards is keyed to locations numbered on Plate 1 along the preferred pipeline routes. This map also shows the San Andreas and other related faults, the boundaries of the Alquist-Priolo Special Study Zones, and the existing pipeline routes. Two locations are shown for the Serra fault. The locations mapped by Pampeyan (1981) and Bonilla (1971) are considered more accurate than the regional fault map prepared by Brabb and Olson (1986).

Geologic Hazards Along the Preferred Route for Line 109

Locality 1: The Serra fault mapped by Brabb and Olson (1986) is crossed by the route along Crestwood Drive at about a 30-degree angle. This pipeline fault crossing is probably located within ±200 feet. The maximum displacement likely on the Serra fault is 1 foot of thrust. The level of hazard at this locality is assessed as low.

Locality 2: Here there are two potential pipeline crossings of the Serra fault that range from 30 to 45 degrees, one on Crestwood Drive and one on Rollingwood Drive. The interpretation by Bonilla (1971) provides a more accurate location of the trace than does the reconnaissance study by Brabb and Olson (1986), which shows only one fault crossing on Crestwood Drive. Bonilla's (1971) trace is probably located within ±50 feet. The level of hazard at this locality is assessed as low.

Locality 3: Based on mapping by Brabb and Olson (1986), the tip of the Serra fault intersects the surface close to, if not beneath, the Interstate 280 frontage road. Here the road and the fault are parallel. This fault location is considered to be less accurate than the mapping by Bonilla (1971), which places the trace of the Serra fault 250 feet west of the pipeline route at this locality. The level of hazard at this locality is assessed as low.

Locality 4: The route along San Bruno Avenue crosses the Serra fault at an angle of about 30 degrees at a location identified by both Bonilla (1971) and Brabb and Olson (1986). This pipeline fault crossing is probably located within ±100 feet. The level of hazard at this locality is assessed as low.

Locality 5: Potentially hazardous conditions in this area stem from the proximity of the pipeline route and new valve lot to the 1906 trace of the San Andreas fault and a subsidiary trace within the fault zone west of the intersection of Skyline Boulevard (Highway 35) and Cambridge Way. The subsidiary trace, which has an assumed maximum right slip of 3 feet, is 200 feet west of this road intersection, and is probably located within ±25 feet. The road intersection is 300 to 325 feet east of the 1906 trace of the San Andreas fault, which places it and the new valve lot within the zone of distortion observed in 1906 along nearby fence "C". The level of hazard at this locality is assessed as low to moderate.

Geologic Hazards Along the Alternate Route for Line 109

Locality 6: According to the reconnaissance study of faulting in San Mateo County by Brabb and Olson (1986), the alternate route for Line 109 might cross the Serra fault at about a 45-degree angle near the intersection of Crestwood Drive and Fleetwood Drive. Due to its relatively poor topographic expression, it is unlikely that the fault is located within ±200 feet. The level of hazard at this locality is assessed as low.

Locality 7: This area of the route along Fleetwood Drive might have a 20- to 30-degree intersection with the projected trace of a north-trending subsidiary fault recognized by Pampeyan (1981) that trends parallel to and west of Glenview Drive. Like other subsidiary faults within the San Andreas fault zone, it is assumed capable of generating a maximum horizontal right slip of 3 feet. The projected pipeline fault crossing is probably located within ±200 feet. The level of hazard at this locality is assessed as low to moderate.

Locality 8: This area of the route along Fleetwood Drive might have a near-perpendicular intersection with the projected trace of a northwest-trending subsidiary fault identified by Bonilla (1971) to the north. The maximum displacement on this fault is considered to be 3 feet of right slip. The projected pipeline fault crossing is probably located within ±100 feet. The level of hazard at this locality is assessed as low to moderate.

Locality 9: This area is a zone of potential intersection of the route along Sneath Lane and the two projected subsidiary faults: the northwest-trending fault north of Sneath Lane (Bonilla, 1971) described for Locality 8, and the north-trending subsidiary fault recognized by Pampeyan (1981) described for Locality 7. The zone of intersection of the pipeline route and the two projected fault traces is at least 200 feet wide, with pipeline fault crossing angles of approximately 70 degrees. The level of hazard at this locality is assessed as low to moderate.

Locality 10: This area of the route along Plymouth Way might have a 70-degree intersection with the projected trace of the northwest-trending subsidiary fault recognized to the north by Bonilla (1971) and described for Locality 8. The projected pipeline fault crossing is probably located within ±200 feet. The level of hazard at this locality is assessed as low to moderate.

Locality 11: In this area, the route along Glenview Drive crosses the projected faulted contact between Franciscan Complex rocks on the west and beds of the Merced Formation on the east; the angle of intersection is about 25 degrees. Based on the mapping of Pampeyan (1981), which depicts the Franciscan/Merced contact primarily as a depositional feature, it is improbable that this contact has a deep-seated tectonic origin, even if evidence for shearing has been observed between the two different geologic units. Shearing at the contact may be the result of flexural slip during uplift and folding of the block east of the San Andreas fault, or it may be the result of creep, a gravity-driven process that may have enabled Franciscan rocks to override the Merced beds locally. In a worst-case scenario, the contact is a subsidiary fault that could experience a maximum of 3 feet of right slip, with an up-on-the-west dip-slip component of up to 3 inches. The faulted contact is probably located within ±100 feet. The level of hazard at this locality is assessed as low to moderate.

Locality 12: Here a landslide deposit might be present near or beneath Glenview Drive south of its intersection with Earl Avenue. Brabb and Pampeyan (1972b) mapped a landslide deposit having a maximum dimension of 50 to 500 feet on the east side of Glenview Drive. This may be the same landslide shown on a map of the Crestmoor Highlands prepared by Associated Geotechnical Engineers (1976); the mapped headwall lies west of Glenview Drive, and is

110 to 180 feet wide in the artificial fill that underlies the pavement. The engineering reports we reviewed for this area contain no documentation of the construction of keys, benches, or other ground stabilizing measures prior to placement of the fill. Consequently, the susceptibility of this slide to reactivation by strong ground shaking or some other triggering mechanism is unknown, but may be low because of improved drainage conditions during development. The sidewalk on the east side of Glenview Drive at the intersection with Earl Avenue shows signs of settlement and minor downslope movement. Were sliding to occur here in the future, its likely direction of movement would be to the east, approximately perpendicular to Glenview Drive. The level of hazard at this locality is assessed as low.

Locality 13: Glenview Drive is parallel to and within 100 feet of a subsidiary fault mapped by Pampeyan (1981). In this study, subsidiary traces of the San Andreas fault are assumed capable of experiencing up to 3 feet of horizontal right slip. Near the junction with San Bruno Avenue, Glenview Drive is within and trends parallel to the zone of distortion due to ground warping observed along the San Andreas fault during the 1906 earthquake. The level of hazard at this locality is assessed as low.

Locality 14: The alternate pipeline route crosses a faulted contact between Franciscan Complex rocks on the west and beds of the Merced Formation on the east; the angle of intersection is about 65 degrees. The faulted contact is described for Locality 11, and is probably located within ±100 feet. The level of hazard at this locality is assessed as low to moderate.

Locality 15: The route in this area passes through approximately 200 feet of artificial fill placed on a steep, landslide-prone canyon wall. Downslope movement has partially removed the support from beneath a sidewalk on the north side of San Bruno Avenue. Cracks suggestive of downslope movement were observed in the west-bound lanes of San Bruno Avenue, south of the distressed sidewalk. The level of hazard at this locality is assessed as low to moderate.

Geologic Hazards Along Line 132

Gas Transmission Line 132 originally was installed through San Bruno in 1948, making it 12 years younger than Line 109. It was constructed using more recent construction methods, and is not scheduled for replacement within this decade, because the welding methods and joint types meet current standards. In our evaluations of this pipeline route, we identified that existing Line 132 is exposed to some low to moderate hazards of slope failure and crossings of the Serra fault, as described above for the coincident localities along the alternate route for Line 109. These are not considered significant hazards to the pipeline; there is no evidence of a modern, butt-welded steel gas transmission pipeline having ruptured as a result of moderate levels of earthquake-induced relative ground deformation (moderate movement is considered to be less than two to four pipe diameters). However, because a small portion of Line 132 crosses the significantly greater hazard of the San Andreas fault, it was considered prudent to re-route this portion of Line 132 at the same time Line 109 was being replaced.

Locality 10: Evaluations conducted for the alternate route for Line 109 indicated a hazard due to potential subsidiary faulting and ground distortion related to the projected trace of the northwest-trending fault recognized by Bonilla (1971) and described for Locality 8. The level of hazard at this locality is assessed as low to moderate.

Locality 16: This preferred new route lies within 150 to 325 feet of the 1906 trace of the San Andreas fault, and within 20 to 250 feet of a subsidiary fault trace shown on the Alquist-Priolo Special Studies Zone map of the Montara Mountain Quadrangle. It is parallel or nearly parallel to both faults, and crosses neither one. This route is within the zone of distortion due to ground warping likely during a repetition of a 1906-type earthquake. The level of hazard at this locality is assessed as low to moderate.

4 - ENGINEERING EVALUATION OF PIPELINES

PG&E uses current technology to design and build our pipelines to withstand a repeat of the 1906-type earthquake, both to ensure public safety and to ensure the supply of gas to our customers on the peninsula. Due to the potential for surface rupture of approximately 10 feet on the San Andreas fault in this area, we plan to relocate the pipelines to eliminate all crossings of the main trace of the San Andreas fault. As described in Section 3, we are aware of other faults and splays of the San Andreas, and other potential geologic hazards along the preferred routes. These pose a much lower hazard to the pipelines, and we have considered special materials and methods to design and build our pipelines to withstand these lesser hazards.

Some of the hazards described in Section 3 have the potential to damage or deform a buried gas pipeline due to localized displacement of portions of the line, causing the displacement to be absorbed by elastic deformation, plastic deformation, buckling or stretching of pipe walls, and ultimately, straining of the pipe to rupture. The performance of the pipeline depends upon the amount of the displacement, the geometry of the displacement, the distance over which the displacement is distributed along the pipeline, the behavior of the soil in which pipe is buried, and the strength of the pipe.

To analyze the potential for damage, PG&E has evaluated past pipeline performance in earthquakes. We have used the quantification of this experience along with data from extensive previous testing programs to perform up-to-date computer analyses. Realistic, worst-case scenarios along the routes have been analyzed, representing crossings of faults subsidiary to the San Andreas fault, zones of ground distortion, and areas of slope failure.

There is no evidence worldwide of a modern butt-welded steel gas or oil transmission pipeline having ruptured as a result of moderate levels of relative earthquake-induced lateral ground deformation (moderate deformation is considered to be less than two to four pipe diameters; in the case of Lines 109 and 132, approximately 4 to 10 feet). The favorable performance of pipelines experiencing moderate ground deformation in past earthquakes is important, because seismic factors usually were not considered in the original design.

The available information suggests that buried pipe is extremely rugged, provided some capacity for relative axial and lateral movement is provided. A pipe may be damaged during a large earthquake, and may need to be replaced for long-term reliability. Our goal, however, is to preserve safety.

LOCATIONS ANALYZED

Certain portions of the preferred and alternate routes identified in Section 3 as having low to moderate levels of hazard were described for our seismic design consultant, EQE Engineering, Inc., who calculated the potential stresses and strains in the pipelines. We also asked them to model portions of existing Line 132 to assess the integrity of pipe not planned to be replaced at this time. The analyses addressed the effects of permanent ground deformations related to a design basis event that is essentially a repeat of the 1906 earthquake. The areas of concern were:

- Thrust deformation postulated in connection with slip on the Serra fault zone paralleling Interstate 280 (Localities 1, 2, 3, and 4),
- The proposed location for a new valve station within the zone of 1906 ground distortion on the west side of Skyline Boulevard (Locality 5 and the southern part of Locality 16),
- Projected subsidiary fault crossings and zones of ground distortion in the vicinity of the 2600 block of Sneath Lane (Localities 7, 8, 9, and 10),
- Thrust deformation associated with the contact between the Franciscan and Merced formations near the intersection of San Bruno Avenue and Glenview Drive (Localities 11 and 14 and the northern part of Locality 16), and
- The potential for seismically induced slope failure on the north side of San Bruno Avenue (Locality 15).

REPRESENTATION OF GROUND DEFORMATION

The ground deformations considered in the analyses were shear-zone deformation, ground warping, thrust deformation, and slope failure.

Shear-Zone Deformation: Six analyses were performed to evaluate shear zone deformation, all related to the existing and alternate pipeline route generally between Catalpa Way and Plymouth Way (Localities 7, 8, 9, and 10). The analyses addressed different aspects of the impact of variation in maximum soil restraint, pipeline wall thickness, construction details, and orientation of shear zone deformations. The deformation was characterized as right slip that attains a maximum relative displacement of 3 feet across a zone 10 to 70 feet wide. The application of 3 feet of distortion over 10 feet is a highly conservative bounding of the observed maximum displacement adjacent to the San Andreas fault in 1906. Shear-zone deformations were located along the pipeline routes to produce realistic worse-case loading conditions. Criteria for selecting locations gave preference to locations proximate to bends or points of significant change in direction. The orientation of the shear deformation was selected to induce the greatest amount of deformation over the shortest length of pipeline. Shear-zone deformation was assumed to extend through the entire area of Localities 7, 8, 9, and 10, and was not limited to a single pipeline location.

Ground Warping: Ground-warping deformation was defined in terms of the distance from the main fault active in 1906, the amount of ground warping, and the orientation of the warping with respect to the pipeline routes. For Locality 5 and the southern part of Locality 16, ground warping was considered to be parallel to Skyline Drive and extend approximately 250 feet from the proposed location for the valve station. The amount of ground deformation was taken to be 1.6 percent. The results showed minimal impact on the proposed pipelines at this level, indicating the pipelines can withstand substantially higher amounts of deformation and not experience significant strains.

For Localities 11 and 14 and the northern part of Locality 16, the orientation of ground warping was assumed to be perpendicular to the orientation of San Bruno Avenue at its intersection with Glenview Avenue. The maximum extent of ground warping was taken to be approximately 125 feet from the center of the intersection, and the amount of warping approximately 2.2 percent, representative of the ground warping observed in 1906.

Thrust Deformation: Two thrust (or reverse fault) deformation scenarios were postulated. A minor amount (3 inches) of reverse deformation was postulated to intersect San Bruno and Glenview Avenues. The dip of the thrust zone was estimated as 80 degrees and the angle of intersection with the pipeline was estimated to be 25 degrees across Glenview Avenue (Locality 11), and 65 degrees across San Bruno Avenue (Locality 14). The minimum width of the deformation zone was estimated to vary from 5 feet to 10 feet.

Thrust deformation was also postulated in connection with the Serra fault zone. The location of this postulated thrust coincides with the preferred route for Line 109 and is generally parallel to Interstate 280 (Localities 1, 2, 3, and 4). The magnitude of thrust deformation was estimated to be as large as 12 inches, at a dip of 20 degrees to 40 degrees. Possible intersection angles of the proposed pipeline were estimated to be 30 degrees, 60 degrees, and 90 degrees. The minimum width of the thrust zone in these areas was estimated to be less than 20 feet. In all cases, the magnitude of any accompanying horizontal shear was estimated to be as much as 3 feet.

Slope Failure: The area of artificial fill on the north side of San Bruno Avenue between Glenwood and Alpine (Locality 15) was assumed to experience slope failure, imposing two different load conditions for the pipe. In one case, sliding uncovered the pipeline and it was allowed to deform under its own weight. In the second case, a nominal amount of fill placed additional load on the pipe. The weight of fill that might remain attached to the pipe was estimated as 120 pounds per foot for the 24-inch pipe; a weight of 200 pounds per foot was used in the analysis. The width of the area of postulated slope failure was estimated to be as great as 200 feet, based upon the extent of the artificial fill.

PIPELINE MODELING

In these analyses, new Line 109 was taken to consist of 24-inch-diameter Grade X-60 steel pipe having a wall thickness of 0.312 inches. Line 132 was taken to consist of 30-inch-diameter Grade X-42 steel pipe (wall thickness of 0.375 inches), 30-inch-diameter Grade X-52 steel pipe (wall thickness of 0.312 inches), and new 24-inch-diameter Grade X-60 steel pipe (wall thickness of 0.312 inches). Operating internal pressure for both pipelines was taken to be 400 pounds per square inch. The initial analyses assumed abrupt transitions at changes in pipeline direction. This effectively treats all bends as though they are miter joints instead of standard elbows or engineered bends. Modeling the pipeline in this manner is considered to be conservative because it tends to concentrate strains at a particular circumferential location.

SOIL MODELING

The soil along the pipeline routes in the San Bruno area was taken to consist of the dense, weakly cemented sandstone of the Merced Formation. This material is characterized by a dry density of 130 to 135 pounds per cubic foot, unconfined compressive strength of

2000 pounds per cubic foot, an angle of internal friction of 40 to 45 degrees, and a coefficient of pressure at rest of approximately 0.3. Backfill for pipe beneath the pavement generally is 48 inches, 12 inches thicker than the minimum required by current regulations. The trench dimensions provide for 6 inches of backfill between the pipe and the in situ material, compacted to 95 percent of optimum density. This is assumed to result in a placed density less than 120 pounds per cubic foot. The angle of internal friction and the coefficient of pressure at rest are assumed to be the same as those in the in situ material.

Relative movement of the surrounding soil with respect to a buried structural element imparts loads on that element. A key characteristic of soil loading is that the magnitude of these loads is limited by the gross failure of the soil. For example, the maximum lateral load that can be imparted to a buried pipe is related to the load necessary to develop a failure plane in the soil. Once this load has been reached, further relative displacement only serves to move soil along the failure plane. Under large lateral loads, pipe may undergo some vertical uplift as it follows the failure plane of the soil. The characteristics of the soil and the parameters of the pipes were applied to the analyses to estimate the maximum axial, lateral, and vertical forces the soil can place on the pipes as a result of differential movement. The effects of pavement over the backfill covering the pipeline also were assessed and found to be insignificant.

EVALUATION CRITERIA

Evaluations of the planned and existing pipelines were implemented using finite element models of the pipeline segments impacted by the permanent ground deformations. The computer code ANSYS was used to perform the analysis. The technique involved modeling the soil surrounding the pipeline using discrete nonlinear springs that represented the soil stiffness and maximum loads that could be transferred to the pipe by the soil. The pipeline was modeled using nonlinear pipe elements that allowed computation of maximum strains in the pipe under the combined loading of internal pressure and external soil loading.

A screening approach was implemented in the evaluation of different pipeline configurations. In this approach, analyses were initially performed using a conservative set of assumptions. Those configurations that were found to be satisfactory by a wide margin under conservative assumptions were dropped from further consideration.

Sensitivity studies were then carried out for those configurations having the highest predicted response. Selection of a configuration for sensitivity analysis was not necessarily an indication of unacceptable results under conservative assumptions. The screening was used primarily as a means to limit the total scope of sensitivity analyses for the many ground deformation conditions examined. The set of sensitivity analyses also provided information on the level of conservatism in the screening analyses and the impact of changes in pipe wall thickness and definition of ground deformation.

When strained in tension, a well-designed pipeline is very ductile and is capable of mobilizing large strains associated with significant yielding before rupture. Stress concentrations due to weld discontinuities and non-uniformities in the pipe wall thickness, yield point and backfill properties may lead to pipeline failure at lower strain levels, however. Accordingly it is common practice to limit the maximum tensile strains well below the rupture level of the steel. With good quality control of pipeline fabrication and backfill placement (typical of modern pipeline construction), reasonable tensile strain limits are on the order of 2 percent to 5 percent.

For the PG&E pipeline evaluation, allowable strain levels were established for which detailed examination was not necessary. At strains in excess of these levels, further justification was required to demonstrate acceptable pipeline performance.

Tensile strains of 2 percent to 3 percent were considered to have no potential for leading to pipeline failure. In compression, the theoretical wrinkling strain was used as a level below which further justification of adequacy was considered unnecessary. The theoretical limit on compressive strains associated with the onset of wrinkling for the various pipelines ranges from 1.25 percent to 2.50 percent.

Strain-based criteria were not employed in one analysis case. Assessment of the impact of slope failure on the north side of San Bruno Avenue focused on the maximum span of pipeline that could be exposed. This analysis scenario assumed the exposed pipeline undergoes unencumbered displacement in the vertical direction. Because this situation is not displacement-controlled, stress-based criteria are appropriate.

Guidance for the selection of an appropriate stress level can be found in Subsection NC of the ASME Boiler and Pressure Vessel Code (1989). The analysis case is consistent with Level D conditions in the ASME Code. For this situation, the allowable longitudinal stress is 75 percent of the ultimate material strength. For X-60 pipe, this translates to an allowable stress of 60,000 pounds per square inch.

ANALYSIS RESULTS

New Lines 109 and 132

Maximum compressive strain for all locations of the new Lines 109 and 132 was computed to be less than 1.6 percent. Given that PG&E plans to use a 0.50-inch wall thickness at the locations of high strain, this level of strain is well within the capacity of the 24-inch X-60 pipe. Likely stresses induced by a slope failure at Locality 15 are below 15,000 pounds per square inch.

Existing Line 132

The existing Line 132 at the intersection of Plymouth Way and Glenview Drive, and in the vicinity of San Bruno Avenue and Glenview Drive are the most severely strained cases examined. Maximum calculated compressive strains for the portion of Line 132 in the vicinity of San Bruno Avenue exceed the theoretical wrinkling strain limit by only 10 percent; these strains are judged acceptable based upon the conservative approaches taken in the analyses. Primary contributors to the very high conservatism in the analyses are the selection of shear zone location (which is based upon projecting subsidiary fault traces), shear zone orientation, and width of the shear zone deformation.

Bends in Line 132 in the vicinity of the intersection of Plymouth Way and Glenview Drive are calculated to exceed the theoretical wrinkling strain by a factor of 2 to 3. Where localized, these high compressive strains indicate a potential for some local plastic shell buckling of the pipe wall. Although there is evidence of pipes undergoing this level of compressive strain and sustaining no tearing of the pipe, the Plymouth Way/Glenview Drive situation is more severe because of the potential occurrence of these high compressive strains at bends.

MITIGATION MEASURES

The inherent ruggedness provided by the design specifications for new high-pressure pipelines and related gas-handling equipment is adequate to mitigate the hazards identified during these studies. Existing pipeline configurations examined in this study were found to have similar levels of inherent ruggedness, despite having been originally installed using no specific seismic design considerations. By building to existing codes, minor fault displacements, minor slope failures, and differential settlement are not significant hazards to buried welded steel pipe. Although existing pipeline design and construction standards provide for adequate safety, PG&E has elected to provide extra safety at selected locations.

Several measures may be applied to mitigate potentially adverse geologic conditions along pipeline routes. The first of these is route selection, which we plan to implement by relocating Line 109 and a segment of Line 132 to eliminate the present crossings of the San Andreas fault. Advantageous placement of the pipeline within the preferred corridors will be used to mitigate slope failure hazards. For example, by placing a pipeline on the uphill (cut) side of a street, we can avoid a locally steep slope adjacent to the downslope (fill) side of the street.

In addition, seismic hazards can be mitigated by pipeline design. Heavier-walled pipe will be used, and specially engineered, large-radius bends will be designed and installed where it may be advantageous to enhance the ability of the pipeline to distribute forces that may occur as a result of ground deformation. Table 2 presents the hazard localities along the routes, and the selected mitigative techniques.

Localities 1-4, 6, 12, and 13: No special mitigation measures are necessary. By building to existing codes, minor fault displacements, minor slope failures, and differential settlement will not present significant hazards to the planned buried welded steel pipe.

Locality 5: We will use approximately 700 feet of special heavy-wall/ductile pipe (0.5-inch wall thickness) on Cambridge Line all the way to the new valve lot. Bends will use long-radius elbows.

Localities 7-10: For the new Line 109, we will use approximately 2000 feet of special heavy-wall/ductile pipe (0.5-inch wall thickness) all the way from Locality 7 to Locality 10. Bends will use long-radius elbows. A small segment of existing Line 132 will be replaced with heavy-wall/ductile pipe in the vicinity of Plymouth Way and Glenview Drive to mitigate the potential for high compressive strains.

Table 2

HAZARDS AND MITIGATION MEASURES ALONG PIPELINES 109 AND 132

Locality Number	Hazard to Pipeline	Level of Hazard	Mitigation Measure
1	Crosses Serra fault	Low	Standard design
2	Crosses Serra fault twice	Low	Standard design
3	Parallel to Serra fault	Low	Standard design
4	Crosses Serra fault	Low	Standard design
5	Within 1906 zone of ground distortion; close to San Andreas fault traces	Low to moderate	Heavy-wall/ductile pipe (0.5 inch) and long-radius elbows on Cambridge Lane to the new valve lot
6	May cross Serra fault	Low	Standard design
7	Crosses projected trace of subsidiary fault	Low to moderate	Heavy-wall/ductile pipe (0.5 inch) and long-radius elbows from Locality 7 to Locality 10
8	Crosses projected trace of subsidiary fault	Low to moderate	
9	Crosses projected traces of two subsidiary faults	Low to moderate	
10	Crosses projected trace of subsidiary fault	Low to moderate	
11	Crosses projected faulted Franciscan/Merced contact	Low to moderate	Heavy-wall/ductile pipe (0.5 inch)
12	May cross landslide deposit	Low	Standard design
13	Parallel to subsidiary fault; within 1906 zone of ground distortion	Low	Standard design
14	Crosses faulted Franciscan/Merced contact	Low to moderate	Heavy-wall/ductile pipe (0.5 inch)
15	Crosses artificial fill placed on steep slope	Low to moderate	Install on south side of San Bruno Avenue
16	Within the 1906 zone of ground distortion; close to San Andreas fault traces	Low to moderate	Heavy-wall/ductile pipe (0.5 inch) and long-radius elbows from San Bruno Avenue and Skyline Drive to the new valve lot

Locality 11: We will use approximately 300 feet of special heavy-wall/ductile pipe (0.5-inch wall thickness) at this locality.

Locality 14: We will use approximately 300 feet of special heavy-wall/ductile pipe (0.5-inch wall thickness) at this locality.

Locality 15: We will install this segment of pipe for Line 109 on the south side of San Bruno Avenue to avoid the steep slope.

Locality 16: We will use approximately 3000 feet of special heavy-wall/ductile pipe (0.5-inch wall thickness) for the new segment of Line 132 from the intersection of San Bruno Avenue and Skyline Drive, down Skyline Drive, all the way to the new valve station. Long-radius elbows will be used at the bend locations.

5 - REFERENCES

Bonilla, M. G., 1964, Bedrock-surface map of the San Francisco South Quadrangle, California: U. S. Geological Survey Miscellaneous Field Studies Map MF-334, scale 1:31,680.

Bonilla, M. G., 1959, Geologic observations in the epicentral area of the San Francisco earthquake of March 22, 1957; *in* San Francisco Earthquakes of March 1957: California Division of Mines Special Report 57, p. 25-38.

Bonilla, M. G., 1971, Preliminary geologic map of the San Francisco South and part of the Hunters Point quadrangles: U. S. Geological Survey Miscellaneous Field Studies Map MF-311, scale 1:24,000.

Brabb, E. E. and Olson, J. A., 1986, Map showing faults and earthquake epicenters in San Mateo County, California: U. S. Geological Survey Miscellaneous Investigation Series Map I-1257-F, scale 1:62,500.

Brabb, E. E. and Pampeyan, E. H., 1972a, Preliminary geologic map of San Mateo County, California: U. S. Geological Survey Miscellaneous Field Studies Map MF-328, scale 1:62,5000.

Brabb, E. E. and Pampeyan, E. H., 1972b, Preliminary map of landslide deposits in San Mateo County, California: U. S. Geological Survey Miscellaneous Field Studies Map MF-344, scale 1:62,500.

Brabb, E. E., and Pampeyan, E. H., 1983, Geologic map of San Mateo County, California: U. S. Geological Survey Miscellaneous Investigation Series Map I-1257-A, scale 1:62,500.

Brabb, E. E., Pampeyan, E. H., and Bonilla, M. G., 1972, Landslide susceptibility in San Mateo County, California: U. S. Geological Miscellaneous Field Studies Map MF-360, scale 1:62,500.

Brown, R. D., 1972, Active faults, probable active faults and associated fracture zones, San Mateo County, California: U. S. Geological Survey Miscellaneous Field Studies Map MF-355, scale 1:62,500.

Clifton, E. H., and Hunter, R. E., 1991, Depositional and other features of the Merced Formation in sea cliff exposures south of San Francisco, California; *in* Sloan, D., and Wagner, D. L., eds., Geologic excursions in northern California--San Francisco to the Sierra Nevada: California Division of Mines and Geology Special Bulletin 109, p. 35-44.

Cox, A., and Engebretson, D., 1985, Change in motion of Pacific plate at 5 MBP: Nature, v. 313, p. 472-474.

DeMets, C., Gordon, R. C., Stein, S., and Argus, D. F., 1987, A revised estimate of Pacific-North America motion and implications for western North America plate boundary zone tectonics: Geophysical Research Letters, v. 14, no. 9, p. 911-914.

Hall, N. T., 1984, Holocene history of the San Andreas fault between Crystal Springs Reservoir and San Andreas Dam, San Mateo County, California: Seismological Society of America Bulletin, v. 74, p. 281-299.

Harbert, W., 1991, Late Neogene relative motions of the Pacific and North American plates: Tectonics, v. 10, p. 1-16.

Harbert, W., and Cox, A., 1989, Late Neogene motion of the Pacific plate: Journal of Geophysical Research, v. 94, no. B3, p. 3052-3064.

Lajoie, K. R., Helley, E. J., Nichols, D. R., and Burke, D. B., 1974, Geologic map of unconsolidated and moderately consolidated deposits of San Mateo County, California: U. S. Geological Survey Miscellaneous Field Studies Map MF-575, scale 1:62,500.

Lawson, A. C., 1908, The California earthquake of April 18, 1906; report of the State Earthquake Investigation Commission [reprinted 1969]: Carnegie Institution of Washington, Publication 87, two volumes, atlas.

Lisowski, M., Savage, J. C., and Prescott, W. H., 1991, The velocity field along the San Andreas fault in central and southern California: Journal of Geophysical Research, v. 96, no. B5, p. 8369-8389.

Niemi, T. M., and Hall, N. T., 1992, Late Holocene slip rate and recurrence of great earthquakes on the San Andreas fault in northern California: Geology, v. 20, no. 3, p. 195-198.

Pampeyan, E. H., 1975, Geologic map of the San Andreas fault zone in San Andreas Lake, San Mateo County, California: U. S. Geological Survey Miscellaneous Field Studies Map MF-652, scale 1:6,000.

Pampeyan, E. H., 1983, Map showing the 1906 San Andreas fault trace and related features in the Montara Mountain and San Mateo 7 1/2-minute quadrangles, San Mateo County, California: U. S. Geological Survey Miscellaneous Field Studies Map MF-1488, scale 1:24,000.

Pampeyan, E. H., 1981, Geologic map of the Montara Mountain Quadrangle, San Mateo County, California: U. S. Geological Survey Open-File Report 81-451, scale 1:12,000.

Smith, T. C., 1981, Fault evaluation report, Serra fault, San Francisco: California Division of Mines and Geology, unpublished report FER-119, 9 p.

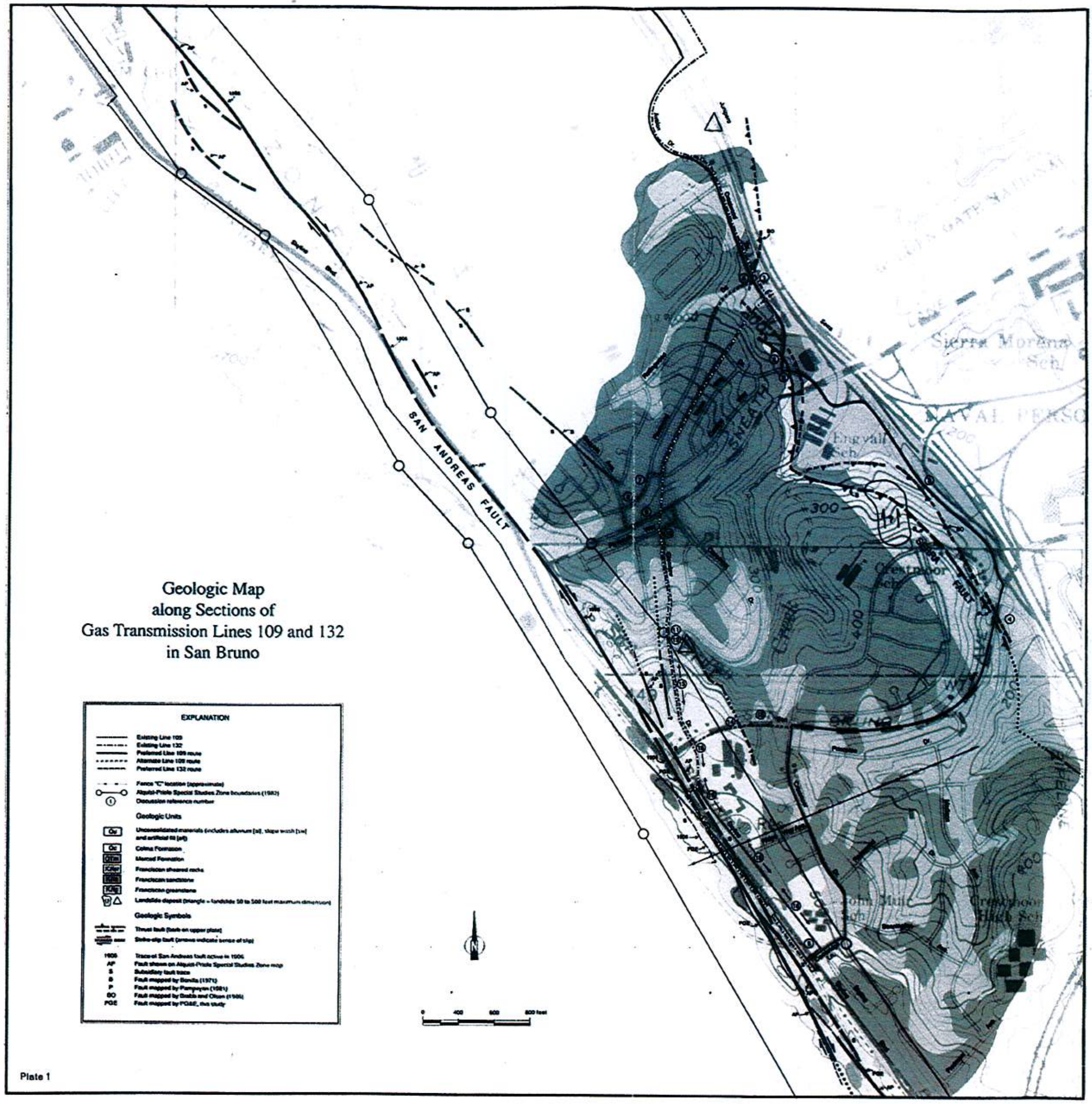
Wahrhaftig, C., and Sloan, 1989, Geology of San Francisco and vicinity: Twenty-eighth International Geology Congress, Field Trip Guidebook T105, San Francisco Bay Region, California, American Geophysical Union, Washington, D.C.

Ward, S. N., 1990, Pacific-North America plate motion; new results from very long baseline interferometry: Journal of Geophysical Research, v. 95, no. B13, p. 21,965-21,981.

Wieczorek, G. F., Wilson, R. C., and Harp, E. L., 1985, Map showing slope stability during earthquakes in the San Mateo County, California: U. S. Geological Survey Miscellaneous Investigation Series Map I-1257-E, scale 1:62,500.

Working Group on California Earthquake Probabilities, 1988, Probabilities of large earthquakes occurring in California on the San Andreas fault: U. S. Geological Survey Open-file Report 88-398, 84 p.

Working Group on California Earthquake Probabilities, 1990, Probabilities of large earthquakes in the San Francisco Bay region, California: U. S. Geological Survey Circular 1053, 51 p.



Geologic Map
along Sections of
Gas Transmission Lines 109 and 132
in San Bruno

Plate 1