

## PRINCIPAL EARTHQUAKES IN NEW ZEALAND IN 1991

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During 1991 there were two earthquakes which exceeded magnitude 6 in New Zealand, one near Taupo on July 12 (6.4) and one north of Wanganui on September 9 (6.3). Both were of intermediate depth (71 and 87 km respectively). Their magnitudes were comparable with that of the Edgecumbe earthquake in the Bay of Plenty in March 1987. The September 9 shock was felt from Coromandel to Christchurch, and resulted in about 2500 claims to the Earthquake and War Damage Commission, mostly from Wanganui. The Observatory received two isolated reports of intensity MM VII, but nothing else above MM V, in keeping with the focal depth of the event. High intensities in earthquakes are a well-known feature of Wanganui, established first by Hayes (1936). The Observatory conducted an intensity survey, with the assistance of the Wanganui Chronicle, and despite the limitations of a procedure which relies solely on questionnaire returns from the public, definitely established amplification of ground motion due to weak ground. The pattern was nevertheless found to be an extremely scattered one with very little in the way of systematic microzoning effects.

The July 12 shock was also felt as far south as Christchurch, but only at moderate intensities. Effects near the epicentre were not as great as near Wanganui on September 9, because of the different geological basement in the Taupo area.

There were two more earthquakes exceeding magnitude 6 offshore: 140 km north-east of East Cape on November 20, and 40 km north of Tauranga but 285 km deep, on November 16. Neither was felt very strongly onshore.

On January 29 there were two shallow earthquakes within five hours, both about 15 km south of Westport in the area of the lower Buller Gorge. They have been named the Hawk's Crag earthquakes, and were the subject of a field survey and subsequent analysis. Their magnitudes were 5.6 and 5.8. They caused some chimney damage in Westport, Waimangaroa and Inangahua. Goods were displaced off shelves in Reefton, Hokitika and Greymouth. Felt reports have been received as far away as Paraparaumu and Christchurch. There were a few aftershocks, but rather less than expected for main shocks of this magnitude, and this is an item of current investigation.

Occasional aftershocks of the earthquakes near Weber in Southern Hawkes Bay, in February and May 1990, have continued, all of them small. Aftershock sequences such as this do tend to persist for many months after the main shocks.

On February 15 an earthquake of magnitude 5.5 occurred off the coast from Greymouth. It was felt throughout much of the northern and western South Island, although no damage has been reported. This is at the southwestern end of the Main Seismic Region: between Greymouth and Milford Sound, earthquakes are less frequent despite the presence of the Alpine Fault which runs much of the length of the South Island.

A deep earthquake (106 km) occurred to the south of Patea on 9 June. The magnitude was 5.8, and it was felt from New Plymouth to Greymouth. Earthquakes at that depth are common in the South Taranaki Bight.

Southern Fiordland experienced an earthquake of magnitude 5.0 on September 5. It was centred near the head of Dusky Sound, and was reported felt as far east as Dunedin. Focal depth was 74 km.

Goods were shaken from shelves in Ruatoria on 31 October, when an earthquake of magnitude 5.0 occurred near East Cape. At the same time a swarm of very small earthquakes was in progress near Kaikoura, attracting considerable public attention. This phenomenon of a swarm of small events is one which needs further study in New Zealand. It is simply not known how often these occur, because the sensitive network which can now detect these has not long been in place, a product of the recent upgrading of instrumentation. On such occasions, there is always an outside chance that the swarm will develop into a major earthquake, but the process is not understood. It is fortunate that the most common outcome seems to be that the swarm dies away within a few days, as indeed happened in Kaikoura.

### Reference

Hayes, R.C. 1936. Intensity distribution in New Zealand earthquakes. *N.Z.J. Sci. Tech.* XVIII, 508-511.

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# EARTHQUAKE RECONNAISSANCE REPORT

## Damage to the Power Generation and Transmission Facilities in the Loma Prieta Earthquake of 17 October 1989

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### ABSTRACT

The magnitude 7.1 Loma Prieta earthquake, at 5.04 pm on 17 October 1989, caused deaths, damage to properties and disrupted transportation, utilities and communications. Electricity and gas in the area affected by the earthquake were supplied by Pacific Gas and Electric (PG&E) Company which served more than 10 million people in northern and central California. The company's 1988 annual report showed a total sale of 68537 GWh of electricity. The earthquake caused considerable damage to power generation facilities at Metcalf, San Mateo and Moss Landing. Facilities at Potrero and Hunter Points also experienced minor damage. Damage occurred to old items of equipment which were not designed to PG&E's current seismic specifications. Those which were located on sites near the epicentre of the earthquake suffered the most damage. According to PG&E's report, issued soon after the earthquake, about 1.4 million PG&E customers lost electric power, some for up to 48 hours, and a total cost of damage between US \$30 millions and US \$50 millions has been estimated. There were other smaller power generation plants in the area besides those owned by PG&E. Most were built recently and, to the author's knowledge, they suffered little damage during the earthquake.

### 1. INTRODUCTION

This report has been prepared as part of those prepared by a 3-man earthquake reconnaissance team sent to San Francisco by the New Zealand National Society for Earthquake Engineering in the first week of December 1989. The author's brief was to cover the damage to power generation facilities.

### 2. DESCRIPTION OF DAMAGE AT THE SUBSTATIONS

Most of the damage occurred at San Mateo, Metcalf and Moss Landing sites. By the time the author visited these sites, the damaged equipment was cleared and repairs were well under way. The locations of these sites are shown on Fig.1.

In this report, the photographs of the damage were taken by E. Matsuda of PG&E, while other photographs were taken by the author.

#### 2.1 Damage at San Mateo Substation

San Mateo is a 200/115/66 kV substation located about 30km south of Down Town San Francisco. It was built on flat and relatively soft ground alongside Freeway 101. Its location is about 65km north of the epicentre.

The earthquake intensity experienced at San Mateo has been estimated at MM7. Ground acceleration was estimated at 0.2g.

However, the closest strong motion record was made about 3.2km away in Foster City and showed a peak horizontal acceleration of 0.16g(1).

The major damage at San Mateo was to one General Electric (GE) model ATB4 and three GE model ATB4 and three GE model ATB7 live-tank 220 kV circuit breakers. The breaker support insulators were cracked at the base as shown in Figures 2 & 3, in a classic bending failure mode of a weak column supporting a heavy interrupter head at the top. These breakers were replaced with dead tank breakers (Fig.4).

There was other minor damage as described in Ref.1. However, most items of the equipment, including 230 kV bulk oil circuit breakers (Fig.5), withstood the earthquake.

#### 2.2 Damage at Metcalf Substation

Metcalf is a 500/230/115 kV substation located about 5 km south of Down Town San Jose. It was built on flat but harder ground than that at San Mateo. Its location is about 30 km north of the epicentre.

The earthquake intensity experienced at Metcalf has been estimated at MM 7. Ground acceleration was estimated at 0.3g. However, records obtained about 11 km southeast and 11 km west of the substation showed peak horizontal accelerations of 0.28g and 0.19g respectively (1).

Damage at Metcalf substation mainly occurred in the 500 kV switchyard. The damaged equipment included 500 kV live-tank circuit breakers, current transformers, lightning arresters and a transformer. However, items in the 230 kV switchyard and the control building withstood the earthquake without any damage.

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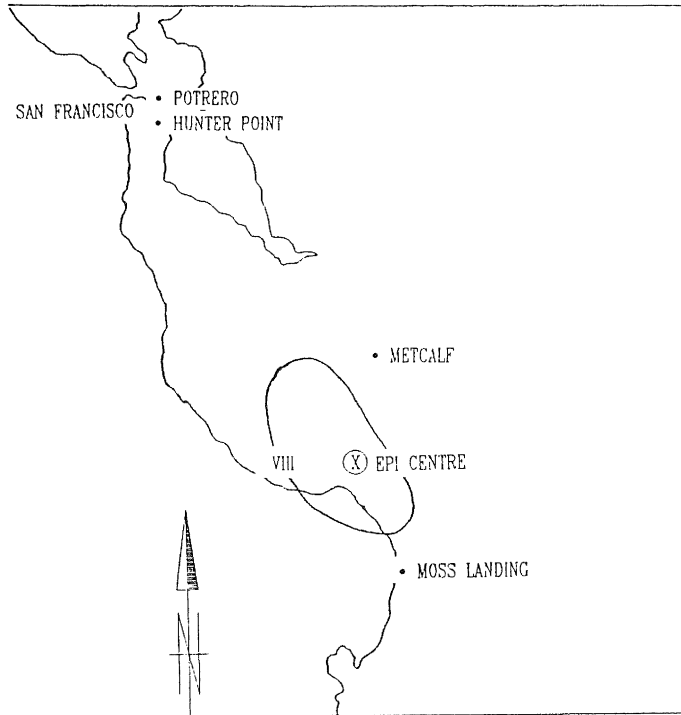


Figure 1 - SITE LOCATION  
(After US Geological Survey Circular 1045 -  
lessons learned from the Loma Prieta, California,  
Earthquake of October 17, 1989).

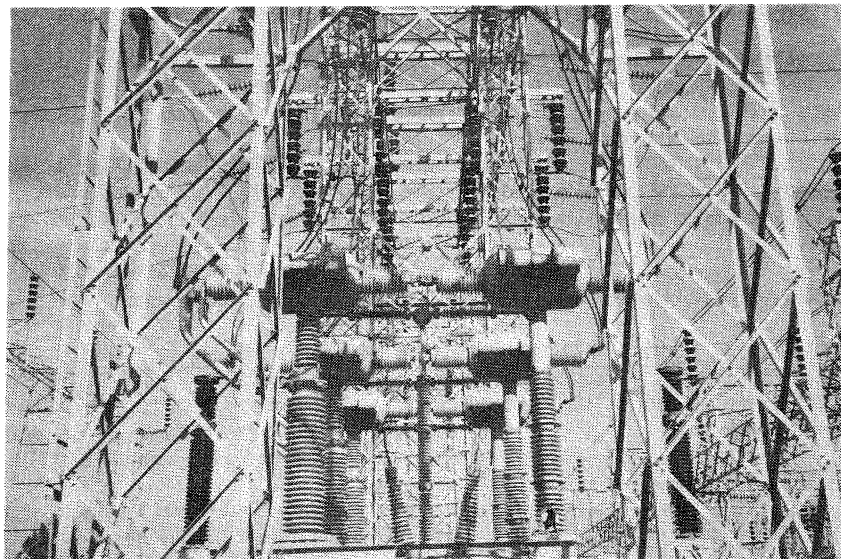


Figure 2 - DAMAGED 230kV AIR BLAST CIRCUIT  
BREAKER AT SAN MATEO SUBSTATION

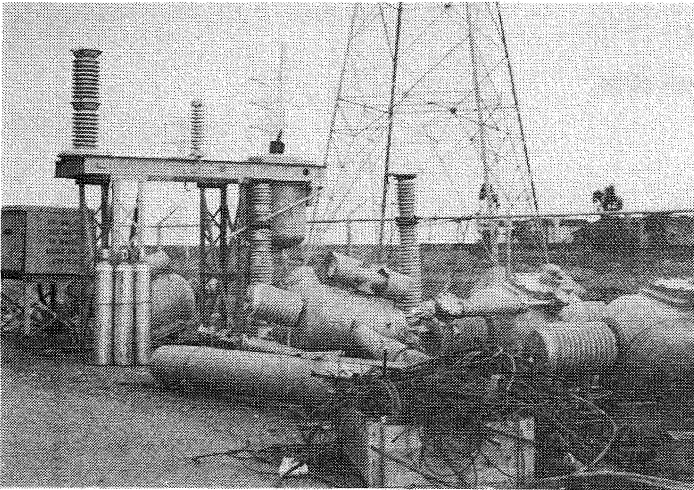


Figure 3 -  
REMAINS OF DAMAGED CIRCUIT  
BREAKER - SAN MATEO

Figure 4 - DEAD-TANK 230 kV CIRCUIT BREAKER  
INSTALLED AFTER THE EARTHQUAKE,  
SAN MATEO.

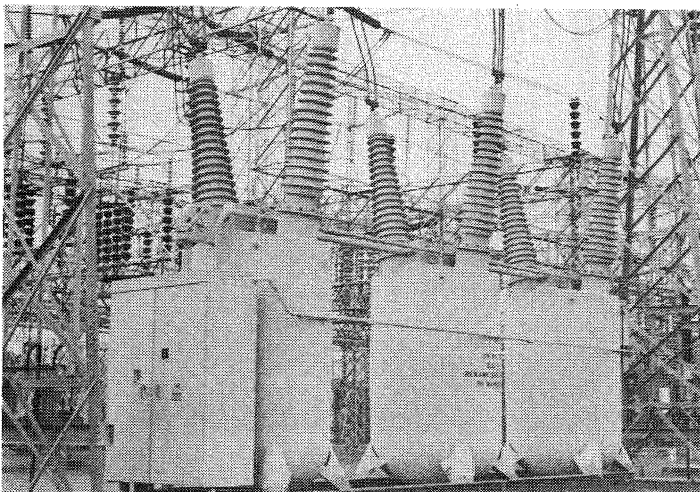
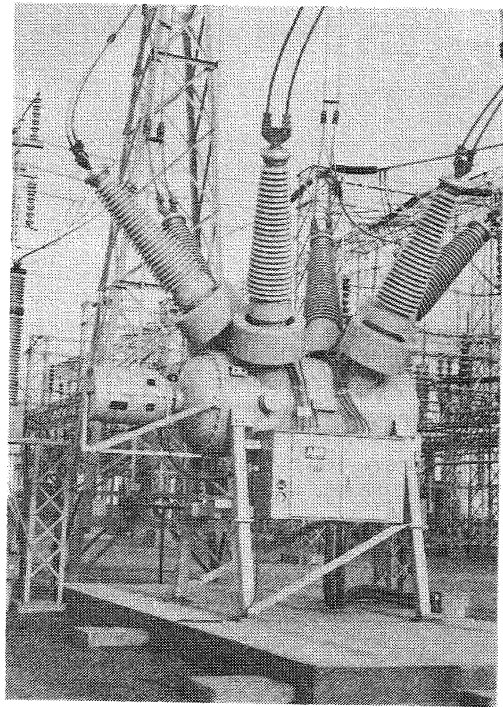


Figure 5 -  
230 kV BULK OIL CIRCUIT BREAKER DID  
NOT EXPERIENCE ANY DAMAGE -  
SAN MATEO.

### Transformers

There were two banks (Banks 11 and 12) of seven single phase 374/200 MVA, 500/230 kV transformers at Metcalf.

The damage included:

- i) A 500 kV bushing on transformer 11C shifted on its support which put it out of service (Fig.6). This transformer was replaced by the spare unit.
- ii) Severe oil leaks at the flange joining the top header of the radiator to the main tank of transformer 12C (Figures 7 & 8). This occurred as the radiators swayed during the earthquake.
- iii) Two out of seven 230 kV transformer-mounted lightning arresters associated with bank 11 cracked at the base and fell to the ground (Fig.9).

They were replaced by the units from Bank 12.

### 500 kV live-tank Circuit Breakers

All three of the air blast WE circuit breakers were damaged at the base as shown in Figures 10 & 11. The hold down clamps also failed and allowed the circuit breakers to shift up to 250 mm horizontally (Fig.11).

There were three columns per circuit breaker. Each consisted of four porcelain cylinders, stacked on top of each other, separated by rubber gaskets (1) and an interrupter head at the top. The whole assembly was held together and secured to the support base by post-tensioned fibreglass rods. These rods replaced the original wooden rods as an attempt to strengthen the circuit breakers (Fig.12). Unfortunately, this did not prevent the porcelain bushing from extensive cracking despite the fact that the rods were not damaged.

It should be noted that the Hitachi 500 kV dead tank breaker (Fig.13), which was tested to 0.5g ground acceleration using the sinewave method, was undamaged.

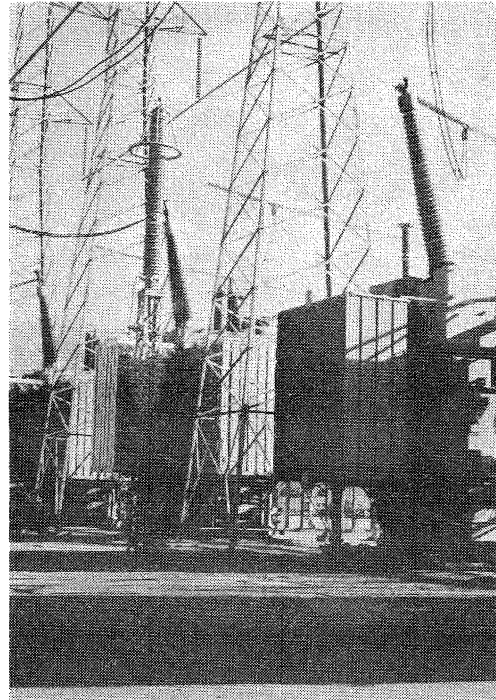


Figure 6 - THE 500 kV BUSHING ON THE RIGHT-HAND SIDE OF THE PHOTOGRAPH WAS REPLACED AFTER THE EARTHQUAKE - METCALF.

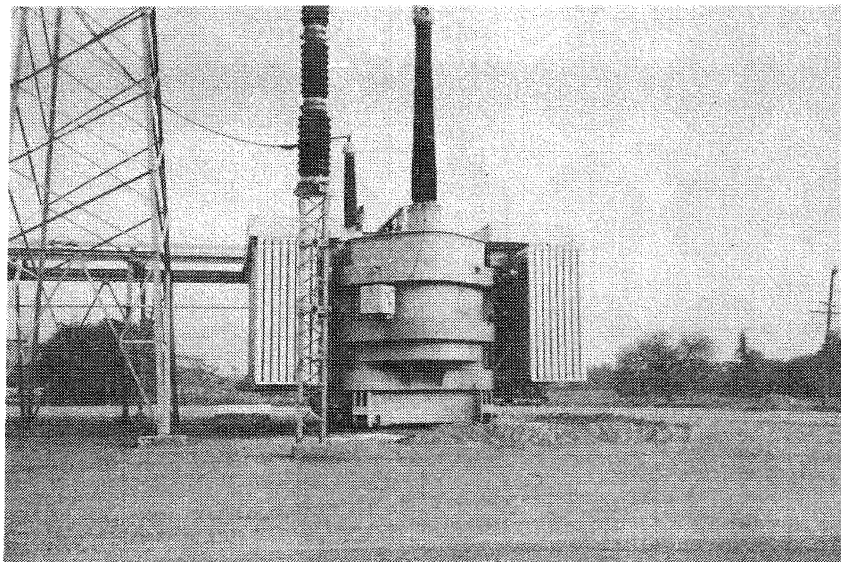


Figure 7 - TRANSFORMER 12C (BANK 12, C PHASE) LOST OIL DURING THE EARTHQUAKE - METCALF.

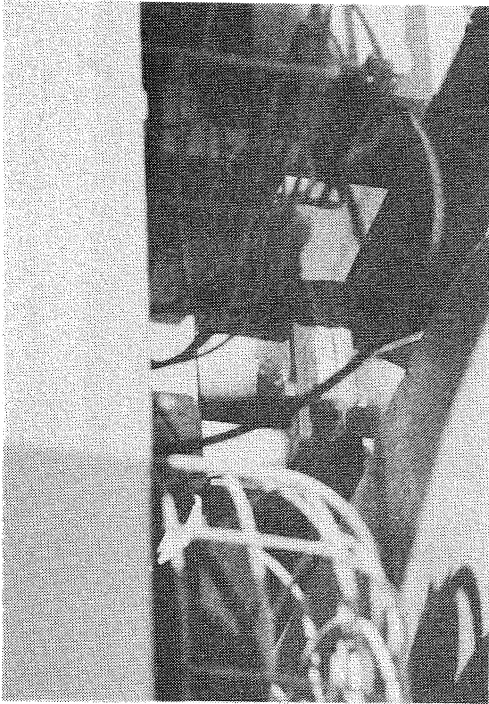


Figure 8 - A CLOSE-UP VIEW OF THE JOINT WHERE THE OIL WAS LEAKED DURING THE EARTHQUAKE - METCALF.

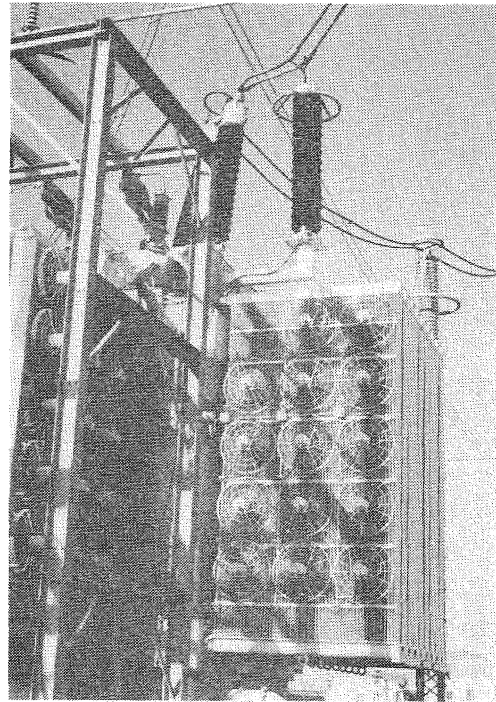


Figure 9 - 230 kV SURGE ARRESTER SUCH AS THIS ON BANK 11 WAS DAMAGED - METCALF.

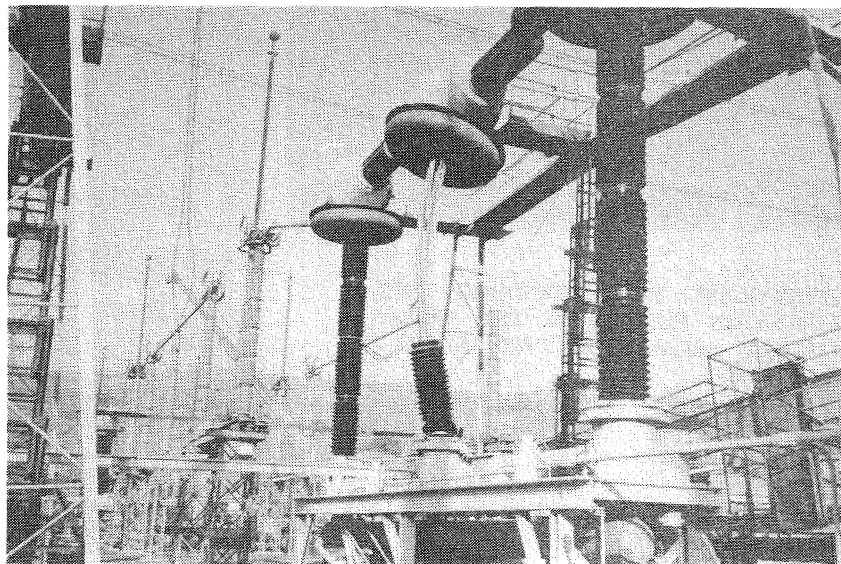


Figure 10 - DAMAGED 500 kV CIRCUIT BREAKER - METCALF.

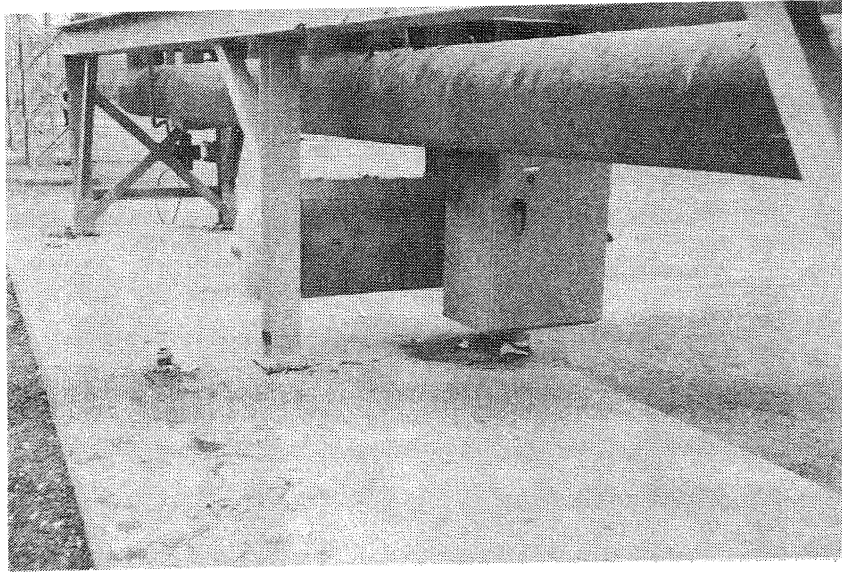


Figure 11 - THE FAILURE OF THE HD BOLT CAUSED THE SUPPORT STAND OF THE 500 kV CIRCUIT BREAKER TO BE SHIFTED. SEE ALSO FIGURE 15 - METCALF.

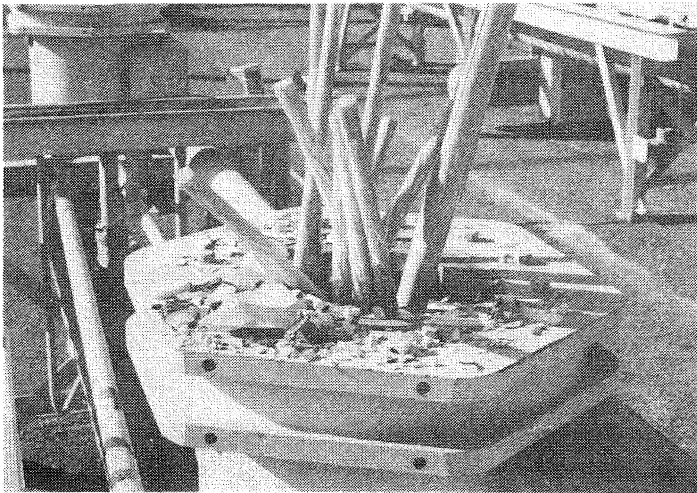


Figure 12 - FIBRE-GLASS RODS SECURING THE PORCELAIN COLUMN OF THE 500 kV CIRCUIT BREAKER TO THE BASE - METCALF.

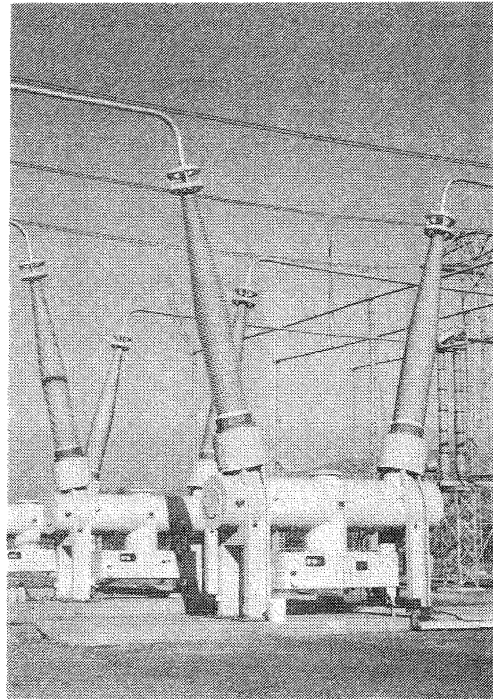


Figure 13 - MITSUBISHI 500 kV DEAD-TANK CIRCUIT BREAKER INSTALLED AFTER THE EARTHQUAKE - METCALF.

#### 500 kV Current Transformers (CT)

There were nine Westinghouse's HDR-2138 ACT 1800 CT's associated with the three circuit breakers. Most suffered oil leaks. Between 757 and 1135 litres (200 and 300 gallons) of oil were lost per unit. A few were damaged as shown in Fig.13. These CT's were very old and did not meet PG&E's present seismic design requirements.

### 2.3 Damage at Moss Landing Substation

Moss Landing substation has 500 kV, 230kV and 115 kV switchyards. Compared with the other sites, about 25 km southeast, Moss Landing is closest to the epicentre. The damage at Moss Landing was the most severe. It was built on flat and relatively soft ground.

The earthquake intensity experienced at Moss Landing has been estimated at MM 7. Ground acceleration was estimated at between 0.2 g and 0.4 g. Records obtained about 13 km north of Moss Landing, at Watsonville, showed a peak horizontal acceleration of 0.39 g (1).

Damage at Moss Landing substation mainly occurred in the 500 kV switchyard. The damaged equipment included 500 kV live-tank circuit breakers, current transformers, disconnectors, buswork, CCVT (coupling capacitor voltage transformers) and linetraps. Other items in the same switchyard such as power transformers, the control room and the control building withstood the earthquake undamaged. In the 230 kV switchyard, the major damage was to the disconnector switches supported on the gantry structure.

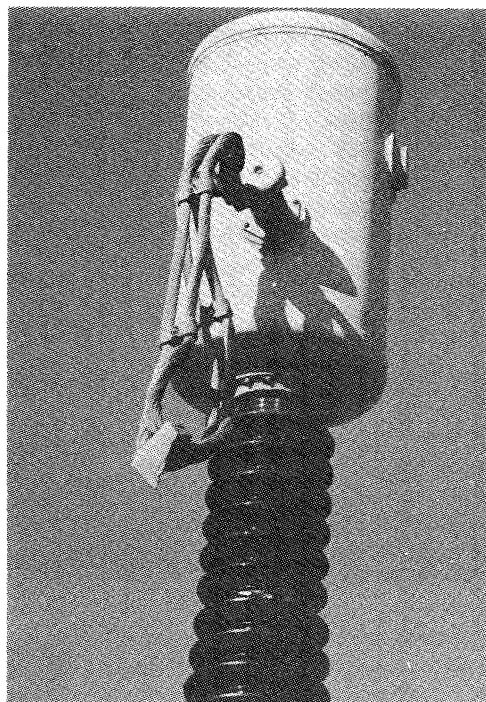


Figure 14 - A CLOSE-UP VIEW OF THE DAMAGED 500 kV CURRENT TRANSFORMER - METCALF.

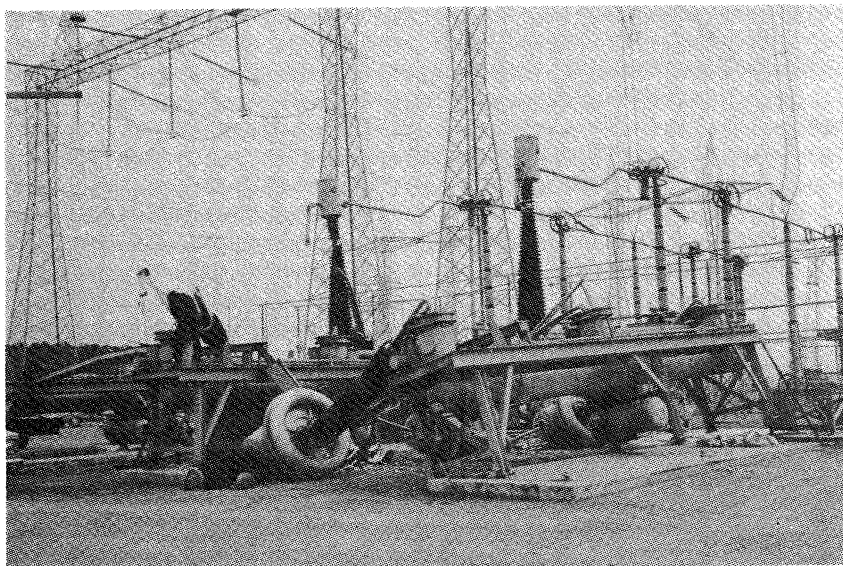


Figure 15 - DAMAGED 500 kV CIRCUIT BREAKER - METCALF.

#### 500 kV live-tank circuit breakers

There were five 500 kV circuit breakers at the site. Four of those, which were similar to those at Metcalf substation, suffered extensive damage. The damage included failure to holding down bolts and failure of support columns as shown in Figures 15 & 16. The fifth one, a modern dead-tank circuit breaker, similar to that in Fig. 13, survived the earthquake.

#### 500 kV Current Transformers (CT)

Ten out of twelve CT's (similar to those at Metcalf substation) suffered damage (Figures 16 & 17).

#### Linetraps and CCVT

One line trap out of four and all four CCVT's associated with the linetraps failed when the support porcelain bushings broke at their base (Fig. 19).

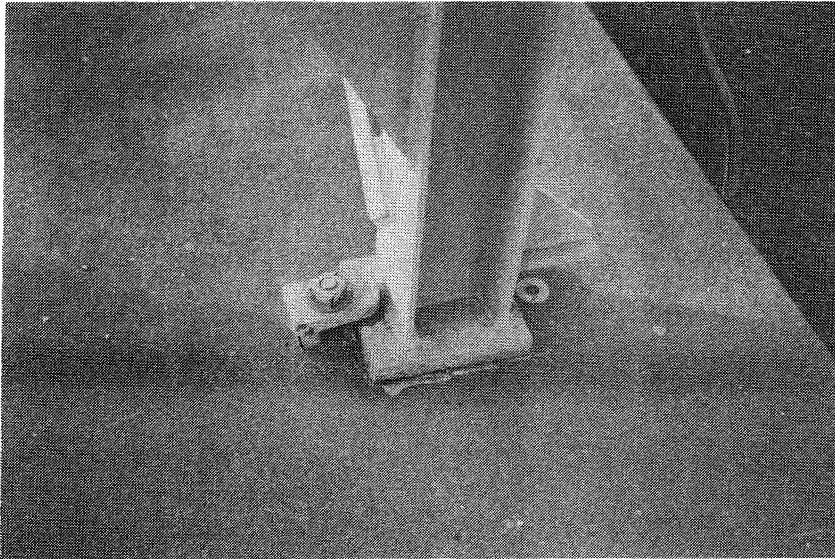


Figure 16 -

UNDAMAGED HOLDING DOWN BOLT FOR  
500 kV CIRCUIT BREAKER SUPPORT  
STAND - METCALF.

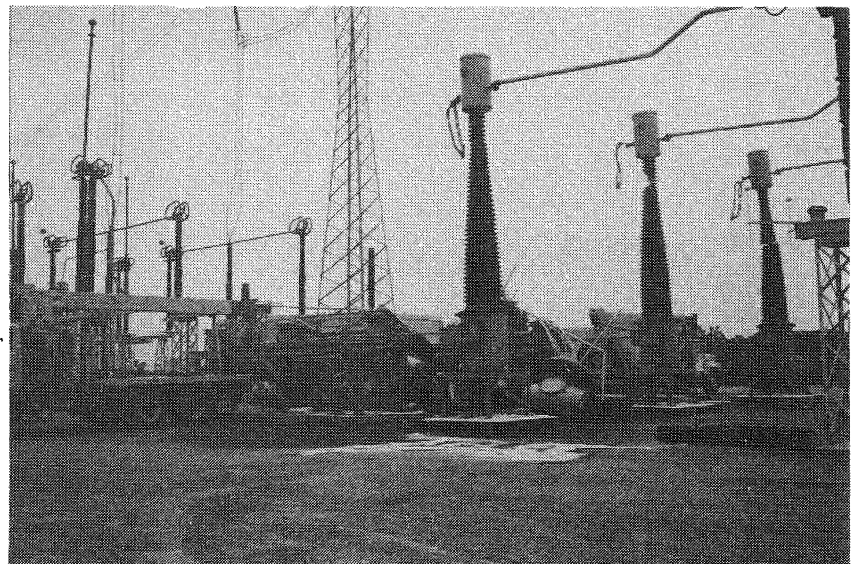


Figure 17 -

DAMAGED 500 kV CURRENT  
TRANSFORMERS - MOSS LANDING.

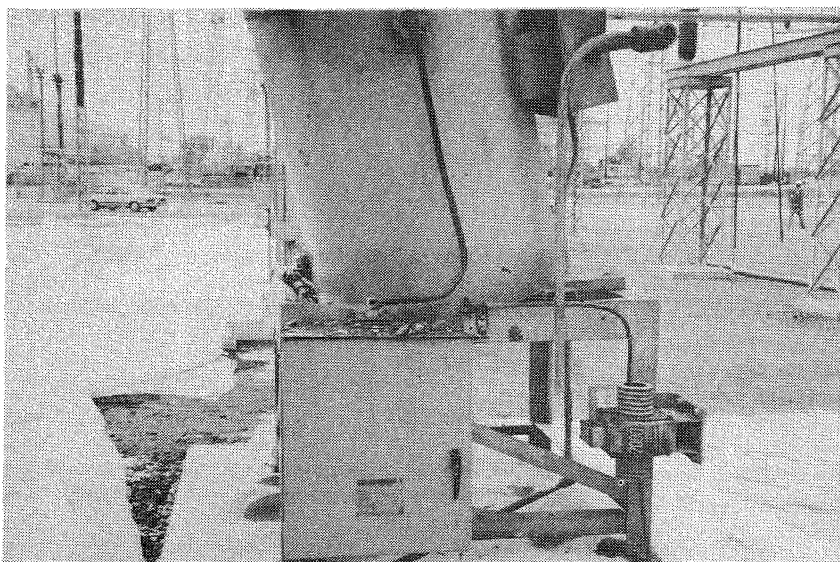


Figure 18 -

DAMAGE TO 500 kV CURRENT  
TRANSFORMER SUPPORT STAND -  
MOSS LANDING.

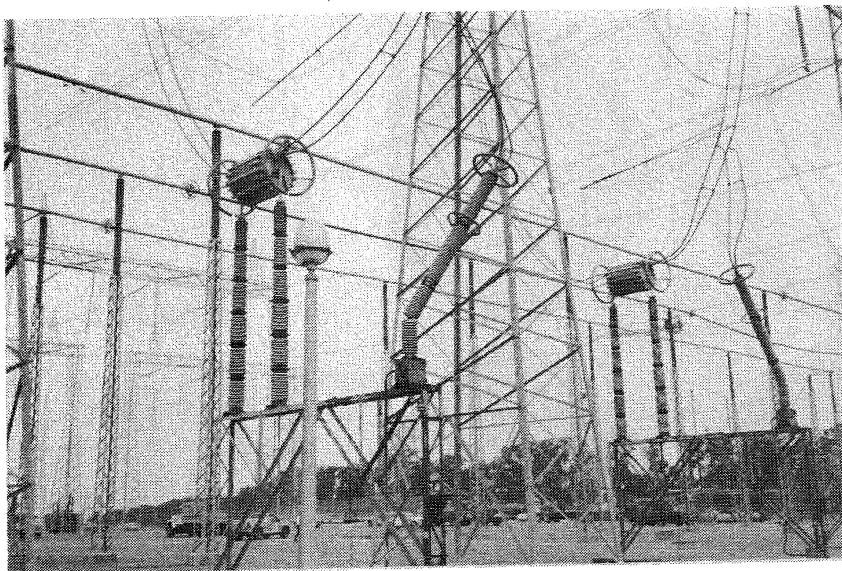


Figure 19 -  
DAMAGED CCVT - MOSS LANDING.

#### 500 kV disconnecter switches

Out of a total of 14 three-phase disconnecter switches units, 12 (three-phase units) were damaged. (Figures 20 & 21).

The two three-phase units connected to the surviving dead-tank circuit breaker did not experience any damage. This suggested the damaged units were pulled down by the damaged CT's and circuit breakers connected to them.

#### 500 kV buswork

A long span of the 500 kV aluminum busbar came down during the earthquake (Fig. 22). This took place because the support insulator broke at the base and the fitting attaching the bus to the top of the insulator also failed.

The buswork was repaired within two days.

#### 230 kV disconnecter switches

Most of 230 kV disconnecter switches supported on gantries were found to be misaligned after the earthquake. On one bay (out of 10), a few disconnecter switches were damaged. The support porcelain broke at the base (Figures 23 & 24).

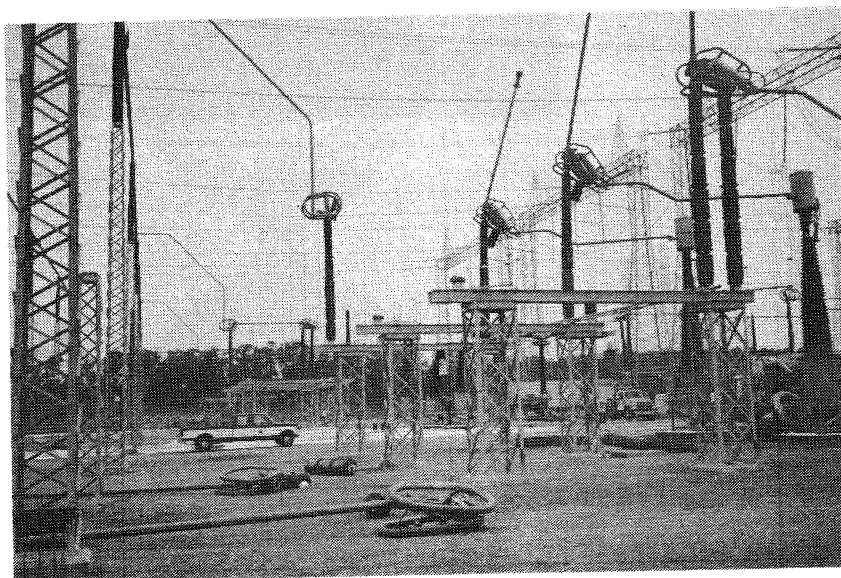


Figure 20 - DAMAGED 500 kV DISCONNECTOR SWITCHES. NOTE THAT NOT ALL SUPPORT INSULATORS WERE BROKEN - MOSS LANDING.

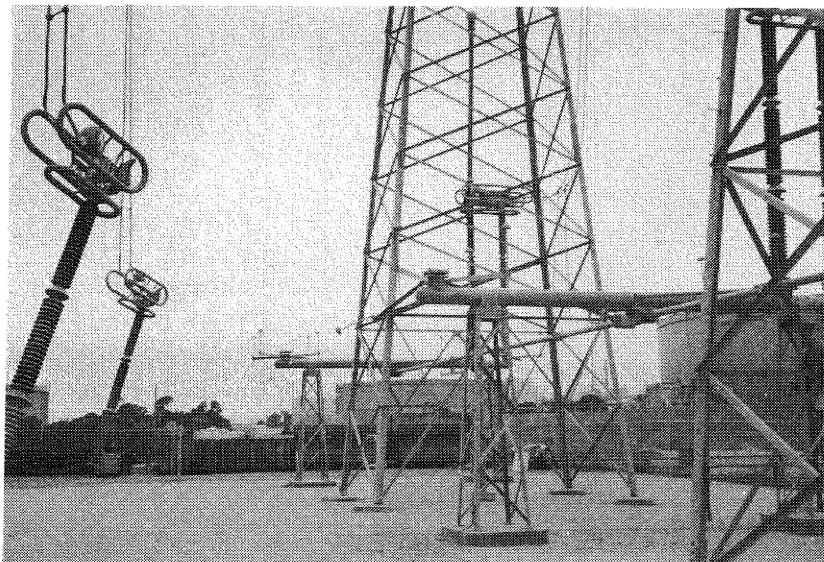


Figure 21 -

DAMAGED 500 kV DISCONNECTOR SWITCHES - MOSS LANDING.

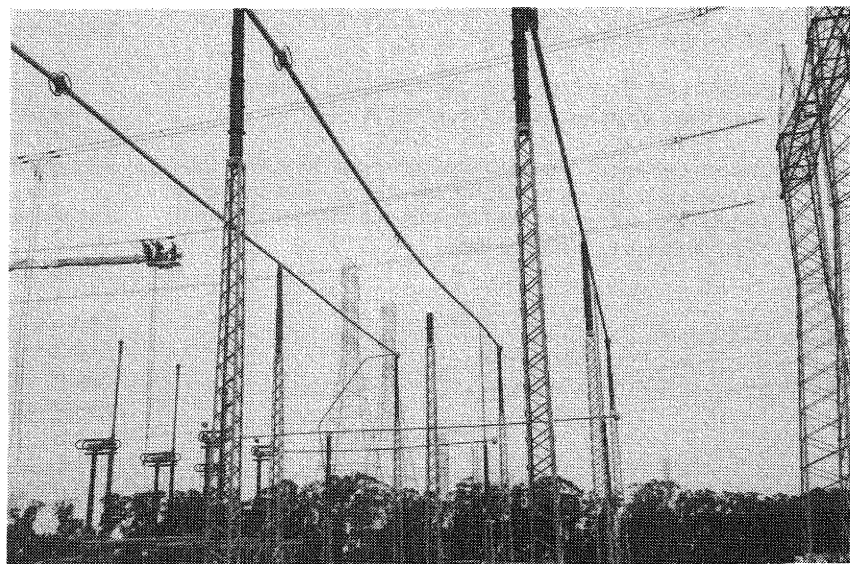


Figure 22 -

DAMAGED 500 kV BUSWORK - MOSS LANDING.

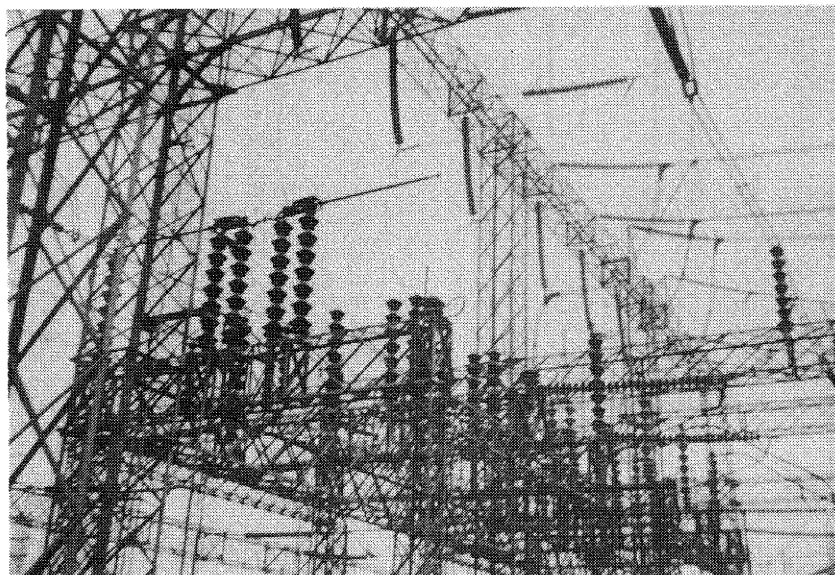


Figure 23 -

DAMAGED 230 kV DISCONNECTOR SWITCHES - MOSS LANDING.

### 3. DESCRIPTION OF THE DAMAGE AT THE POWER STATIONS

#### 3.1 Moss Landing Power Station

Moss Landing Power Station is next to the switchyards, damage of which has been described earlier. It is an oil and gas-fired power station. There are 7 units : the 2x750 MW units were built in the late 1970's, the 3x110 MW and 2x120 MW units were built in the early 1950's.

The 2x750 MW units are Units 6 and 7.

Unit 7 was out of service at the time but Unit 6 was in operation. It was put out of service by the earthquake. It was believed that the shutdown done manually. Other units did not experience any significant damage.

The damaged equipment included water tanks, chimney ties, pipe hanger rods, feed heater supports and air preheater bearings.

In general, the damage was not considered serious. The cost of damage was estimated at \$US 5 millions.

#### Water Tanks

One 1,135,500 litres (300,000 gallon) tank of approximately 16 m in diameter and 12 m high, fabricated from steel plates, was badly damaged. The damage occurred at the base, which was corroded, and allowed water to escape. This created a drop in pressure inside the tank and caused the tank plate to buckle (Figures 24 & 25). The internal roof structure was also damaged.

In itself, the damage of this free-standing tank was not serious. However, as it stored water for fire fighting, the consequence of its damage would have been much more serious if fire had broken out at the site.

It should be noted that there were other tanks at the site which survived the earthquake. The large fuel oil tanks, for example, did not experience any damage.

#### Chimney ties

The 152 m tall chimneys for Units 6 and 7 consisted of a concrete stack with a steel liner inside. The liner was supported against the concrete outer stack by tie rods at 10 m intervals up the stack. The relative movement between the liner and the stack caused the rods to break at the anchor points, both at the liner and the stack ends. However, the majority of the damage was at the liner end.

The damage to various degrees occurred at both chimneys, but did not render them inoperable.

The repairs involved the replacement of the tie rods with a new design, using a bumper system, which allowed for relative movement during earthquakes. This is in line with the current USA design practice.

#### Steam pipe support damage

There were significant lateral movements in steam piping, especially in the main steam pipe. This caused numerous damage to support hangers, lagging and guides. Spring loaded supports experienced damage to the bolts securing the spring base to the anchor. Some springs actually broke.

There was also damage to boiler insulation and leakage from boiler tubes.

#### Feed heater support

The tension-only braces of the three horizontal feed heater's steel support stands were buckled. Concrete support pedestals of other feed heaters were cracked.

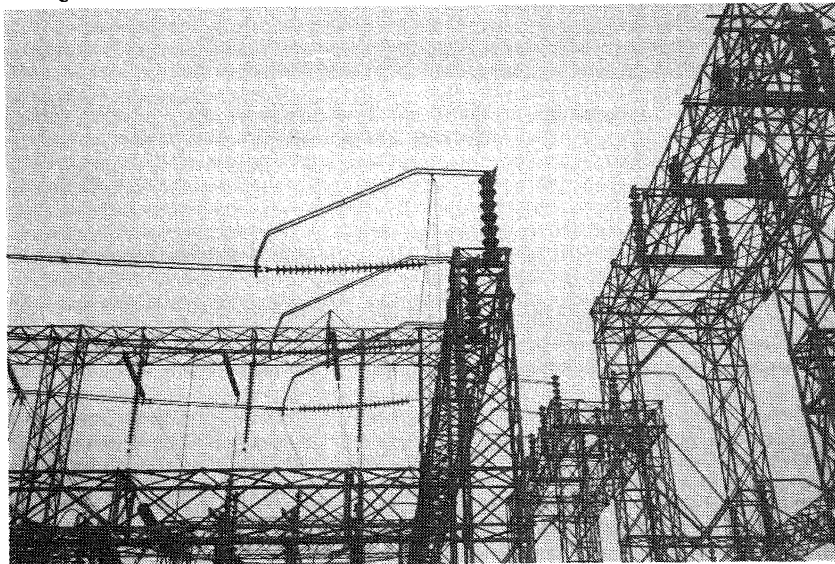


Figure 24 - DAMAGED 230 kV DISCONNECTOR SWITCHES - MOSS LANDING.

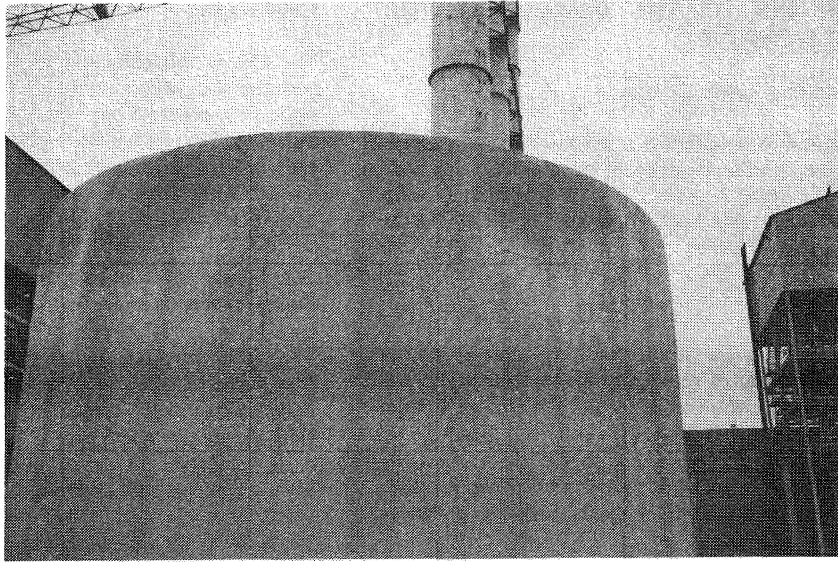


Figure 25 - DAMAGED WATER TANK - MOSS LANDING.

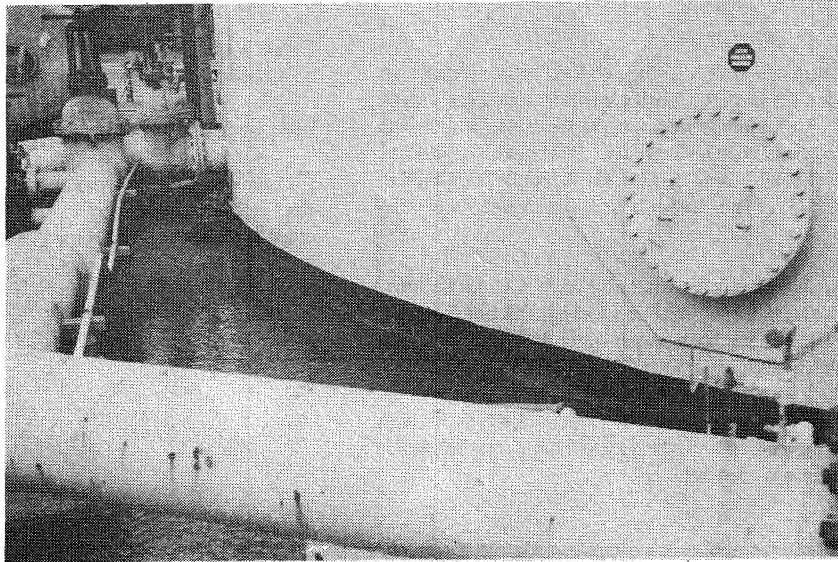


Figure 26 - VIEW OF THE BASE OF THE DAMAGED WATER TANK - MOSS LANDING.

#### Other damage

One low pressure (LP) turbine bearing was damaged when the unit was shut down after the earthquake. This was caused by the loss of AC power which was required to supply the lubricating oil to the bearing.

One air preheater shaft was shifted out of its pedestal.

The steel brace joining the steel structures of Units 6 and 7 was buckled and the base of the cooling water plant crane was shifted.

Overall, the damage was not considered serious.

#### 3.2 Potrero Power Station

Potrero power station has 1x220 MW steam turbine (oil/gas) and 3x50 MW gas turbines. The steam unit was commissioned in 1965 and the gas turbines in 1976.

Potrero and Hunter Point power stations supplied most of the power to San Francisco city. They are located within 1.5 km of each other and about 13 km from the Marina District where extensive damage to houses occurred.

The damage to both stations was considered to be relatively minor. The cost of damage was estimated at US\$2 millions.

At Potrero, the earthquake caused the supply fuel valve to open. Excessive fuel flow shut off the fire in the boiler and tripped the boiler. One of the circuit breakers in the switchyard had a flash-over in B-phase and tripped. This caused a loss of AC power which shut down the air compressors. On the loss of compressed air, the pressure reducing valve on the 13.8 bar (200 psi) auxiliary steam line from the steam drum failed to open. The relief valve downstream of this opened and allowed steam from the steam drum (165 bar = 2400 psi pressure) to escape for 20 minutes before the operators became aware of the steam loss.

The loss of steam caused the steam drum temperature to increase to the point where a differential temperature between the feed water condensate and the steam drum was too high to allow the boiler to be restarted. Fortunately, a US Navy ship was in port at the time and it was used to provide hot steam to heat up the feed water. It took nearly 52 hours before the boiler was fired up again.

### 3.3 Hunter Point Power Station

Hunter Point power station has 2x110 MW and 1x170 MW steam turbines and 1x50 MW gas turbine. The steam units were commissioned in 1949 and 1958 respectively. The gas turbine was a recent addition in 1976.

At the time of the earthquake, 2x110 MW units were operating and, at about 1hr 40 mins after the earthquake, there was a malfunction of relays which caused an overload of the house unit and a subsequent loss of auxiliary power supplied to the main generator. The whole power station lost power completely. Power was not restored until one hour later. The back-up generator failed to start as the vibration monitor did not switch to DC. The inverter failed and no AC power was available.

### 4. DAMAGE TO OTHER NON-PG&E POWER STATIONS

At the University of California, Santa Cruz, the 2.5 MW diesel plant survived the earthquake without any damage. The ground acceleration was measured at 0.4 g. Problems occurred when the unit could not keep up with the load when PG&E power supply was lost.

The 50 MW Cardinal Co-generation plant near Stanford University was designed to withstand 0.5 g ground acceleration. It was built between two and three years ago and withstood the earthquake successfully. Ground acceleration was measured at 0.3 g.

The 120 MW combined cycle (50 MW gas, 70 MW steam) at Gilroy was built in 1987 and withstood the earthquake without any damage. There was some leakage from the 115 kV substation which caused a forced outage for two hours. The ground acceleration was measured at 0.4 g in a school house at about one kilometre from the plant.

## 5. CONCLUSIONS

1. While the damage, as illustrated by the photographs, appeared extensive, it should be viewed in perspective.

Within the area where intensities MM 7 and greater were felt, there were an estimated total of 100 or so substations of various voltages, 1000 or so kilometres of high voltage overhead transmission lines and ten or so power stations. Out of this total system, it would be difficult to refer to the damage as described above as extensive.

As experienced in past earthquakes :

2. The damage to outdoor substation equipment was more extensive and severe than to power station equipment.
3. Live tank circuit breakers were more susceptible to earthquake damage than dead tank circuit breakers.
4. Equipment of 230 kV and 500 kV voltages were more likely to be damaged by earthquakes than those at 115 kV and below. In fact, there was no damage to equipment in this lower voltage rating.
5. The damage was mostly to older equipment of at least 25 years old. Equipment and facilities built to modern seismic design practice suffered little or no damage.

## 6. RECOMMENDATION

The Loma Prieta earthquake has shown that power systems, in general, are quite fragile and it would not take much damage to put them out of operation.

It would be impractical, if not impossible, to ensure that a power system with a mixture of old and new equipment like that of PG&E to remain operational during earthquakes of Loma Prieta magnitude.

It would be more realistic for power system owners to develop an earthquake protection programme based on seismic performance criteria set, not only by earthquake design loads, but also by an outage time, say 48 hours. Once these criteria are selected, the owners would formulate an implementation programme to ensure that their system is designed, strengthened and carries adequate redundancy or spares so that power can be restored within this outage time.

To formulate an implementation programme, a risk assessment of the power system taking into account the structural vulnerability of each component in the system, its importance in the network and the earthquake hazard including local soil conditions where the components are located should be carried out.

## 7. IMPLICATIONS FOR NEW ZEALAND

- 7.1 Our power system equipment are rated at 230 kV AC and below, which are structurally less vulnerable to earthquake damage than 500 kV equipment at Moss Landing and Metcalf substations.
- 7.2 Our current seismic design requirements for power system equipment, which have been applied since 1971, are on the same level if not higher than those specified by PG&E.
- 7.3 If a Loma Prieta-magnitude earthquake were to occur in Wellington, we would expect a similar if not higher level of damage to our power system. This is because the vulnerable items are older transformers on wheels which would take a longer time and more costly to repair if they come off the rails (2).

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