EARTHQUAKE PERFORMANCE OF GAS TRANSMISSION PIPELINES

by

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ABSTRACT

Over 61 years of earthquake performance of steel transmission pipelines operated by the Southern California Gas Company are reviewed The seismic record includes 11 major earthquakes with $M_L \geq 5\ 8$ and epicenters within the transmission system An evaluation is made of the most vulnerable types of piping, failure mechanisms, break statistics, threshold seismic intensity to cause failure, and damage induced by permanent ground displacement The database assembled represents one of the most comprehensive and detailed records of seismic response in a large, complex gas transmission system

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INTRODUCTION

Table I summarizes information about 11 of the most severe earthquakes which have occurred in southern California The table provides data on the earthquake magnitude and maximum intensity, epicentral location, portion of pipeline network subjected to strongest shaking, and general observations about gas transmission and supply line response The 1940 Imperial Valley earthquake is not included in the table because this area was not serviced with natural gas pipelines at the time of the earthquake

No damage or disruption of transmission and supply lines was experienced in six of the earthquakes In some of these cases, the earthquake epicenter and location of surface faulting were relatively close to transmission pipelines For example, the epicenter of the 1986 North Palm Springs earthquake was approximately 5 km (3 mi.) from Lines 2000, 2001, and 5000, which are post-WWII lines of 750 to 900 mm (30 to 36 in) diameter In addition, surface faulting caused by the 1992 Landers earthquake has been traced to within tens of meters of a 150-mm- (6-in)-diameter line conveying gas to Yucca Valley and Joshua Tree and a similar distance from Line 4000, a post-WWII 900-mm- (36-in)-diameter pipeline

Four earthquakes resulted in significant damage to the gas pipeline system They are the 1933 Long Beach, 1952 and 1954 Kern County, 1971 San Fernando, and 1994 Northridge earthquakes Although the 1979 Imperial Valley earthquake did not damage any gas transmission lines, three lines were crossed by surface ruptures along the Imperial fault and excavated for observation and stress relief Case histories of the four earthquakes, which caused the most extensive damage, and associated pipeline response are provided in the next several sections

This paper draws on previous work of O'Rourke and Palmer [1994a, b], and reference should be made to these publications for additional information Transmission and distribution pipelines are defined in accordance with the Federal Code of Regulations [Office of the Federal Register, 1990] and General Order No 112-D pertaining to the State of California [Public Utilities Commission (PUC) of the State of California, 1988] In essence, a transmission line transports gas from a gathering line or storage facility to a distribution center or storage facility, and operates at a hoop stress of 20% or more of the specified minimum yield stress (SMYS) of the pipe steel The Southern California Gas Company (SoCalGas) identifies an additional category of pipeline, referred to as distribution supply line, which is predominantly 50 to 300 mm (2 to 12 in) in diameter and is operated typically in the range from 0 7 to 2 8 MPa (100 to 400 psi)

1933 LONG BEACH EARTHQUAKE

Figure 1 shows the locations of main line breaks of water, gas, and oil lines caused by the 1933 Long Beach earthquake as plotted by Hoff [1934] and superimposed on a map of liquefaction susceptibility prepared by Tinsley, et al [1985] Shaded areas are those Tinsley, et al designate as having "very high" and "high" susceptibility to liquefaction on the basis of geologic age, type of sedimentary

TABLE I Summary of Major Earthquakes in the Area of the Southern California Gas System

Earthquake	Magnitude[1]/ Intensity[2]	Location of Epicenter	Area Most Severely Affected	Gas Pipeline Performance	Selected References
1933 Long Beach	M_L = 6 3 MM VIII - IX	5 6 km (3 5 mi) southwest of Newport Beach	Long Beach, Compton, and shore areas from Manhattan to Laguna Beach	Extensive damage to pipelines of Long Beach Municipal Gas Department, particularly areas of liquefaction	Wood [1933] Bryant [1934] Hoff [1934]
1952, 1954 Kern County	M_S = 7 7 MM VIII - X	40 km (25 mi) south of Bakersfield near Wheeler Ridge	Area of approximately 10,000 km (4000 mi ^{2}) south of Bakersfield	Damage to several transmission lines within 10 to 25 km (6 to 16 mi) of Wheeler Ridge	Newby [1954] Steinbrugge and Moran [1954]
1971 San Fernando	M_L = 6 4 MM VIII - X	13 km (8 mi) northeast of San Fernando	Area of approximately 520 km^2 (204 mi^2) around San Fernando	Serious damage to transmission and supply lines and disruption of service in San Fernando and Sylmar	Southern California Gas Co. [1973] O'Rourke, et al [1992]
1979 Imperial Valley	M_S = 6 6 MM VI - VII	3 km (1 9 mi) south of U S -Mexico border and 10 km (6 2 mi) from Mexicali	Imperial Valley from Brawley to Calexico and Holtville	No damage to transmission lines, although three transmission lines were crossed by surface ruptures along the Imperial fault The lines were excavated for inspection and stress relief	Dobry, et al [1992] McNorgan [1989]
1986 North Palm Springs	M_L = 5 9 MM VII	16 km (10 mi) northwest of North Palm Springs	Area of approximately 250 km^2 (9 6 mi^2) centered on epicenter	No damage or disruption reported. Epicenter was 8 km (5 mi) from three 750- to 900-mm (30- to 36-in) transmission lines	EERI [1986]
1987 Whittier Narrows	M_L = 5 9 MM VIII	5 km (3 mi) east of Rosemead	Crescent-shape area of approximately 500 km^2 with MM VII - VIII centered on Monterey Park	No damage to transmission and supply lines	Schiff [1988]

TABLE I Summary of Major Earthquakes in the Area of the Southern California Gas System (completed)

Earthquake	Magnitude[1]/ Intensity[2]	Location of Epicenter	Area Most Severely Affected	Gas Pipeline Performance	Selected References
1991 Sierra Madre	$M_L = 5.8$ MM VII	20 km (12 mi.) northeast of Pasadena between Cogswell Reservoir and Mt. Wilson	Area including Pasadena, Sierra Madre, Monrovia, and Arcadia	No damage to transmission and supply lines	EERI [1991]
1992 Landers and 1992 Big Bear	$M_S = 7.5$ MM VIII - IX and $M_S = 6.5$ MM VII	Centered between Landers and Yucca Valley	Area including Landers, Joshua Tree, Yucca Valley, and Big Bear Lake	No damage to transmission lines, 900-mm (36-in.) and 150-mm (6-in.) transmission lines were located just north and south, respectively, of the main surface faulting	EERI [1992]
1994 Northridge	$M_S = 6.8$ MM VIII - IX	North central portion of San Fernando Valley	San Fernando Valley, Sylmar, Santa Monica, and Fillmore	Damage to transmission pipelines and widespread disruption of distribution system	O'Rourke and Palmer [1994a,b]

[1]Earthquake magnitudes are reported herein on the basis of published information in terms of local or surface wave magnitudes (M_L or M_S, respectively), with surface wave values given for magnitudes exceeding 6.5

[2]Maximum Modified Mercalli Intensity or range in intensities as reported or inferred from descriptions of damage

deposits, and groundwater depth. Youngest Holocene deposits of fluvial origin are most susceptible The areas with the greatest number of breaks were the mouth of the San Gabriel River (Naples and North Seal Beach) and the North Long Beach/Compton/Clearwater area About 85% of all plotted breaks fall within areas of high and very high liquefaction susceptibility

Pipeline damage caused by the 1933 Long Beach earthquake has been described by Bryant [1934] and Hoff [1934] There were more than 500 main line breaks of water, gas, and oil lines in the areas of maximum seismic intensity [Hoff, 1934] Within the City of Long Beach gas distribution system, there were a total of 119 main breaks, 91 of which were in the high pressure feeder mains [Bryant, 1934] Every failure discovered in the high pressure distribution system occurred at a welded joint, and more than 50 of the 91 breaks were in artificially-filled areas Forty-six breaks were discovered in the large diameter mains [460 to 510 mm (18 to 20 in)] that supplied the Harbor District of Long Beach, which was an area where artificial fills were predominant [Bryant, 1934] Repair crews reported that the original welds lacked proper penetration and proper bond with the pipe body [Bryant, 1934]

Line 765, which is shown in the figure, was constructed in 1931 It was 650 mm (26 in) in diameter, with 6 4 mm (0 25 in) wall thickness. It was composed of Grade A and B steel, and had a maximum allowable operating pressure (MAOP) of 1 0 MPa (150 psi) just before it was removed from service in 1992 The pipeline was constructed with electric arc welds The welding process differed from modern procedures for butt welded transmission pipe in that the weld was applied by unshielded electric arc techniques at opposing belled pipe ends, which were positioned on an underlying steel ring Although the pipeline was located in the region of maximum seismic intensity, including locations of known liquefaction adjacent to the Los Angeles River, there are no records of pipeline damage or repair to this line dating from the time of the 1933 earthquake

1952 AND 1954 KERN COUNTY EARTHQUAKES

Gas pipeline damage caused by the 1952 and 1954 Kern County earthquakes has been described by Newby [1954] and Lind [1954] As a result of this earthquake and a subsequent smaller Kern County earthquake in January, 1954, there were ten incidents of damage at welded transmission line joints and two incidents of leaks at locations of external pipeline corrosion Nine of the damaged welds were oxy-acetylene, and one was at an electric-welded band positioned at the location of an original oxy-acetylene weld Figure 2 shows the locations of the damage relative to the epicenters of the main shock and the January 12, 1954 earthquake, which had a local magnitude of 5 9 Newby [1954] described the damage with reference to the figure as follows

> "It developed that the 12-inch acetylene welded line installed in 1921 had broken welds at the three locations marked 1 on Figure No 1 (Figure 2) The ends of the pipe were from 1/2 to 2 inches apart at the different breaks The 12-inch line that had been reconditioned in 1932, and electric-welded using chill rings, failed at location marked 2 This weld evidently failed from compression and then from tension

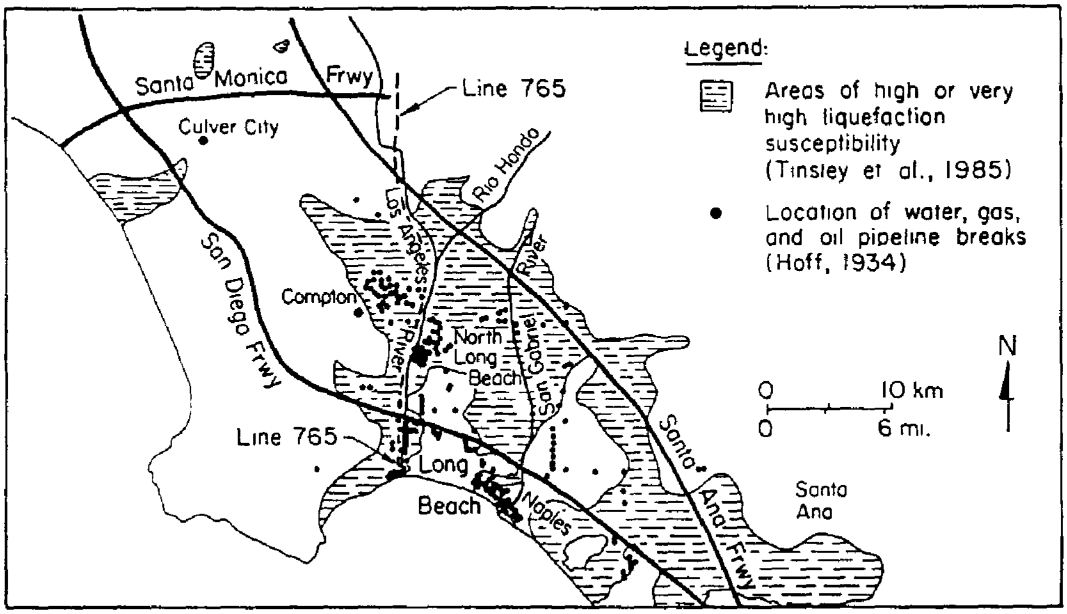

FIGURE 1. Pipeline Damage Caused by the 1933 Long Beach Earthquake [adapted from Hoff, 1934]

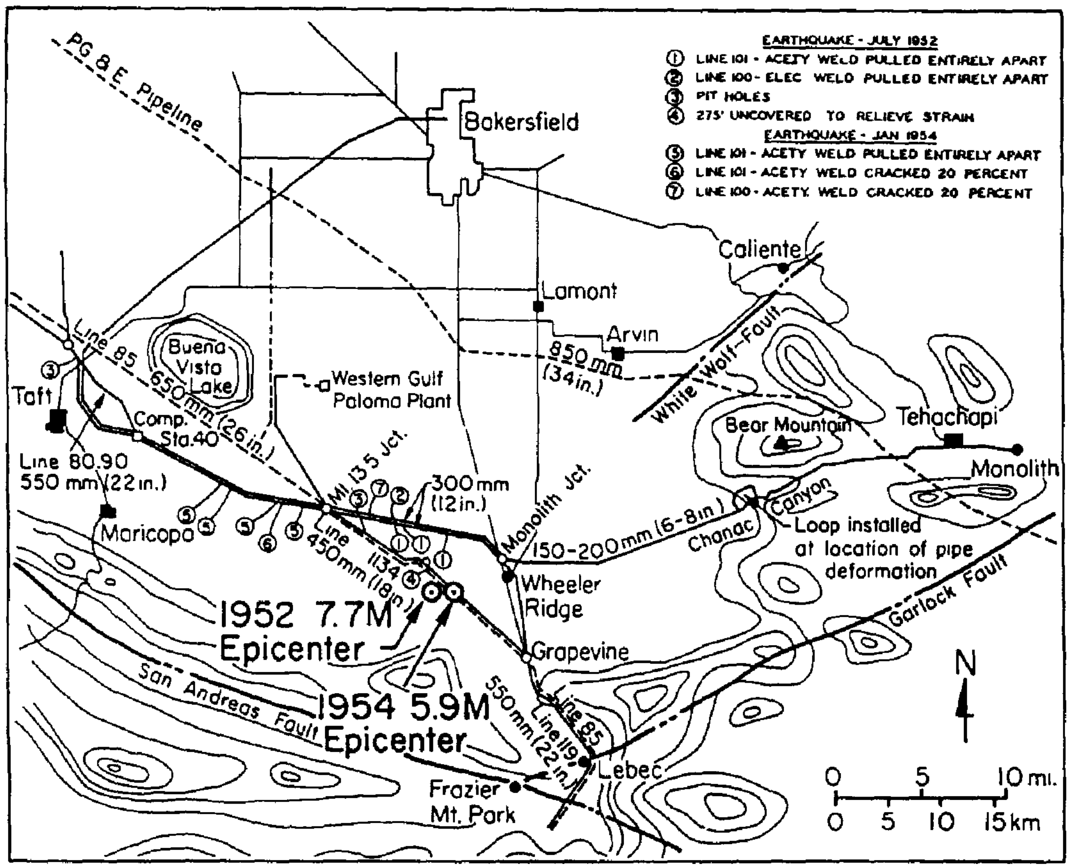

FIGURE 2. Gas Pipeline Damage Caused by the 1952 and 1954 Kern County Earthquakes [adapted from Newby, 1954]

Pit hole leaks popped out on a 22-inch line near Taft and on an 18-inch line at Wheeler Ridge, locations 3 (Figure 2) These leaks were from external corrosion Location 4 shows where 275 feet of 18-inch line was uncovered to relieve strain from the 1952 quake

We experienced another of our many quakes on January 12, 1954 that was not considered serious However, it evidently centered near our two 12-inch lines in the Maricopa Flat area

As shown on Figure 2, this quake parted the acetylene-welded line at four welds at locations marked 5, and cracked an acetylene weld 20% at location marked 6, and on the electric-welded line, a lone acetylene weld cracked 20% at location 7 "

Newby also reported that the 150-mm- (6-in)-diameter line providing gas to Tehachapi was deformed upward from the ground at two locations along a steep hillside where ground ruptures were observed The line was intact The line had been installed in 1926 with oxy-acetylene welds A supplemental pipeline (referred to as a loop in Figure 2) was installed to provide a parallel emergency path The original was kept in service without any repairs

1971 SAN FERNANDO EARTHQUAKE

Gas transmission and supply line damage as a result of the San Fernando earthquake has been described by the Southern California Gas Company [1973] and O'Rourke, et al [1992] Figure 3 shows a map adapted from the Southern California Gas Company [1973] on which are plotted the gas transmission and supply lines most significantly affected by the earthquake, locations of damage between San Fernando and just north of Clampitt Junction, and the approximate zones of permanent ground deformation associated with liquefaction adjacent to the Upper Van Norman Reservoir, as well as surface faulting along the Sylmar and Mission Wells segments of the San Fernando fault

Substantial damage was sustained by Lines 1001 and 115 Line 1001 was a 300-mm-(12-in)-diameter steel pipeline, constructed in 1925 with oxy-acetylene welds and operated at MAOP of 2 4 MPa (345 psi) Because of numerous breaks, predominantly at welds, approximately 9 3 km (5 8 mi) of the line were abandoned Line 115 was a 400-mm- (16-in)-diameter steel pipeline of unknown grade, constructed in 1926 with oxy-acetylene welds In the approximate 9 7-km- (6-mi)-length of pipeline between Clampitt Junction and San Fernando, there were 52 breaks Shell buckling of the pipeline occurred in the vicinity of its crossing of the Sylmar segment of the San Fernando fault [Southern California Gas Company, 1973]

Line 85 was a 650-mm- (26-in)-diameter pipeline, with Grade A steel pipe wall 6 4 mm (0 25 in) thick, operated at MAOP of 1 7 MPa (250 psi) In Figure 3, the location marking the division between the electric arc and oxy-acetylene welded segments of Line 85 is shown North of the division, the line was constructed originally with oxy-acetylene welds In 1932, roughly 30% of the oxy-acetylene welds in this section were reconditioned with electric arc welded reinforcements South of the division,

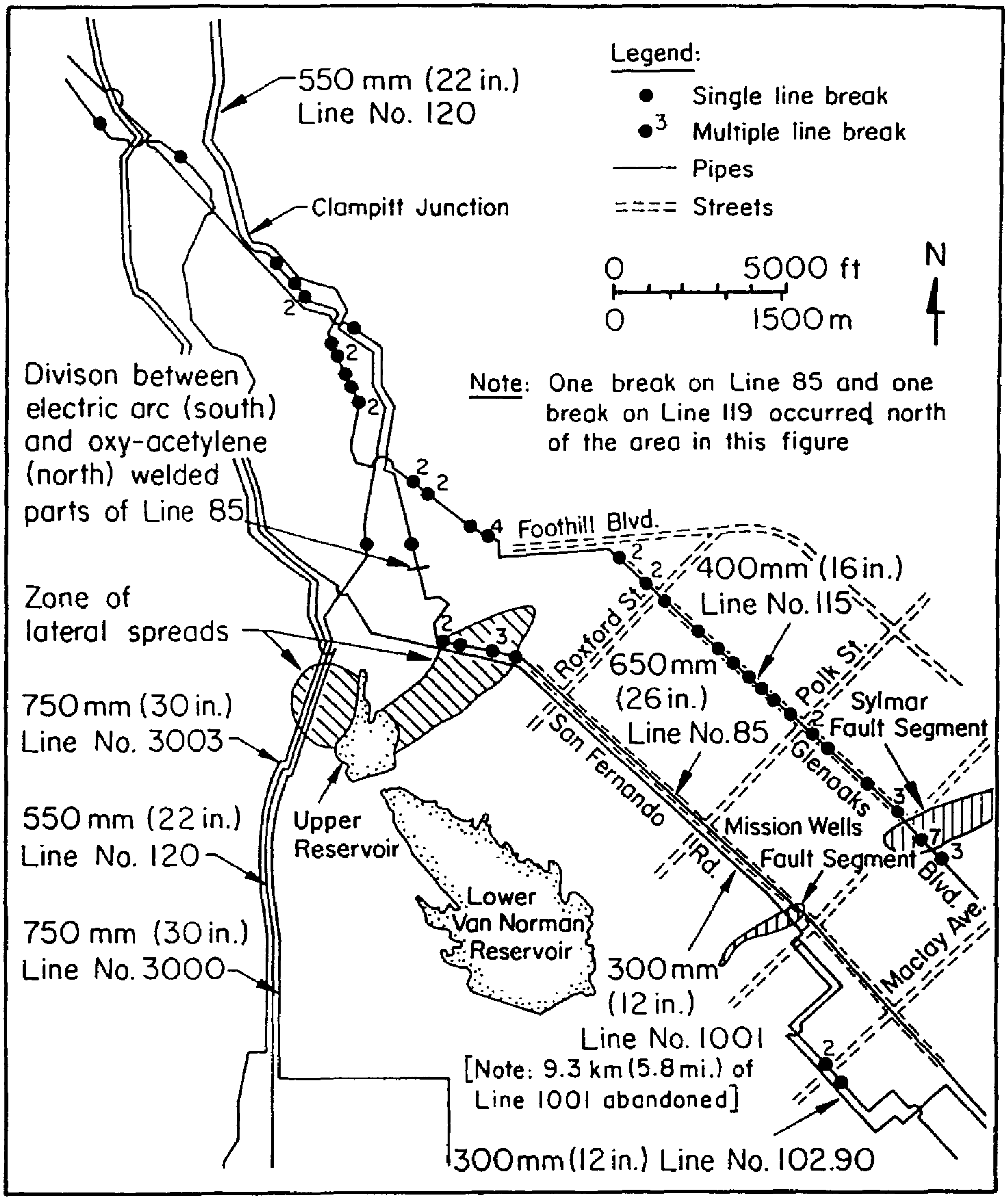

FIGURE 3. Locations of Gas Pipeline Damage, Lateral Spreads, and Fault Segments Associated with the 1971 San Fernando Earthquake [adapted from Southern California Gas Company, 1973]

the line was constructed with unshielded electric arc welded belled pipe in a manner similar to that for Line 765, which was affected by the 1933 Long Beach earthquake.

The electric arc welded portion of Line 85 was damaged at seven locations within the zone of lateral spread along the east side of the Upper Van Norman Reservoir. The partially reconditioned oxy-acetylene welded portion of the line was damaged at three locations north of the division, of which only two are shown in the figure.

The utility corridor on the western side of the Upper Van Norman Reservoir was subjected to as much as 3 m (9 ft) of lateral deformation caused by liquefaction, soil movements were distributed primarily across a 400- to 500-m- (1,300- to 1,640-ft)-length of the corridor Pipelines at this location were of modern construction One 560-mm- (22-in)-diameter (Line 120) and two 760-mm- (30-in)-diameter (Lines 3000 and 3003) gas pipelines, each constructed in 1966 of X-52 steel, were not damaged

Figure 4 shows the locations of damage to Lines 115, 1001, 85, and 102 90 in the San Fernando area at an expanded scale Damage locations were determined from repair records summarized by Southern California Gas personnel [Johnson, 1982] The preponderant form of damage was rupture or leakage at oxy-acetylene welds Also shown on the map are locations of ground failures and surface soil cracks as mapped by the U S Geological Survey and the California Division of Mines and Geology [U S Geological Survey Staff, 1971, Steinbrugge, et al , 1971]

Near the Sylmar segment of the San Fernando fault, there were approximately three compression and ten tensile ruptures of Line 115 One break occurred in Line 1001 at its crossing of the Mission Wells segment of the San Fernando fault, and three breaks were reported in this line in the vicinity of the Juvenile Hall lateral spread on San Fernando Road With the exception of Line 85 damage at the lateral spread, all other breaks in Figure 4 do not appear to be associated with permanent ground movement

1994 NORTHRIDGE EARTHQUAKE

There were 35 non-corrosion related repairs in the transmission system, of which 27 were at cracked or ruptured oxy-acetylene girth welds in pre-1932 pipelines Figure 5 shows a plan view of selected transmission pipelines in the area of most severe ground shaking Locations of damage in the form of pipeline breaks and leaking flanges are shown in the figure

Figure 6 is a map of the area just north of the earthquake epicenter, showing the Aliso Canyon Gas Storage Field and the locations of two gas transmission line breaks on Balboa Blvd The Aliso Canyon facility, which covers some 14 7 km^2 (3,600 acres) and 56 km (35 mi) of access road, is used to store gas in an underground reservoir that once was used for oil production Gas is injected during low demand summer months and withdrawn during high demand winter months Earthquake effects in the facility included deformation of aboveground pipe supports, displacements of runs of injection and withdrawal lines, and structural damage to a fin fan unit used to cool compressed gas before its injection in storage wells The supply of gas from Aliso Canyon was interrupted for five days

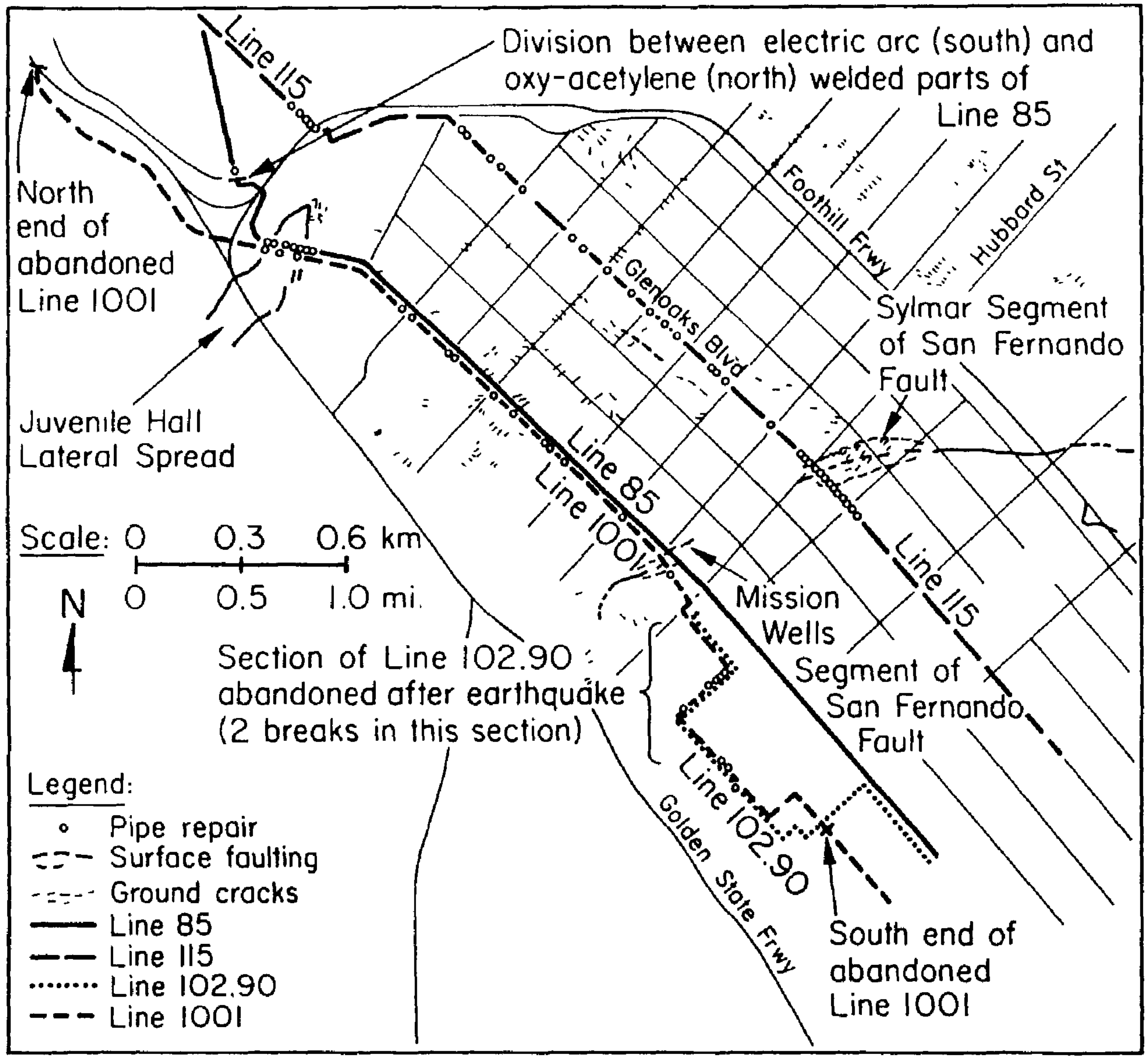

FIGURE 4. Locations of Damage to Lines 115, 1001, 85, and 102.90 in the San Fernando Area as a Result of the 1971 Earthquake

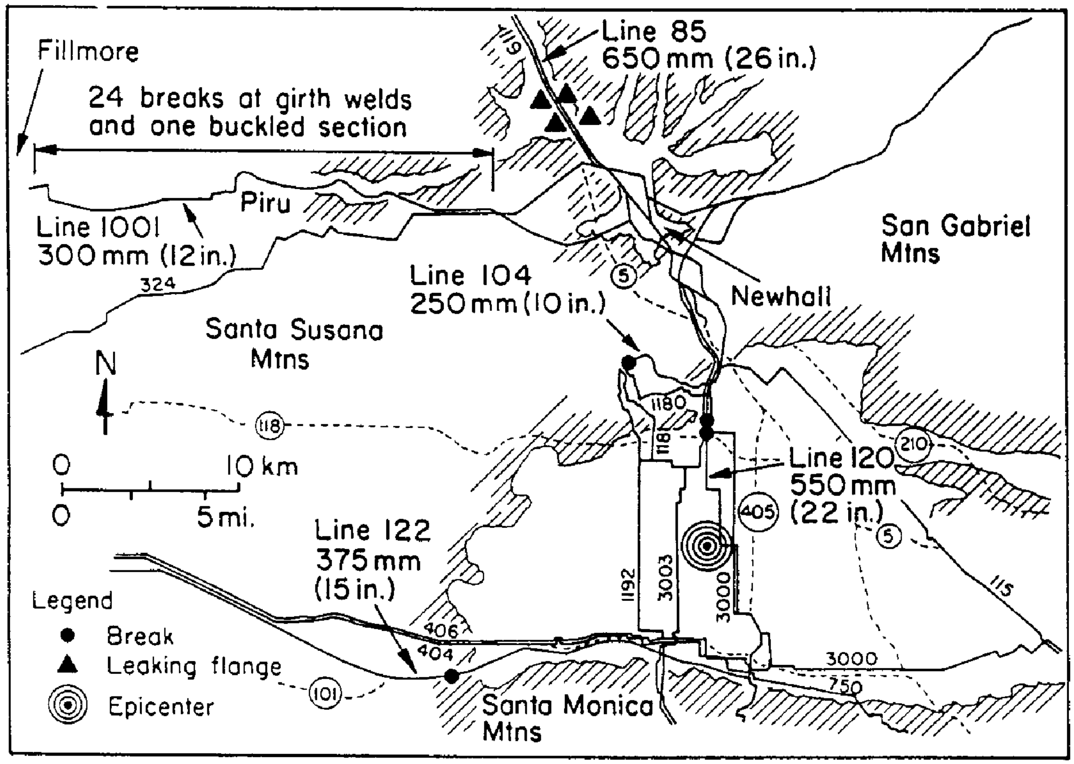

FIGURE 5. Map of Gas Transmission Pipelines in the Area of Strong Ground Shaking

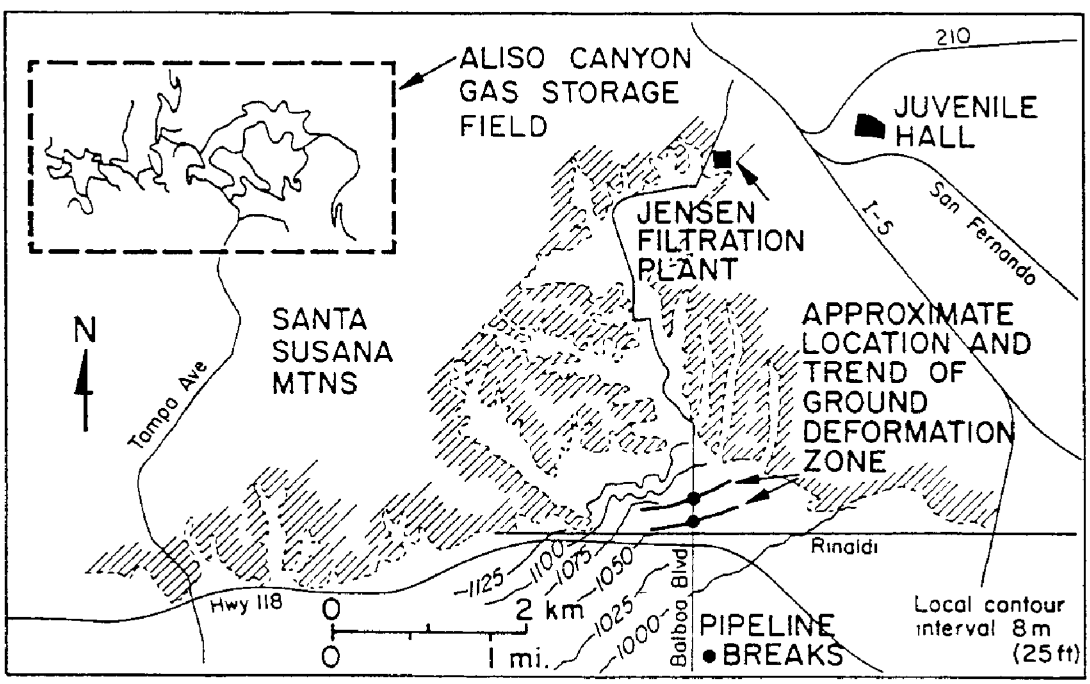

FIGURE 6. Map of the Area North of the Northridge Earthquake Epicenter

As shown in Figure 5, there were 24 breaks at oxy-acetylene girth welds and one location of buckled pipe in Line 1001, which conveys gas between Newhall and Fillmore, many of which were in Potrero Canyon Line 1001 was constructed in 1925, and was operated at the time of the earthquake at 1.7 MPa (245 psi) internal pressure The pipeline is 300 mm (12 in) in diameter, with 5 6-mm- (0 22-in)-thick wall of unknown grade steel

Of the 25 repairs in Line 1001, 18 were in Potrero Canyon Six breaks in oxy-acetylene welds were located in areas adjacent to the Santa Clara River east of Piru and west of Potrero Canyon One oxy-acetylene weld ruptured at the eastern city limits of Fillmore, leaving a crater approximately 2 7 m (9 ft) deep and 4 5 m (15 ft) by 6 m (20 ft) in area. Gas escaping at the location of this break under Highway 126 was ignited by a downed power line

Significant permanent ground deformation was reported in Potrero Canyon [Stewart, et al , 1994] The canyon is filled with alluvial and colluvial deposits to a maximum depth of 80 m (260 ft) Sand boils were observed at several locations along the canyon, and prominent ground ruptures were plotted [Stewart, et al , 1994] Along the southern margin of the canyon, ground cracks were both compressional and extensional, with minor left lateral offsets Multiple ground fractures within zones 2 to 18 m (5 to 50 ft) wide accommodated as much as 600 mm (2 ft) of vertical movement Preliminary evaluation of repairs to Line 1001 in the canyon suggest that about one half to two-thirds of the pipeline ruptures coincide with locations of mapped ground cracks Other locations of pipe damage appear to have occurred in areas lacking significant differential ground displacement A nearby strong motion station on soil recorded a peak horizontal ground acceleration of 0 46 g [Stewart, et al , 1994]

Flange leaks occurred at the four locations shown in Figure 5 at sections of aboveground piping There was also a break in an oxy-acetylene weld in Line 85 at a location approximately 39 km (24 mi) northwest of Newhall, which is not shown in the figure Damage was mainly in the form of flange separation and leaking gaskets One of the flanges was fractured At the damaged locations, Line 85 is a 650-mm- (26-in)-diameter pipeline with a pipe wall 6 4 mm (0 25 in) thick, of Grade A steel, operated at MAOP of 2 2 MPa (317 psi) The ruptured oxy-acetylene weld and four leaking flanges occurred in a partially reconditioned portion of Line 85 The weld failure was at an original oxy-acetylene weld

There was a break at a weld in Line 85 near Taft, approximately 120 km (75 mi) north of the epicenter This section of the pipeline was constructed in 1931 with electric arc welds The line had an MAOP of 2 5 MPa (360 psi) There was a leaking flange at an aboveground section of Line 119 north of the area shown in Figure 4 This section of the 550-mm- (22-in)-diameter pipeline was constructed in 1931 with a wall thickness of 7 9 mm (0 312 in). There is no clear record of weld type The SMYS of the steel and MAOP were 208 MPa (30,000 psi) and 2 5 MPa (360 psi), respectively

A fractured oxy-acetylene girth weld was repaired in Line 122 at the location shown in Figure 5 Although this pipeline is not operated as a transmission line, it nevertheless is described in this paper because of its relatively high operating pressure of 1 MPa (150 psi) The pipeline was installed in 1927 with oxy-acetylene girth welds, 6 4-mm- (0 25-in)-thick wall, and steel of unknown grade

As shown in Figure 5, there was a break in Line 104 inside the Aliso Canyon Gas Storage Field The pipeline is 250 mm (10 in.) in diameter and has an MAOP of 1 6 MPa (228 psi), but it is operated at 1 4 MPa (200 psi) It was constructed with electric arc girth welds in 1941 The pipe has a 5 2-mm- (0 203-in)-thick wall of unknown grade steel

Gas pipeline damage on Balboa Blvd occurred in Line 120, a 550-mm- (22-in)-diameter steel pipeline constructed in 1930 with unshielded electric arc girth welds At the time of the earthquake, the line was operated at about 1 2 MPa (175 psi) The pipe had a wall thickness of 7 2 mm (0 281 in) and was composed of Grade B steel The pipeline failed in tension in a zone of tensile ground deformation about 300 m (900 ft) north of a zone of compressive ground deformation where the pipe failed by compressive wrinkling As shown in Figure 6, the ground rupture zones occurred in the toe area of an alluvial fan and are oriented subparallel to the surface elevation contour lines The pattern of ground deformation suggests that lateral spreading of the alluvial fan sediments took place Nearby boreholes show loose silty sands at depths of 9 to 12 m (30 to 40 ft), although water levels are indicated at considerably greater depths in dense materials

Line 120 had been scheduled for replacement in the Granada Hills area A new 600-mm- (24-in)-diameter pipeline, with electric arc girth welds, X-60 steel, and 6 4-mm- (0 25-in)-thick wall, had been constructed parallel to the older 550-mm- (22-in)-diameter line along McLennan Ave It had not been opened for gas flow at the time of the earthquake Even though it crossed similar zones of tensile and compressive ground deformation, it was not damaged

Figures 7 and 8 show maps of the pipelines in Balboa Blvd near the zones of permanent ground deformation In addition to numerous distribution mains, there were six transmission and water trunk lines at this site There were two 750-mm- (30-in)-diameter gas transmission lines constructed of X-52 steel in the 1950s which were not damaged There was a 400-mm- (16-in)-diameter petroleum pipeline, operated by the Mobil Oil Corporation, which was not damaged The pipeline was composed of X-52 steel and installed in 1991 Two water trunk lines, the 1,240-mm- (49-in)-diameter Granada and the 1,730-mm- (68-in)-diameter Rinaldi Trunk Lines, failed in tension and compression in the tensile and compressive zones of ground deformation, respectively

Gas escaping from Line 120 was ignited by sparks from the ignition system of a pickup truck that had stalled in the area of tensile ground deformation flooded by the ruptured trunk lines The gas fire spread to adjacent properties, destroying five houses and partially damaging an additional structure

A 150-mm- (6-in)-diameter gas distribution pipeline along the eastern side of Balboa Blvd was ruptured in tension and compression in the tensile and compressive ground deformation zones, respectively This pipeline was operated at a pressure of approximately 0 3 MPa (45 psi) Gas escaping from the tensile rupture caught fire

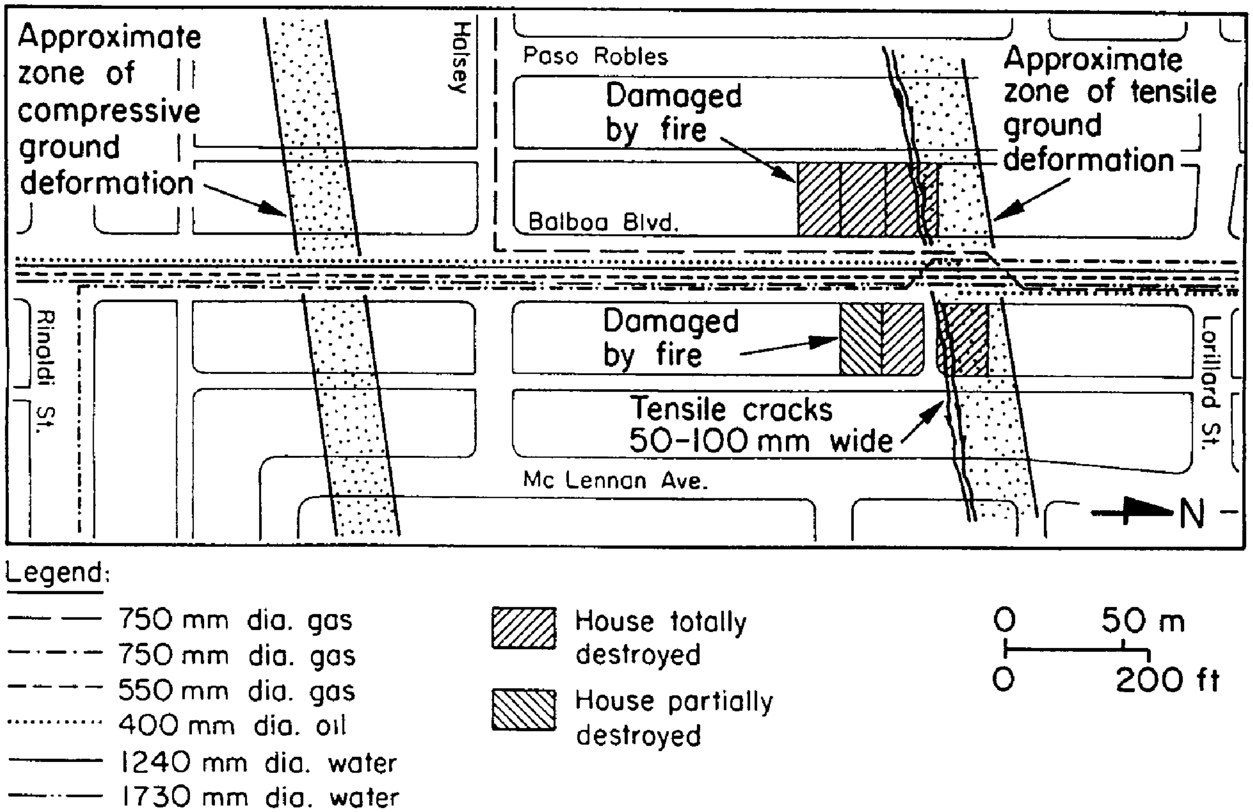

FIGURE 7. Map of Major Pipelines, Fire Damage, and Ground Deformation on Balboa Boulevard

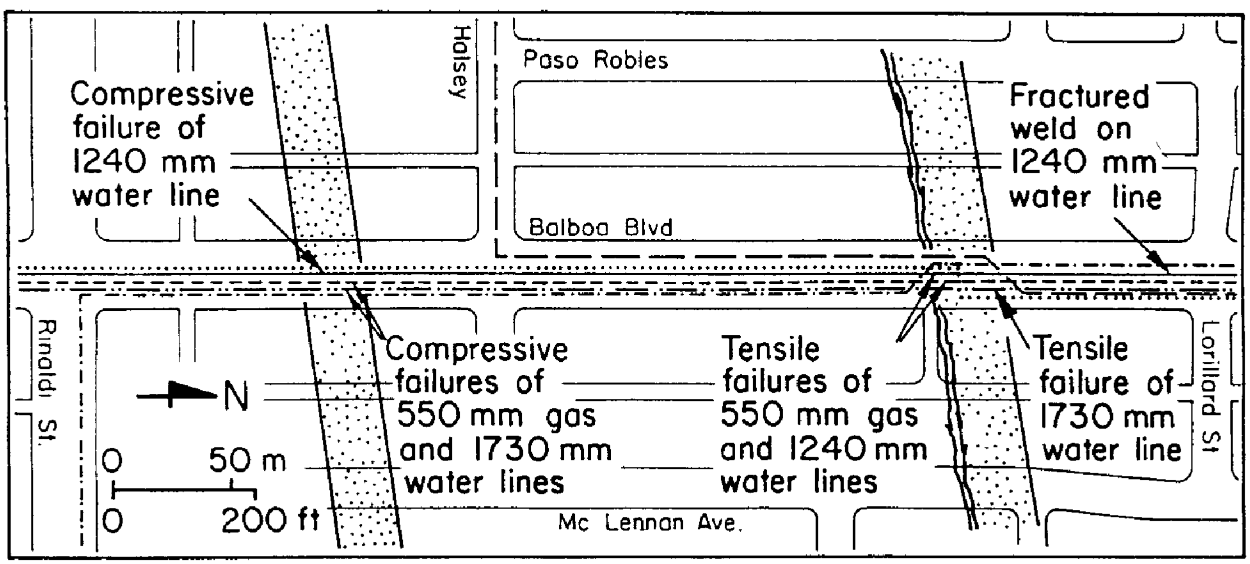

FIGURE 8. Map of Major Pipelines, Ground Deformation Zones, and Locations of Pipeline Damage on Balboa Boulevard

PIPELINE PERFORMANCE STATISTICS

Table II provides a summary of pre-WWII transmission and supply line response in areas where no permanent ground deformation was recorded during the 1933 Long Beach, 1952 and 1954 Kern County, 1971 San Fernando, and 1994 Northridge earthquakes Failures in Lines 1001 and 85 at the Mission Wells segment of the San Fernando fault and the Juvenile Hall lateral spread are not included in the data set Moreover, failures in Line 115 at the Sylmar segment of the San Fernando fault are included in the data set As discussed in the previous section, significant permanent ground deformation was recorded in Potrero Canyon after the 1994 Northridge earthquake The 18 repairs on Line 1001 in Potrero Canyon have been excluded from the table, and only the repairs and distance of pipeline from Fillmore to the Santa Clara River are listed

The information is organized according to pipeline installation date, starting with the oldest lines Damage rates, expressed as repairs per km and mi , were evaluated by dividing the line repairs by the total distance of a given line within the area of highest seismic intensity The review of gas transmission and supply pipeline performance for 11 southern California earthquakes presented in this section shows that pipelines have ruptured predominantly in areas affected by MM VIII or larger Hence, MM VIII or larger was used to establish the approximate limits of most intense shaking The preponderance of damage to pre-WWII pipelines occurred as ruptures at oxy-acetylene welds Damage not associated with pipeline rupture, in the form of leaks at corrosion pits, is not listed in the table

The information in the table can be used to point out some interesting trends, as illustrated in Figure 9 In this figure, the repair rates for the 1952 and 1954 Kern County and 1971 San Fernando earthquakes are plotted according to age of installation Both earthquakes show similar trends, in that the damage rate for pipelines constructed before 1930 are approximately an order of magnitude higher than those constructed during or after 1930

A review of the repair records, and discussions with welders, who repaired lines after the 1971 San Fernando and 1994 Northridge earthquakes, indicate that the damage listed in Table II was predominantly at oxy-acetylene welds This observation does not mean that oxy-acetylene welds are intrinsically weak On the contrary, the metallurgical quality of an oxy-acetylene weld is not significantly different from that of an electric arc weld, provided the work is performed by qualified welders according to proven procedures Well-made oxy-acetylene and electric arc welds are about equal in strength, although the heat-affected zone adjacent to an oxy-acetylene weld is somewhat larger and the joint ductility somewhat less than those associated with an electric arc weld The reason for the higher incidence of weld damage is associated with poor weld quality As described by O'Rourke and McCaffrey [1984], repair personnel reported that many of the welds on Line 115 had characteristics such as poor root penetration, undercutting and overlapping at the toe, and lack of good fusion between the pipe and the weld These types of features result in a flawed weld, and are not representative of the welds achieved under the quality control standards currently in effect

TABLE II. Summary of Pre-WWII Transmission and Supply Line Damage in Areas with No Reported Permanent Ground Deformation

Installation Date	Line No.	Nominal Diameter mm (in.)	Wall Thickness mm (in.)	SMYS[h] MPa (ksi)	Welds	Earthquake	Distance Affected[a] km (mi.)	No. of Repairs	Repairs/km (Repairs/mi.)
1913	100	300 (12)	6.4 (0.25)	unknown	partially reconditioned[b]	1952 and 1954 Kern County	50.4 (31.3)	2[c]	0.04 (0.06)
1920-21	102.90	300 (12)	6.4 (0.25)	unknown	oxy-acetylene	1971 San Fernando	2.9 (1.8)	3	1.03 (1.65)
1921	101	300 (12)	6.4 (0.25)	unknown	oxy-acetylene	1952 and 1954 Kern County	48.3 (30)	8[c]	0.17 (0.27)
1925	1001	300 (12)	5.6 (0.22)	unknown	oxy-acetylene	1971 San Fernando	19.3 (12)	25[d,f]	1.30 (2.08)[d,f]
1925	1001	300 (12)	5.6 (0.22)	172 (25)	oxy-acetylene	1994 Northridge	25.8 (16.0)[k]	7[k]	0.27 (0.44)
1926	115	400 (16)	7.9 (0.312)	unknown	oxy-acetylene	1971 San Fernando	24.5 (15.2)	39[d]	1.59 (2.56)[d,e]
1927	122	380 (15)	6.4 (0.25)	NR[c]	oxy-acetylene	1994 Northridge	19.3 (12.0)	1	0.05 (0.08)
1930	80.90	550 (22)	6.4 (0.25)	240 (35)	not recorded	1952 and 1954 Kern County	10.8 (6.7)	0	0
1930	120	550 (22)	7.9 (0.312)	240 (35)	electric arc[g]	1971 San Fernando	11.3 (7.0)	1	0.09 (0.14)
1930	119	550 (22)	7.9 (0.312)	208 (30)	electric arc[g]	1952 and 1954 Kern County	47.6 (29.5)	0	0
1930	119	550 (22)	7.9 (0.312)	207 (30)	electric arc[g]	1994 Northridge	3.2 (2.0)	0[l]	0[l]
1930	120	550 (22)	7.1 (0.281)	241 (35)	electric arc[g]	1994 Northridge	29.6 (18.4)	0	0
1930	121	650 (26)	6.4 (0.25)	241 (35)	oxy-acetylene	1994 Northridge	1.1 (0.7)	0	0
1931	85	650 (26)	6.4 to 7.9 (0.25 to 0.312)	228 (33)	electric arc[g]	1952 and 1954 Kern County	58 (36)	0	0
1931	85	650 (26)	6.4 to 7.9 (0.25 to 0.312)	228 (33)	partially reconditioned[b]	1952 and 1954 Kern County	36.7 (22.8)	0	0
1931	85	650 (26)	6.4 (0.25)	228 (33)	electric arc[g]	1971 San Fernando	8.7 (5.4)	0[f]	0[f]

TABLE II. Summary of Pre-WWII Transmission and Supply Line Damage in Areas with No Reported Permanent Ground Deformation (completed)

Installation Date	Line No	Nominal Diameter mm (in.)	Wall Thickness mm (in.)	SMYS[h] MPa (ksi)	Welds	Earthquake	Distance Affected[a] km (mi.)	No of Repairs	Repairs/km (Repairs/mi.)
1931	85	650 (26)	6.4 (0.25)	228 (33)	partially reconditioned[b]	1971 San Fernando	14.5 (9.0)	3	0.21 (0.33)
1931	85	650 (26)	6.4 (0.25)	228 (33)	partially reconditioned[b]	1994 Northridge	3.2 (2.0)	4[l,i]	1.56 (2.5)[l,i]
1931	85	650 (26)	6.4 (0.25)	228 (33)	electric arc[g]	1994 Northridge	NA[j]	NA[j,i]	NA[j,i]
1931	765	650 (26)	6.4 to 7.9 (0.25 to 0.312)	207 and 228 (30 and 33)	electric arc[g]	1933 Long Beach	16 (10)	0	0
1937	119	550 (22)	7.9 (0.312)	240 (35)	electric arc[g]	1971 San Fernando	6.5 (4.0)	1	0.15 (0.25)
1941	1134	450 to 500 (18 to 20)	6.4 (0.25)	240 (35)	electric arc	1952 and 1954 Kern County	24.3 (15.1)	0	0
1941	104	250 (10)	5.2 (0.203)	not reported	electric arc	1994 Northridge	3.7 (2.3)	0	0

[a]Based on area of greatest seismic intensity, MM VIII or greater
[b]Originally oxy-acetylene, many welds reinforced in 1932 with electric arc welds and electric arc welded bands and plates
[c]Cumulative breaks at welds for 1952 and 1954 earthquakes
[d]Pipe failures at fault crossing not included
[e]Break rate was locally as high as 6.04 breaks/km (9.72 breaks/mi.) on Glenoaks Blvd. between McClay and Foothill Blvd
[f]Pipe failures at location of lateral spread on San Fernando Rd. not included
[g]Unshielded electric arc using belled end pipe with underlying steel ring (NOTE: further studies of Line 119 constructed in 1930 are being conducted to establish weld characteristics)
[h]Specified Minimum Yield Stress
[i]One pipeline break recorded in area where MMI ≤ VII
[j]Not applicable because entire section of pipeline outside MMI ≥ VIII area
[k]Based on pipeline repairs and distance between Fillmore and Potrero Canyon
[l] Four leaking flanges in Line 85 and one leaking flange in Line 119 in area where MMI ≤ VII

TABLE III. Summary of Pre-WWII Transmission and Supply Line Damage in Areas with Permanent Ground Deformation

Installation Date	Line No	Nominal Diameter mm (in.)	Wall Thickness mm (in.)	SMYS[b] MPa (ksi)	Welds	Earthquake and Pipeline Response and Ground Deformation
1925	1001	300 (12)	5.6 (0.22)	unknown	oxy-acetylene	1971 San Fernando: 1 break at fault crossing; approx. 200 mm (8 in.) thrust and 30 mm (1.2 in.) lateral offset. Three breaks at lateral spread on San Fernando Rd.; approx. 2 m (6.5 ft) lateral displacement perpendicular to the line.
1925	1001	300 (12)	5.6 (0.22)	unknown	oxy-acetylene	1994 Northridge: 18 breaks in Potrero Canyon in area affected by dynamic consolidation of alluvial sediments, liquefaction, and compressive deformation at the toe of slopes along south side of canyon.
1926	115	400 (16)	6.4 (0.25)	unknown	oxy-acetylene	1971 San Fernando: Approx. 3 compression and 10 tension failures at fault crossing; 600 mm (24 in.) thrust and 1.9 m (6.2 ft) lateral offset
1930	120	550 (22)	7.9 (0.312)	240 (35)	electric arc	1994 Northridge: One compression and one tension failure at ground deformation on Balboa Blvd. in Granada Hills.
1931	85	650 (26)	6.4 (0.25)	228 (33)	electric arc[a]	1971 San Fernando: 7 breaks at lateral spread on San Fernando Rd.; displacement same as above.
1941	104	250 (10)	5.1 (0.203)	unknown	electric arc	1994 Northridge: One break consisting of buckle and split at weld at an overbend in Aliso Canyon Gas Storage Field.
1948	6000	200 (8)	7.1 (0.281)	240 (35)	electric arc	1979 Imperial Valley: No damage; approx. 400 mm (16 in.) of cumulative lateral movement at fault crossing.
1966	120	550 (22)	7.1 (0.281)	360 (52)	electric arc	1971 San Fernando: No damage; approx. 2 to 3 m (6 to 10 ft) of ground movement at lateral spread along utility corridor on west side of Upper Van Norman Reservoir.
1966	3000	750 (30)	9.5 (0.375)	360 (52)	electric arc	1971 San Fernando: Same.
1966	3003	750 (30)	9.5 (0.375)	360 (52)	electric arc	1971 San Fernando: Same
1966	6001	250 (10)	4.8 (0.188)	290 (42)	electric arc	1979 Imperial Valley: No damage; approx. 315 mm (12.4 in.) of cumulative lateral movement at fault crossing.

[a] Unshielded electric arc using belled end pipe with underlying steel ring; [b] Specified Minimum Yield Stress

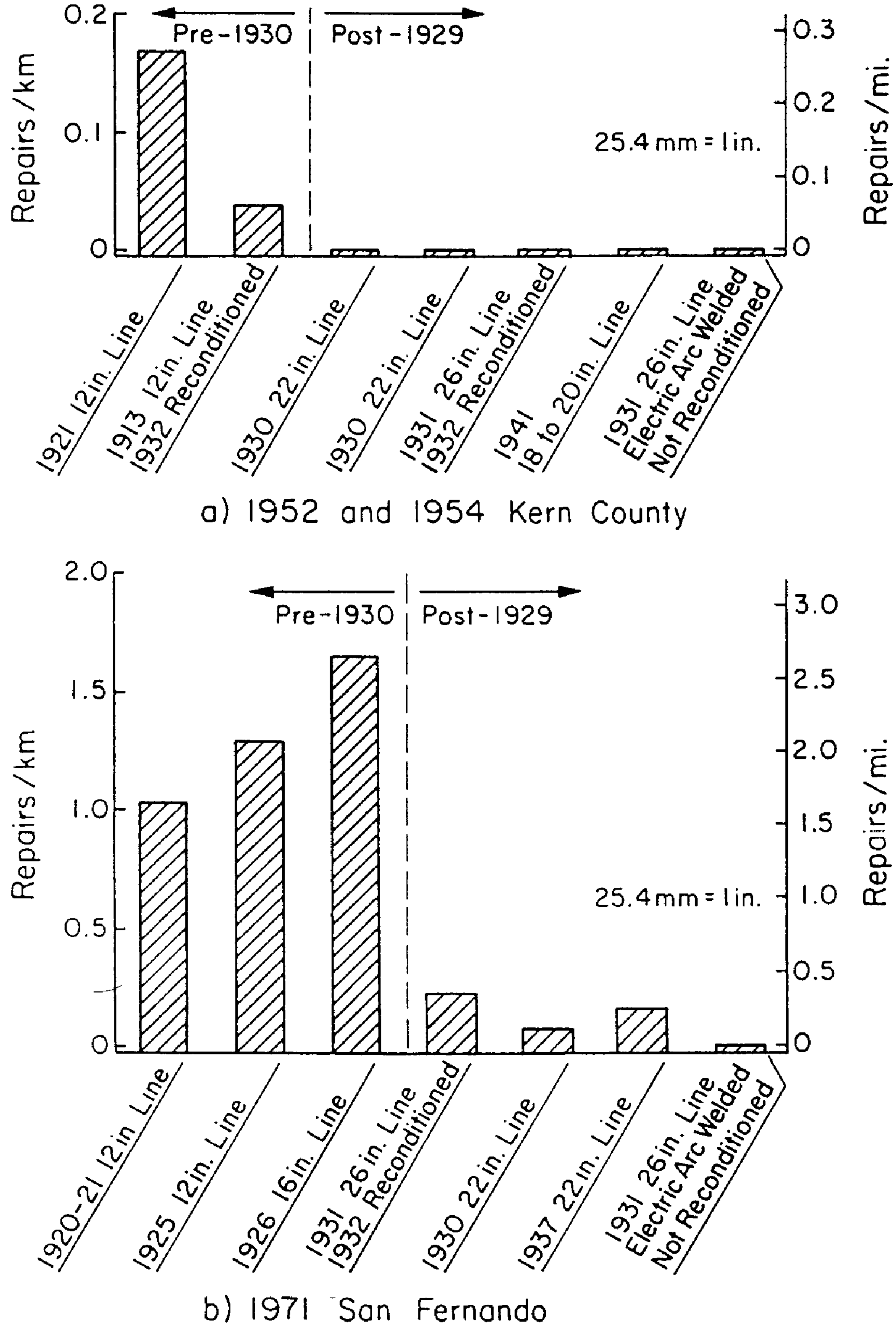

FIGURE 9. Damage Rates for Gas Transmission and Supply Lines in Areas with No Reported Permanent Ground Deformation

Table III provides a summary of transmission and supply line response to permanent ground deformation generated by surface faulting, liquefaction, dynamic consolidation, and slope movement. Only pipelines with nominal diameters equal to or larger than 300 mm (12 in.) are listed in the table All damage occurred in pre-WWII oxy-acetylene welded and electric arc welded pipelines. No breaks nor disruption of supply has been experienced in gas pipelines constructed with quality welds administered by modern electric arc techniques. The table indicates that breaks were not sustained in modern, electric arc welded pipelines at locations of surface faulting and lateral spreads, even though the severity of ground deformation in these instances generally was consistent with that causing rupture in pre-WWII oxy-acetylene and electric arc welded pipelines

SUMMARY

A review of the seismic performance of gas transmission and supply lines reported in this work shows that nearly all pipeline repairs occurred in areas with MMI $\geq$ VIII. The earthquake-related damage occurred primarily in the form of ruptures at oxy-acetylene girth welds

Table IV and Figure 10 summarize all gas transmission and supply line repairs The formats of the table and figure are similar to those presented by O'Rourke and Palmer (1994a,b) with several notable exceptions The repair statistics are grouped under categories in which damage occurred in areas either with or without reported permanent ground deformation Previous treatment of the statistics grouped repairs according to damage by either traveling ground waves or permanent ground deformation Grouping the data according to the absence or presence of permanent ground deformation is more consistent with the evidence The absence of reported ground displacements does not eliminate the possibility of movement which escaped observation However, a careful check of damage locations, which had been inspected and/or mapped for ground movements, does show that many locations of damage to oxy-acetylene welded lines are in areas which lack significant permanent differential ground movement and thus were likely affected by traveling ground waves

The evaluation of repair statistics in this work benefits from observations published after O'Rourke and Palmer (1994a,b) reported their findings Specifically, the observations of permanent ground deformation in Potrero Canyon (Stewart, et al , 1994) has been used to identify 18 breaks in Line 1001 inside an area of significant permanent soil displacements In this work, mapping the location of reported repairs to Lines 115 and 1001 at the Sylmar segment of the San Fernando fault and Juvenile Hall lateral spread, respectively, has resulted in a small number of additional damage locations being associated with areas of permanent ground deformation Further study of repair statistics (Johnson, 1982) has resulted in a total count of 52 breaks in Line 115, one less than the number previously used by O'Rourke and Palmer

Pipelines with the highest incidence of damage are those constructed before 1930 with oxy-acetylene welds, some of which have experienced damage at a relatively high rate of over 1 repair/km (1 61 repairs/mi) Oxy-acetylene welding for major transmission lines appears to have been discontinued by SoCalGas after 1931

TABLE IV. Summary of Earthquake-Related Gas Pipeline Repairs

Type of Damage	Damage at Locations Where No Permanent Ground Deformation Recorded Number of Repairs	Damage at Locations of Permanent Ground Deformation: Number of Repairs
Break in pre-WWII oxy-acetylene girth welded pipeline	88[a]	35[e]
Break in pre-WWII electric arc girth welded pipeline	4[b]	10[e]
Leakage at locations of corrosion	2[c]	---
Leaking flanges	5[d]	---

a Refer to Table I Note that repairs to partially reconditioned Line 85 during the 1971 San Fernando earthquake were at oxy-acetylene welds and one of the repairs in Line 100 was at an oxy-acetylene weld Repairs include damage to Line 122 during the 1994 Northridge earthquake
b Refer to Table II
c Includes leaks detected in Lines 80 90 and 1134 during the main 1952 Kern County earthquake
d Refer to Table I
e Refer to Table II

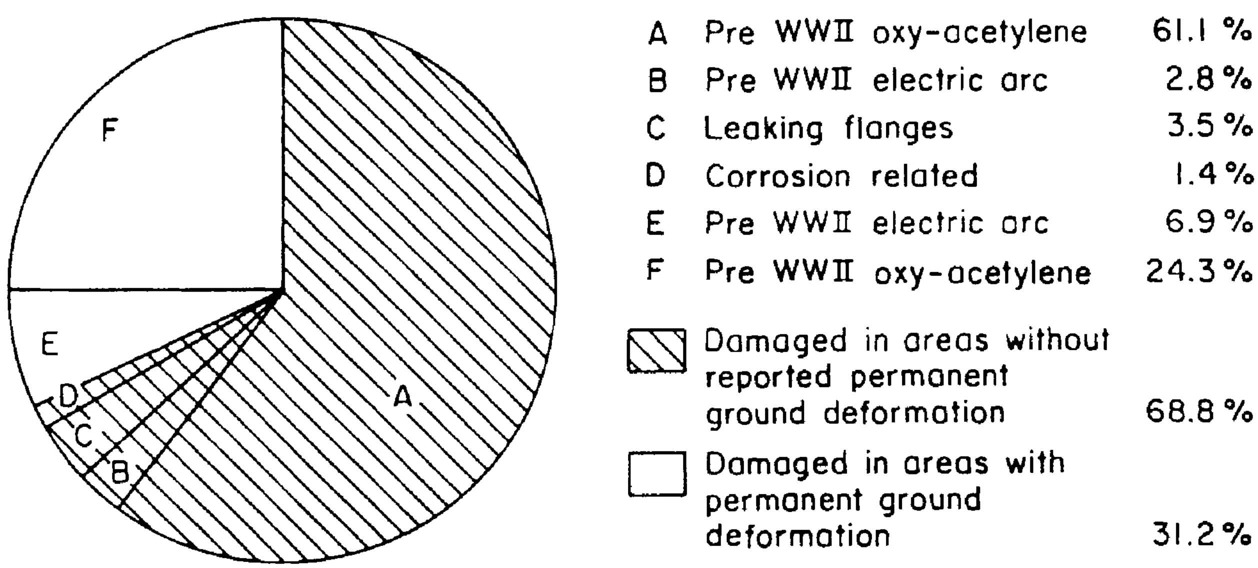

FIGURE 10. Pie Chart Showing Relative Proportions of Earthquake-Related Repairs Associated with Various Categories of Damage

In contrast to oxy-acetylene welded piping, pre-WWII pipelines with unshielded electric arc welds have fared much better in areas where permanent ground deformation has not been reported Damage under these conditions accounts for only 2 8% of the total repairs, which is over 20 times less than the damage in similar areas to oxy-acetylene welded lines

Damage from permanent ground deformation associated with surface faulting, liquefaction-induced lateral spread, dynamic consolidation, and slope movement represents 31 2% of the total repairs This relatively low portion is associated with the relatively small percentage of surface area influenced by ground failure during an earthquake Damage from permanent ground deformation can nonetheless be severe, resulting in some of the most conspicuous damage during a seismic event Pipeline ruptures on Balboa Blvd. during the 1994 Northridge earthquake, and along Glenoaks Blvd during the 1971 San Fernando earthquake, are examples Permanent ground deformation damage during previous earthquakes has been confined entirely to oxy-acetylene and pre-WWII electric arc welded pipelines

Post-WWII electric arc welded transmission pipelines in good repair have never experienced a break or leak during a southern California earthquake A very small amount of damage can be attributed to leaks at pipe walls thinned by corrosion, such as the corrosion-related leakage detected after the 1952 Kern County main earthquake Modern electric arc welded pipelines have been subjected to severe permanent ground displacement which has damaged adjacent welded water trunk lines, such as those subjected to 2 7 m (9 ft) of lateral spread next to the Jensen Filtration Plant during the 1971 San Fernando earthquake Likewise, ground movement on Balboa Blvd during the 1994 Northridge earthquake ruptured the pre-WWII electric arc welded Line 120, but did not damage two adjacent post-WWII electric arc welded transmission lines

The lack of damage to post-WWII electric arc welded pipelines does not mean they are immune to permanent ground deformation On the contrary, there is substantial experience with modern pipeline failures in areas of severe landslides Nevertheless, the repair record shows that modern electric arc welded gas transmission lines in good repair are the most resistant type of piping, vulnerable only to very large and abrupt ground displacement, and generally highly resistant to traveling ground wave effects and moderate amounts of permanent deformation

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