SEISMIC PERFORMANCE

OF

PIPING IN PAST EARTHQUAKES

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SEISMIC PERFORMANCE OF PIPING

The seismic performance of power piping can be examined in two ways. What may be expected due to the intrinsic characteristics of the piping that are built in due to design and construction practice? A second approach is to examine the performance of comparable piping in past earthquakes. In the following pages both questions are addressed.

ANSI B31.1 Code

In the United States, power piping in general is designed to meet the requirements of the ANSI (formerly USAS) B31.1 Code for Power Piping. For the present discussion, the 1967 version of this code with supplements are the issues of concern. There was little or no basic change in B31.1 between the 1967 and 1955 versions. The 1955 version, however, was a major departure from the previous issue of 1942 and supplements. In fact it was in the 1955 version of B31.1 that the basic rules and technical philosophy were established for the design of power piping that are in the main and under different labels still in use today.

The advanced features and underlying technical sophistication of the B31.1 Code have gone relatively unnoticed in this era of rapid technical change and innovation. The B31.1 approach first established in 1955 contained design rules for low cycle fatique, incorporated the maximum shear stress theory, and contained other improvements. The ASME Boiler and Pressure Vessel Code contained none of these features at that time. In fact it was not until the Nuclear Vessel Code came out nine years later in 1964 that these technical improvements were applied to pressure vessels.

The fundamental basis of piping design lies in developing a system that has the correct flexibility and, at the same time, is sufficiently well controlled. The concept of controlled flexibility is the key to successful piping design. The Code recognizes this with an entire section devoted to piping flexibility. The approach can be seen from the following, quoted from paragraph 119.5 of the Code:

> Power piping systems shall be designed to have sufficient flexibility to prevent pipe movements from causing failure from overstress of the pipe material or anchors, leakage at joints, or detrimental distortion of connected equipment resulting from excessive thrusts and moments. Flexibility shall be provided by changes of direction in the piping through the use of bends, loops or offsets; or provisions shall be made to absorb thermal movements by utilizing expansion, swivel or ball joints or corrugated pipe.

Explicit guidance is given to obtain balanced systems and to avoid problems of strain concentration caused by uneven flexibility. In this connection the concept of elastic followup is discussed. Design configurations vulnerable to strain concentration are explained and cautioned against.

The basic importance of the fact that piping operates in a strain range due to thermal expansion is recognized and explained. It is the strain range that is limited by the Code even though the limitation appears as a limit on calculated stress. Since piping in the thermal expansion process is in a strain controlled loading situation, the magnitude of the strain range can be controlled by a psuedo-elastic stress calculation. This subtle concept was later adopted by ASME Section III.

The phenomena of low cycle fatique is addressed in the design of B31.1 piping systems also. The basic allowable value of expansion stress is multiplied by a factor f which is related to the number of stress cycles. The factor functions as an allowable stress reduction factor due to fatigue service. The values of f are given below, where N is the number of stress cycles.

N	f
7,000 and less	1.0
7,000 to 14,000	0.9
14,000 to 22,000	0.8
22,000 to 45,000	0.7
45,000 to 100,000	0.6
100,000 and over	0.5

The stress range reduction factors are based upon tests of full size pipes made by Markl (1). Not only is the basic fatigue process considered, but also the deleterious effect on fatigue strength of various fittings, elbows, tees, etc. This is accomplished by a requirement to multiply the basic components of the expansion stress by " stress intensification factors" denoted by i. The numerical values of i were also derived from full scale tests and are given in the Code. The stress intensification factor bears only a nominal relation to the stress concentration factors of elasticity, rather i for a given fitting is related to the ratio of the fatigue strength for the fitting to that of straight pipe. It is in fact a fatigue strength reduction factor.

These various fatigue considerations have been condensed and codified in apparently simple terms; but it is important to keep in mind that the approach has a basis in full scale testing and where simplifications have been made they are conservative. It is also true that even today with apparently inexhaustible computer resources available, a single piping system is an extraordinarily complex structure and there are hundreds of piping systems in a power plant. It can be seen the simplifications are not only desirable, they are necessary.

Although an evidently straight forward consideration, the use of the shear stress instead of the normal stress is worth mentioning. The advanced technical nature of B31.1 can be better understood when it is realized that the widely accepted Boiler and Pressure Vessel Code used the less accurate maximum principal stress up until 1964.

The tabulated value of allowable stress in the hot condition is S_h. In B31.1, S_h is based on the lower of 5/8 Yield Strength or 1/4 Ultimate Strength at operating temperature, except certain austenitic materials are permitted S_h values at temperature up to 90% of yield strength because of the greater toughness and ductility of these materials. These values of allowable stress are the lowest in use for any piping in the United States. Nuclear piping has higher allowables, as does B31.3 Refinery and Chemical Plant Piping. B31.4 and B31.8 for Gas and Oil Transmission piping respectively permit allowable stresses up to 72% of the ultimate strength. When nuclear plant piping was moved under the aegis of ASME Section III, the safety Class 3 and 2 continued to be designed by B31.1, however, the allowable stress for the faulted plant condition was raised to 2.4 S_h from 1.8 S_h. Mention is made of certain of these facts as an observation of the conservative nature of the B31.1 Code even when compared to other codes that use the same calculational basis.

B31.1 and Later Codes

The first version of the B31.1 Code was published in 1935, and a revised second edition was published in 1942. Then a third edition was issued in 1951. This was a period of rapid development in piping design methods and it was found desirable to publish another revised edition of the Code in 1955. A brief history is given in the foreward to the 1955 edition of B31.1. What is not mentioned there, however, is that the 1955 edition of the piping code had several far reaching engineering improvements, which have been mentioned earlier herein.

The development of the 1955 edition and some of the changes therein are discussed in (2). Subsequently, new editions have been published, and although there were a number of changes and minor revisions, no new concepts were introduced.

In 1969 the ANSI B31.7 Code for nuclear piping was first published. THe basic philosophy of this code was to have nuclear primary system piping designed to similar criteria as nuclear primary system vessels. This required B31.7 to adopt similar approaches to the different possible types of failure and provide comparable margins as Section III of the ASME Code. The modes of failure for which protection is provided explicitly by the stress analysis and evaluation procedures of Section III are bursting, excessive plastic deformation, progressive distortion, thermal and mechanical fatigue failure. Of course other possible types of failure are considered in other areas of the Code, specifically in materials selection and fabrication guidelines.

The obvious approach to develop a piping code comparable to Section III for vessels was to attempt to adapt the existing B31.1 Code, which was done. However, as it turned out, the B31.1 Code already contained almost every provision of Section III, in a different format perhaps, but all the basic concepts were in place. The development of B31.7 then was a matter of recasting the original provisions of B31.1 into Section III format. Only one technical addition was required that could be considered a new concept, and that was the addition of consideration for radial temperature gradients through pipe walls. In certain situations or processes this could be an important consideration, but in nuclear plants it rarely determines the acceptability of piping systems. The net result is that B31.7, even though different in appearance and permitting slightly thinner pipe walls due to higher Section III S values, was not fundamentally different from the B31.1 Code. This was especially true in the most important aspects of piping design, the limitation on the main expansion strain range and thermal fatigue considerations. The stress indices, C_2 and K_2 of B31.7 (and Section III), are even generally related to the old i indices of B31.1.

$$C_2 K_2 = 2i$$

This relationship and other background on the development of the current ASME Section III Piping Code is in a forthcoming edition of the ASME Criteria Background Booklet (3).

The essential point of the preceding discussion has been to make clear that steel piping designed to meet the requirements of the older B31.1 Code would, almost without exception, also meet ASME Section III requirements for nuclear piping.

Seismic Performance of Piping

How has piping performed in past earthquakes? Although there appear to be no controlled experiments of seismic performance of actual piping systems, there is, nevertheless, a surprising amount of interesting data on the response of piping to actual earthquakes. In the following, power plant behavior in several recent earthquakes, Imperial Valley 1979, Miyagi-Ken-Oki 1978, Managua 1972, San Fernando 1971, Alaska 1964, Kern County 1952, Long Beach 1933 is discussed. The observations pertaining to the Kern Steam Station in the Kern County earthquake, and the Enaluf Steam Plant in the Managua earthquake are particularly interesting. Both these plants were designed by conventional procedures, both underwent severe ground shaking and neither suffered <u>any</u> failures of the piping systems. The maximum ground accelerations were estimated to be as high as possibly 0.6 g at Enaluf, which was right next to the main fault causing the quake, and about 0.25 g for the Kern County Steam Plant. Here it is clearly seen that piping systems correctly designed for normal service are relatively impervious to earthquake damage. The basic concept of controlled flexibility built into power piping renders these systems even more resilient than the buildings from which they are supported.

Long Beach Steam Station*

This station was located on Terminal Island in Long Beach, California, about four miles from the fault that caused the Long Beach earthquake on March 10, 1933. This earthquake was of magnitude 6.3 and caused accelerations at the site of the steam plant estimated to be about

0.25 g. Damage in Long Beach itself was very extensive, but there were no actual accelerometer records of the earthquake.

At the steam station site there were actually three independent plants. Plant I consisted of one unit and was built in 1911. It was either out of service or in intermittent service in 1933 and the building was severely damaged in the earthquake. Plant 2 consisted of 2 units and was built in 1922. Plant 3 consisted of 3 units and was built in 1928. This and subsequent information was obtained from W. F. Swiger (4) of the Stone & Webster Engineering Corporation, designers and builders of the plant. For other reasons it was necessary to re-examine the design of the plant at a later time and it was determined the plant structures were designed for lateral static forces of 0.2 g. Foundations of both plants were heavily reinforced concrete mats supported by wooden piles 50 to 60 feet long driven to hard sands. No information is available on seismic design of the piping and equipment, but considering the state of the art it is probable that either the 0.2 g static design was used, or else seismic design was not considered.

Neither plant, that is to say, none of the five units, suffered any significant damage. Some minor damage such as to lighting fixtures was reported, however the steam plants either operated through the earthquake or were shut down due to loss of load and were back in operation the same day. The important point is that 5 steam units designed with at most static methods to a g level (0.2) probably lower than actually experienced (0.25) was undamaged and in particular, no piping was damaged.

Kern County Steam Station

This oil fired 60 MW steam plant was designed and built in 1947-8. It is located on the Kern River near Bakersfield, California, about 25 miles from the epicenter of the July 21, 1952 Kern County earthquake.

This earthquake, sometimes referred to as the Taft, the Tehachapi, or the Arvin-Tehachapi, was of magnitude 7.7. It was the most severe earthquake recorded in the continental United States since that of 1906 in San Francisco. It occured along the White Wolf fault south and east of Bakersfield. Damage was extensive in Bakersfield and to oil production facilities in the area and to the Southern Pacific Railroad. The railroad tunnel near Bealville crossed the fault and was destroyed (5).

The structures of the plant were designed for 0.2 lateral load on a static basis with stress limits increased by 0.33 for combined dead, live, and earthquake loadings. Foundations are soil bearing footings at shallow depth. Anchorage systems of all major equipment including switch gear were carefully reviewed for resistance to lateral loads.

This is one of the first electric power plants to have piping designed by dynamic analysis. The Biot (6) smoothed response spectrum was used for the design of the main steam and boiler feedwater piping. The response spectrum was normalized to 0.1 g at ground level and 0.3 g at the top floor of the buildings, with linear interpolation at other levels. In this way an amplified response spectra was available at every floor, even though it was of narrow band and heavily damped compared to spectra used for nuclear plants. The spectra was applied for the steam and feed lines by calculating the first natural frequency of each span of pipe considered as a simply supported beam, then applying the appropriate lateral g force. Based on the dynamic analysis of the main piping, psuedo-static g loads were developed for other piping systems. These loads were also used to design guides and stops and to find loads acting on the supporting structure. It is of interest to note that some guides and stops on the main steam line had gaps or rattle space of as much as two inches (5).

An acceleration record obtained at Taft, California was further from the epicenter than the Kern County Plant. Maximum acceleration recorded at Taft was 0.17 g and it was estimated that ground acceleration at the plant site was a substantial 0.25 g. The plant operated through the earthquake with no significant damage. It was shut down after the earthquake due to loss of load but was returned to service in a few hours. There was some minor damage to oil tank seals and a small house turbine thrust bearing, but no damage at all to piping systems. This is a clear example of the almost complete seismic protection that is provided by even the most rudimentary seismic design procedures (by today's standards). Of course, there was even greater inherent reserve in the piping systems due to their natural controlled flexibility.

The Alaska Earthquake of 1964

This earthquake of 8.4 magnitude was the largest recorded earthquake of modern times. It was centered east of the city of Anchorage, near the town of Valdez. There was widespread destruction throughout the area, not only from earth vibration, but from the tsunami, the failure of poor soils, and fire.

In a panel discussion on the Nuclear Piping Code, some observations were noted of piping behavior by an experienced piping engineer with a leading Architect/Engineer (7) who reviewed the damage at two power stations immediately following the earthquake. The power station at an air base in the earthquake zone had no damaged piping although there were some "bent hanger rods", damaged lighting fixtures and an overturned control panel due to absence of anchor bolts.

A second power plant in the earthquake zone incurred more damage to the plant, although there were no piping failures. There were failures of some equipment supports made of malleable iron, and an ash handling line connected with patented couplings is reported to have failed due to improper support.

The significant finding of the observations of reference (7) is that two power plants rode out the Alaska Earthquake with no failures of the piping, even though the exact g levels at the sites were not reported and the design basis was not given other than to say "very little was done in the way of seismic design for the protection of anything" (7).

A brief mention is made in reference (5) of the Chugach Electric Company plant in Anchorage. This fossil fueled plant of about 50 MW was built between 1949 and 1957. The plant was designed to 0.1 g by the Uniform Building Code. The buildings were of steel frame construction with corrugated panel walls. There was no damage in the turbine room nor to piping and critical equipment. There was minor damage in the boiler room consisting of bending of some bracing members and appreciable damage to framing supporting the coal bunkers. Many piping hangers on the main steam lines were broken, but the piping itself was undamaged. The plant was returned to service at full power in less than 10 days.

The consulting firm of Ayres and Hayakawa of Los Angeles was asked to review all non-structural damage to buildings due to the Alaska Earthquake as part of the investigation performed by the National Academy of Sciences at the request of President Lyndon Johnson. In their report (8) power plants were not discussed separately, rather observations of piping systems of all types were discussed on a generic basis. The discussion is based on a study of large modern structures located, with few exceptions, in Anchorage.

The reference report addresses general piping systems of all types, but mainly that required in modern buildings. With the exception of certain fire protection piping, none was seismically designed. Because of the broad basis of the report, the following paragraph is quoted directly from the section entitled "Piping Systems".

> The overall damage to piping systems was surprisingly low. Many instances were reported where piping systems remained intact, despite the significant structural and nonstructural damage suffered by the building. For example, the plumbing pipes in the Enlisted Men's Service Club at Fort Richardson remained standing after the earthquake although the walls around them collapsed. Contractors also reported that most systems were put back into service when pressure-testing revealed no leaks.

The general conclusion was that piping systems are basically earthquake resistant. Failures occur if at all at threaded fittings. Welded steel pipe does not fail. One instance of power piping failure was noted. Small steam pipe drain lines anchored to building walls were torn from the steam line as it responded to the earthquake at the Fort Richardson power plant. This is the type of unbalanced design warned against in the piping code. Properly detailed systems had no problems.

San Fernando, California, 1971

The San Fernando Earthquake of 1971 was centered in the northern part of the San Fernando Valley. Ground accelerations of 0.1 to 0.19 g were recorded in Los Angeles at distances of 35 Km and 0.37 g at Lake Hughes, 25 Km from the epicenter. Figure 2 shows recorded g levels for the 1971 earthquake at various locations near Los Angeles. There was severe damage to a number of structures in the valley.

The Valley Power Plant is a fossil fuel plant with three units on the site located about 5 to 9 miles from the epicenter. Accelerations at the site are estimated to be in excess of 0.25 g based upon the location of various recordings. The station was designed to 0.2 or 0.25 g although actual details are not known.

In any event there was no damage to the plant. It was tripped off the line by action of sudden pressure relays and loss of load, but was back on the line inside 2 hours (9). There was significant motion of the piping and seismic hold down bars came into play (10), but other than insulation the piping itself was undamaged. This is a graphic example of the basic point that well designed piping to regular commercial practice is highly resistant to earthquake damage.

There were other power plants in the area at Playa del Rey, San Pedro and Seal Beach that were not as close to the epicenter as the Valley Plant and none of these were damaged. The San Fernando Power Plant is an old hydro plant built in 1921 and there was a structural failure of the building which led to a penstock failure. There were numerous failures of electric transmission facilities due to cracking of porcelain bushings and movement of poorly anchored equipment. There were no piping failures in the San Fernando Earthquake.

Managua, Nicaragua, 1972

An earthquake of magnitude 7.5 struck Managua on December 25, 1972. There was much damage and great loss of life. The loss of life was largely unrelated to damage of industrial buildings and facilities since the earthquake occurred near midnight. A report on the damage was sponsored by the National Science Foundation and several professional societies together with the Ministry of Public Works of Nicaragua (11).

Figure 3 taken from (11) shows the fault lines along which movement occurred running through the city of Managua. The location of two industrial facilities, the ESSO refinery and the ENALUF Power Plant are also noted. The earthquake response of these two facilities will be discussed since they contain industrial piping systems of interest for present purposes.

A complete acceleragraph record was obtained at the ESSO refinery. The peak measured acceleration was 0.39 g E-W, and 0.34 g N-S. The design of the refinery met provisions of the Uniform Building Code for 0.2 g, including tall fractionating towers, some of which exceed several hundred feet. There was almost no damage at the refinery and none to the piping systems. Some piping jumped out of saddle supports and was pushed back into place. The facility was shut down for an inspection but was operating at full capacity within 24 hours even though there was a loss of offsite power. The refinery provides a clear example of the seismic capacity of welded steel pipe.

Based on the earthquake magnitude, acceleration record at the refinery and the location of the ENALUF Plant immediately adjacent to the causative fault, it is probable this plant experienced accelerations on the order of 0.6 g. The power plant consists of three oil fired units, one of 50 MW and two of 20 MW. All three units were taken off-line by protective relays. The plant suffered some damage but none to the piping systems. It was one of the first industrial facilities restored to service after the earthquake. One unit was operating in two weeks, the second in three weeks. Operation of unit 3 was delayed due to turbine problems.

The specific damage to the three units is listed in Table 3. Note that no damage occurred to the piping, and that many of the problems resulted from absent or inadequate anchors. For example, turbine bearings were lost because emergency D.C. oil pumps were inoperative due to the batteries tumbling out of their racks.

The basic facts about the power piping however are that with unknown and probably no seismic design applied, the piping sustained accelerations on the order of 0.6 g ground motion with no failure. Modern welded steel piping with built in controlled flexibility is inherently highly resistant to earthquake damage.

Miyagi-Ken-Oki, Japan, 1978

The Miyagi-Ken-Oki or Miyagioki earthquake occurred on June 12, 1978 in the northeastern part of Honshu, main island of Japan. It was of magnitude 7.4 and the epicenter was located just offshore about 100 km, nearly due east of the modern city of Sendai and at a depth of 40 km. This earthquake was well characterized because of the many strong motion accelerograph stations in Japan. Fig. 4, taken from reference (12) shows the epicenter, the locations of the city of Sendai, the Fukushima Nuclear Power Plant, and several accelerograph stations.

This severe earthquake caused widespread damage in Japan. Approximately 28 km of earthen river dikes were damaged due to soil liquefaction and subsequent slumping, cracking, and settlement. Several thousand landslides and rockslides occurred both on natural slopes and artificial fill. In the modern city of Sendai, with a metropolitan area population of over one million, damage appeared to be confined to local areas, evidently related to soil conditions. Of particular importance was the fact that engineered high-rise buildings up to 18 floors that experienced 0.25 g at ground level (measured) suffered no serious damage. Several smaller, less well engineered buildings were badly damaged.

The Fukushima Nuclear Power Plant complex south of Sendai had five operating BWR plants and one under construction. The free field maximum acceleration at the site was 0.12 g. With the exception of one broken ceramic transmission line insulator, there was no damage to the site at all. Although not stated in Ref. (12), it is probable the design basis for the nuclear plants exceeded the 0.12 g so there should have been no damage. It is reassuring that there was none.

The new Sendai Thermal Plant is an oil fired facility with one unit of 350 MW (1971) and one of 600 MW (1973). The plant is located about 15 km east of Sendai. No accelerogram was obtained because the instrument at the site was being inspected at the time of the earthquake. However, in all probablility the site experienced accelerations that were at least in the 0.25 g to 0.40 g range that were felt in Sendai, 15 km further from the epicenter. A seismic alarm at the site was triggered at about 0.15 g.

The seismic design applied to the plant was not reported. Minor damage was sustained inside the boilers; evidently some "spacer" tubes were sheared and suspended assemblies within the boiler pounded nearby structures. The details of this damage are not known, but it could not have been severe; repairs were made in six days. There was no damage to the power piping, although an additional reference on this topic, Ref. (13) confirmed there were no piping failures such as leaks or cracks, but that there were some deformations and missing anchor bolts for the pipe hangers. Ref. (13) makes no reference to the boiler tubing.

As in the San Fernando earthquake, ceramic insulators in electric power substations were shown to be vulnerable. A substation near Sendai experienced major damage to the insulators, lighting arrestors, etc.

One additional facility deserves mention in this discussion on power piping performance in earthquakes. Some failures did occur when a large propane gas-holder, 38 meters in diameter, of the telescoping type collapsed and fell onto the piping systems in a gas plant. Obviously this was not a failure of the piping itself, but of the tank. This tank was located near Sendai.

Five other power plants ranging from 250 to 600 MW, Ref. (12), were affected by the Miyagioki earthquake of June, 1978. These plants experienced intensities of 2 to 5 on the Japanese scale, corresponding to IV to VIII on the MMI scale; e.g. the intensity at the New Sendai Plant discussed above was 5 on the Japanese scale. All of these additional plants were operating at the time of the earthquake and none were damaged. One of the five was shut down for one hour and inspected, but nothing was found.

El Centro Steam Power Plant

The El Centro power plant is located about 5½ miles from the epicenter of the 1979 Imperial Valley Earthquake. This earthquake, which occured on October 15, 1979, was 6.4 on the Richter scale and there were several aftershocks, the largest of which was magnitude 5.2. The Imperial Valley is an active seismic area and was the site of the 1940 El Centro record, which has been widely used in seismic engineering.

Perhaps because of the seismic activity in the area it was very well instrumented and several strong motion records were obtained. In fact, this is probably the best recorded earthquake that has occured to date. Certainly it is the first time so much "near field" data has been obtained. A map of the region is given in Fig. 5, which shows the locations of the fault, the epicenter, the power plant and several motion recording stations. This Figure is reproduced from Ref. (14).

Figure 6 presents acceleration records from several of the sites on the map. A reasonable estimate of the motion experienced at the power plant can be obtained by averaging that recorded at stations 8, 9, and at the "Differential Array". On this basis, the plant experienced about .5g horizontally and about .6 g vertically. In view of the large number of records and the consistency thereof, especially when distance from the fault is considered as well as distance from the epicenter, it

The failed coupling was of an unusual design. Basicly it consists of an ordinary steel coupling with a liner of threaded fibreboard inserted. The pipes being joined are then screwed into the fibreboard. The purpose of these couplings is to eliminate stray electrical currents. Further the couplings which failed were on long spans of piping with no extra supports.

The failure of these two components, especially considering their construction and the levels of motion is hardly surprizing. Perhaps more important are the miles of piping and cable trays that did not fail or otherwise cause any problems, even though evidence of special considerations to obtain a seismically resistant design were minimal. Of special interest was the only set of hydraulic snubbers in the plant which were on the main steam line where it entered the turbine hall on the ground floor that evidently failed to lock at all, but the pipe was not damaged even though it appeared to have executed substantial vibratory displacements.

The oil tank was a thin shell structure 135' in diameter which evidently developed a vacuum due to sloshing oil and buckled. Such failures are not unknown and, in fact, might be expected. The wooden cooling tower that was damaged was 30 years old and in poor condition. Three of the four wooden towers were not damaged.

Taken altogether, it can be seen that piping and equipment in good condition with no special design features survived the earthquake. The damage that was observed can be attributed to design that is completely unsuited for seismic conditions, (the oil tank and vallett coupling) and to equipment in severely deteriorated physical condition (water pipes and cooling tower).

would appear that for once the degree of uncertainty about acceleration levels experienced at the site is minimized.

The plant has four units; Unit 1 of 20 MW, built in 1949; Unit 2 of 33 MW, 1952; Unit 3 of 44 MW, 1957; and Unit 4 of 80 MW, 1968. Units 1 and 2 were down for maintenance when the earthquake occurred. Units 3 and 4 were tripped off line evidently due to loss of load. Unit 3 was restored to service 5 minutes after the main shock and Unit 4 was restored to service five hours later. During the five hour outage, leaks in the generator hydrogen cooler water supply were repaired.

The damage at the plant was surveyed by a team of engineers from the Pacific Gas and Electric Co. (15), the U.S. Nuclear Regulatory Commission (16), as well as the present writer. In general, there was a great deal of motion at the site, and various traces of the motion were observable, e.g. skid marks of reheater feet, bent seismic stops, etc. There were some failures; leaks occurred in the water supply for the hydrogen coolers as mentioned above; a two inch vallett pipe coupling failed; a buckling failure occurred in an oil storage tank; old wooden forced draft cooling towers sustained damage to the wooden structure; and a lightning arrester broke off a transformer. There was no other serious damage.

At first the most disturbing of the above was the damage to the hydrogen cooler water line and the failed pipe coupling. The water pipes were carbon steel, 3 and 4 inches diameter. There is a severe corrosion problem with this particular piping, evidently due to the character of the water. There had been leaks due to corrosion in these lines before the earthquake which had been weld repaired. The new leaks caused by the earthquake were of a similar type and were also weld repaired.

Conclusion

The available data and observations on the behavior of power piping in actual earthquakes has been reviewed. In general, it is seen that even for power plants experiencing severe ground motion, the piping remains intact. The data that have been surveyed clearly raise the question of the wisdom of designing piping for earthquake resistance by supporting it ever more rigidly. Linear analysis shows the gain of some conservatism by so doing. In the real non-linear world will this conservatism prove to be an illusion? May it even prove to be a liability, since it was obtained by sacrificing piping flexibility?

Acknowledgement

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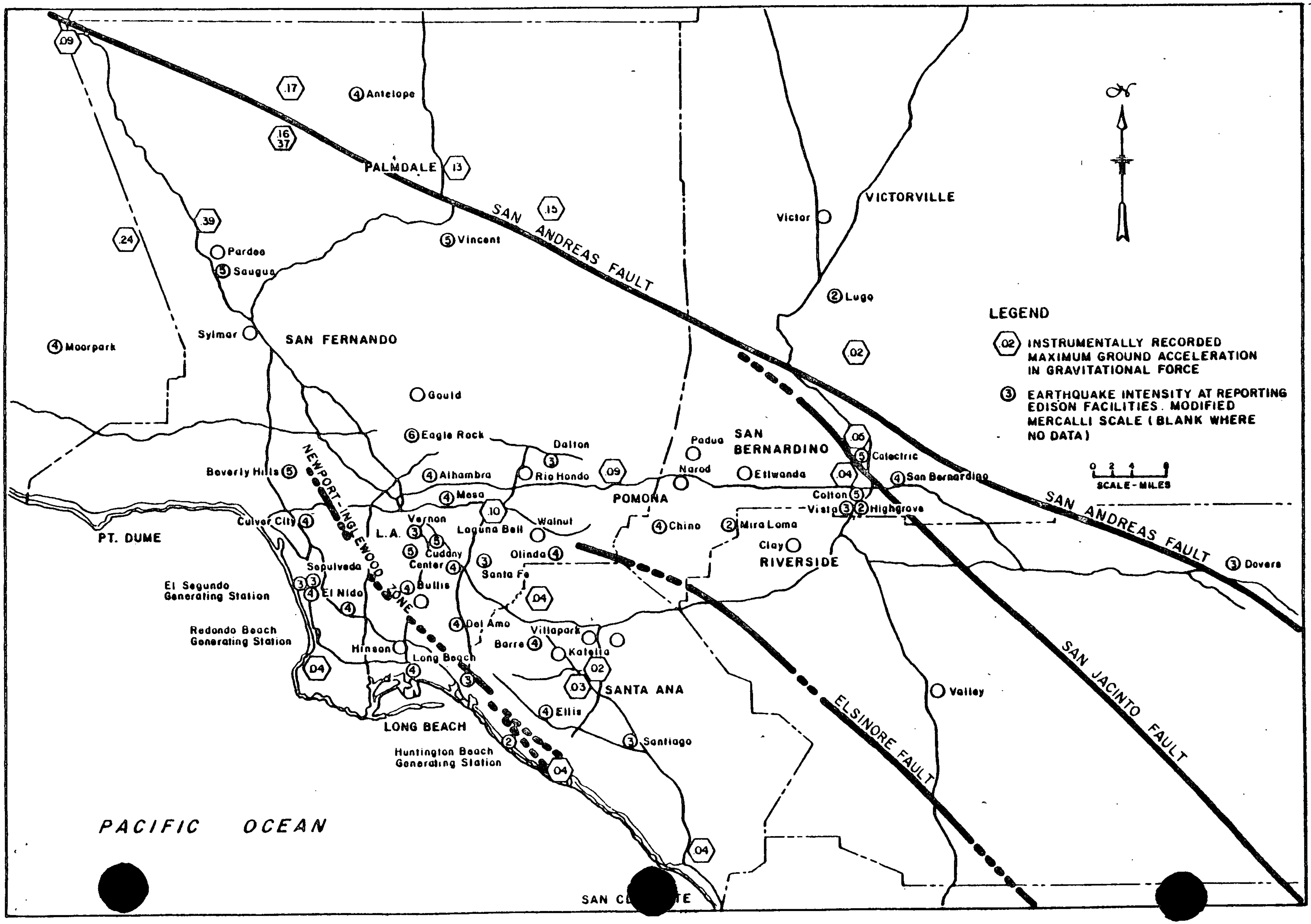
SAN ANDREAS FAULT
SAN JACINTO FAULT
ELSINORE FAULT
NEWPORT-INGLEWOOD ZONE
PALMDALE
VICTORVILLE
SAN FERNANDO
SAN BERNARDINO
POMONA
RIVERSIDE
L. A.
SANTA ANA
LONG BEACH
PT. DUME
PACIFIC OCEAN
LEGEND
.02 INSTRUMENTALLY RECORDED MAXIMUM GROUND ACCELERATION IN GRAVITATIONAL FORCE
3 EARTHQUAKE INTENSITY AT REPORTING EDISON FACILITIES. MODIFIED MERCALLI SCALE (BLANK WHERE NO DATA)
SCALE - MILES
0 2 4 8
4 Antelope
5 Vincent
Victor
2 Lugo
Pardee
5 Saugus
Sylmar
4 Moorpark
Gould
6 Eagle Rock
Dalton
3
Padua
Narod
Ellwanda
5 Calectric
4 San Bernardino
Colton 5
Vista 3
2 Highgrove
Beverly Hills 5
4 Alhambra
Rio Hondo
4 Mesa
Vernon
Laguna Bell
Walnut
4 Chino
2 Mira Loma
Clay
Culver City 4
3 Dovers
Cudahy
Center 4
Olinda 4
3
Santa Fe
Sepulveda
El Segundo Generating Station
4 El Nido
4 Bullis
4 Del Amo
Villapark
Barre 4
Katella
Redondo Beach Generating Station
Hinson
Long Beach
3
4 Ellis
3 Santiago
Huntington Beach Generating Station
Valley
SAN CLEMENTE
.09
.17
.16
.37
.13
.15
.39
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.02
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FIG. 1

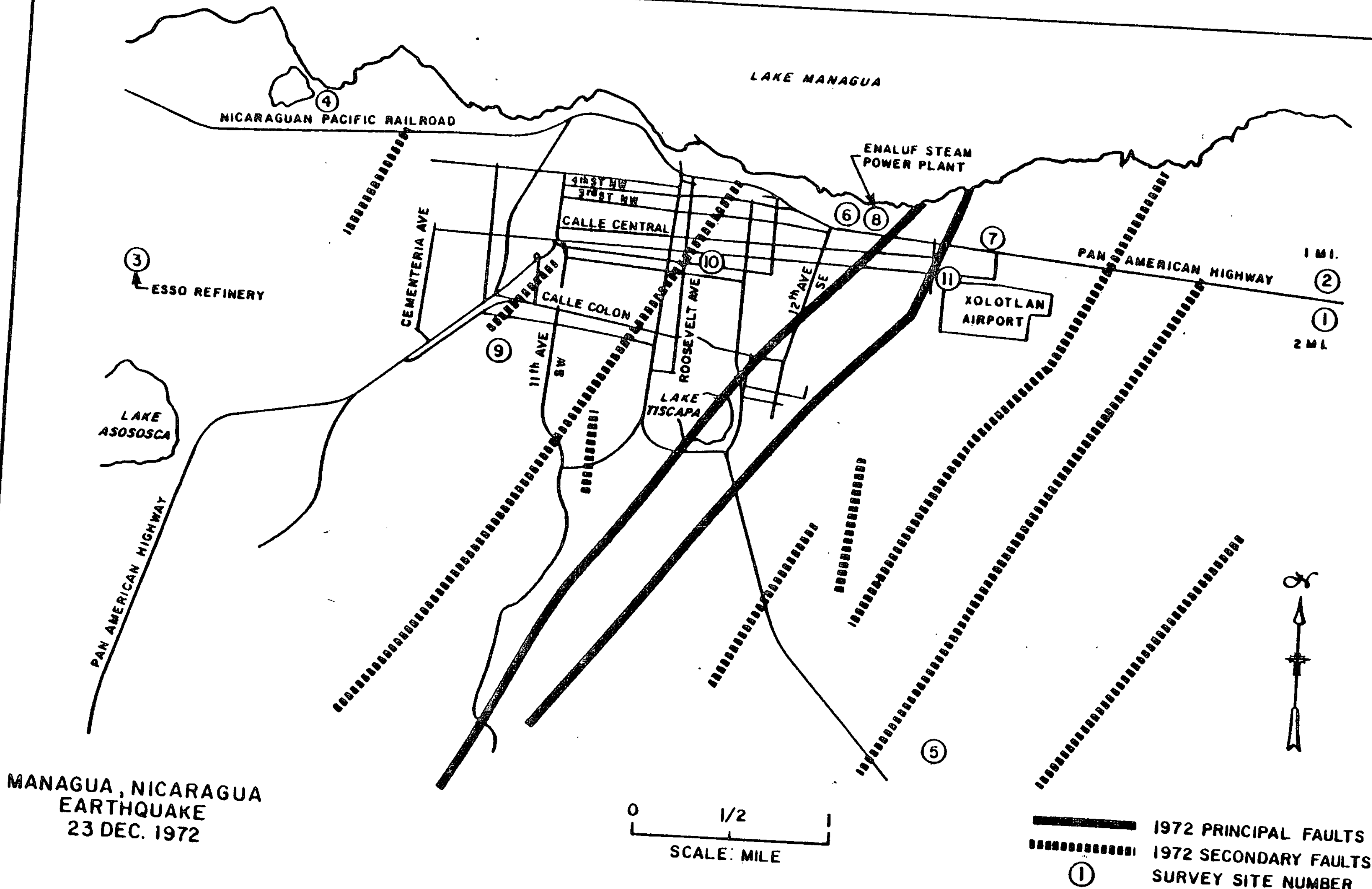
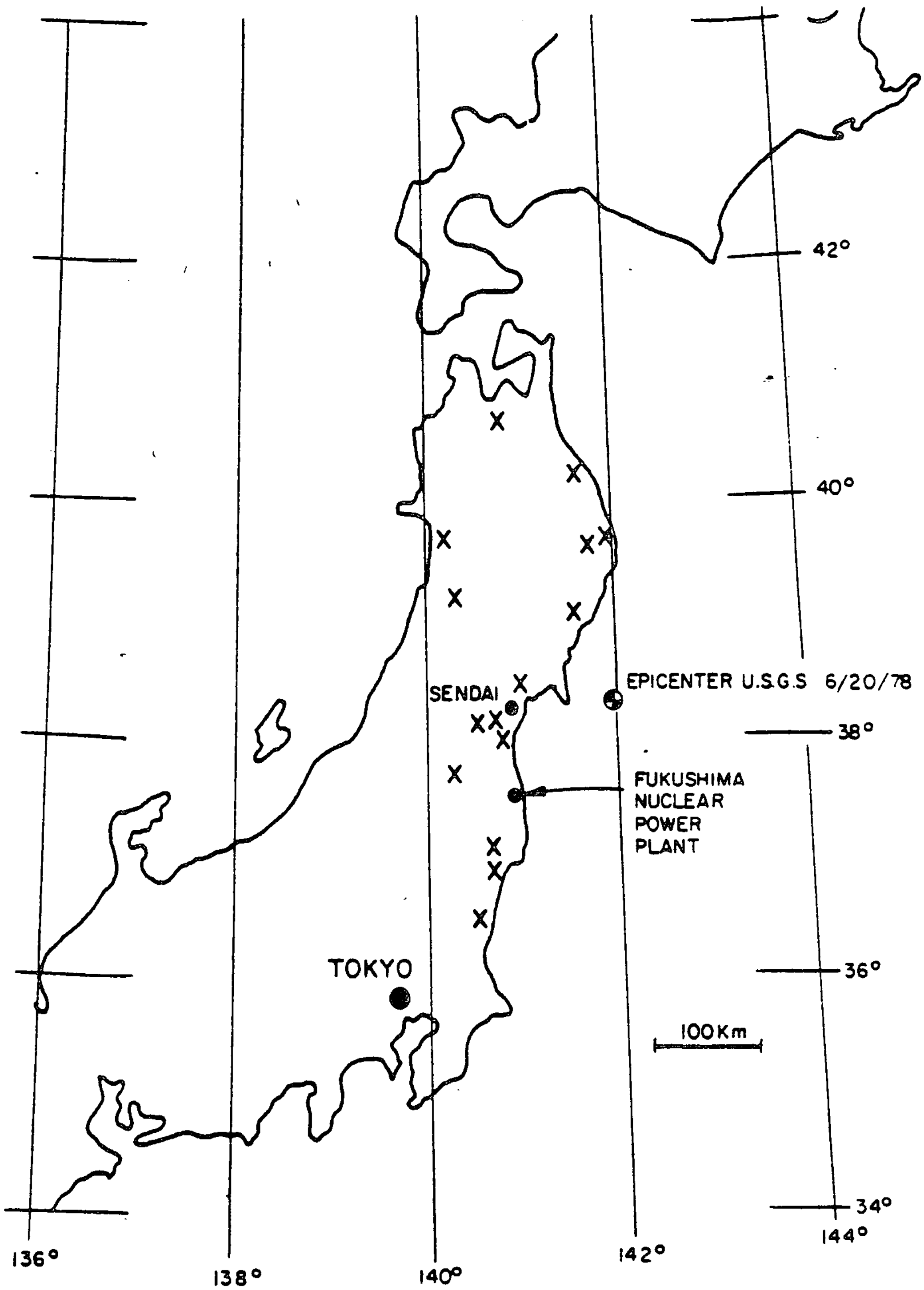


FIG. 2

MAP OF MANAGUA, NICARAGUA SHOWING THE LOCATIONS O[illegible] FACILITIES AND BUILDINGS REFERRED TO IN THIS [illegible]PORT
SEE TABLE I FOR A L[illegible] OF THE FACILITIES



X, SEISMIC ACCELEROGRAPH STATION

FIGURE 3 LOCATIONS OF ACCELEROGRAPH SITES PROVIDING SIGNIFICANT RECORDINGS OF JUNE 12, 1978

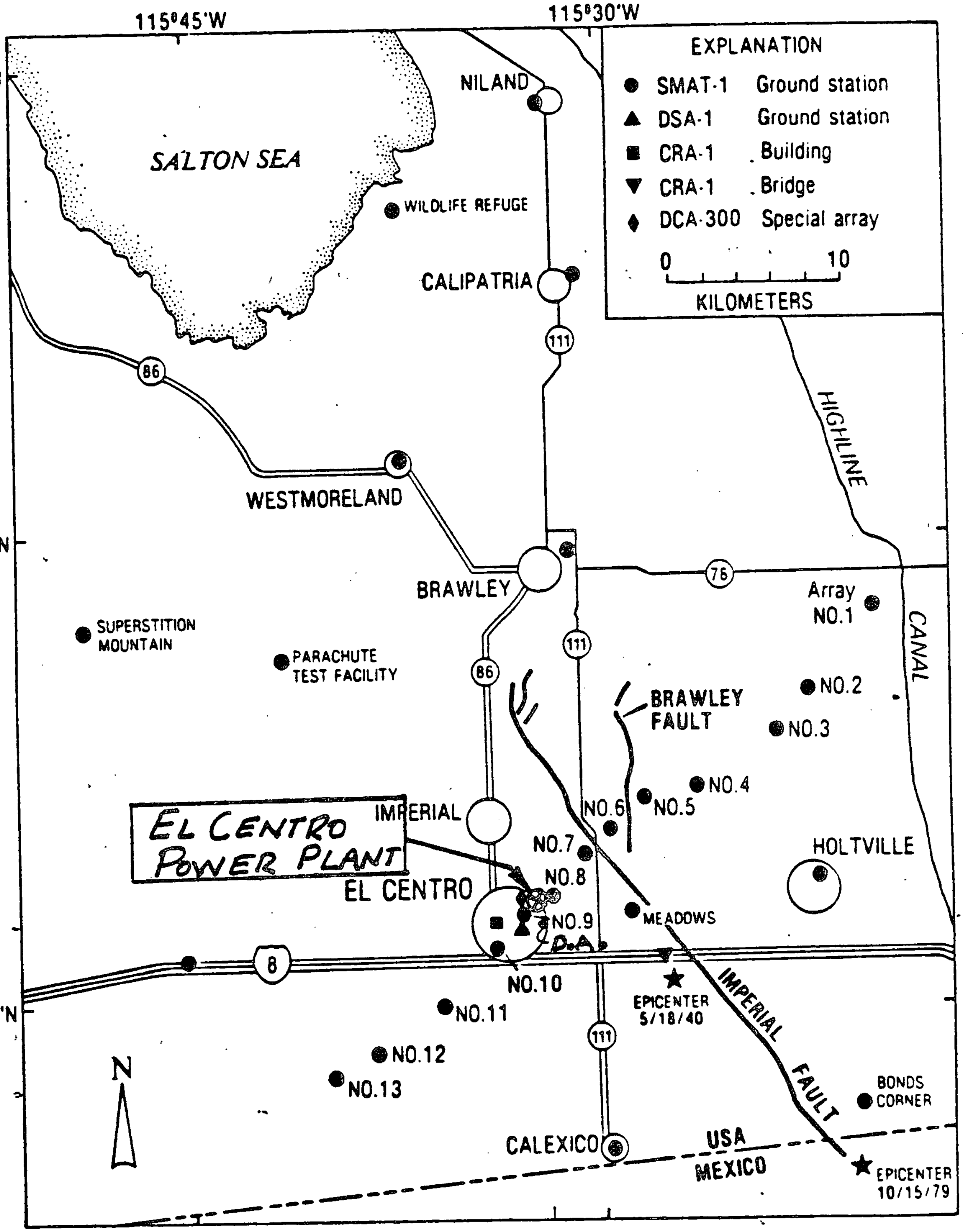


Figure 4- Strong-motion stations in the Imperial Valley, California.
R.L.Porcella and R.B.Matthiesen
U.S.Geological Survey Open-File Report 79-1654, October 1979

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MEASURED ACCELERATIONS, G's

SEISMIC STATION	DIRECTION NE-SW	NW-SE	VERT.	EPICENTRAL DISTANCE, KM
5	.40	.56	.71	28
6	.45	.72	1.74	27
7	.52	.36	.65	26
8	.50	.64	.55	27
9	.40	.27	.38	26
DIFF. ARRAY	~.51	~.39	.93	26

Fig. 5

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