REVIEW OF

AGING-SEISMIC CORRELATION STUDIES ON NUCLEAR POWER PLANT EQUIPMENT

By

M. Subudhi

January 1985

Engineering Technology Division
Department of Nuclear Energy
Brookhaven National Laboratory
Upton, N.Y. 11973

1.0 INTRODUCTION

During the last decade the issue relating to aging-seismic correlation of nuclear grade equipment and their sub-components has received special attention by both the NRC and the utility industry with the aim of preventing any catastrophic failures of aged components during a seismic event. This report summarizes the work performed by the Seismic Qualifications Utility Group (SQUG) based on real earthquake data, by NUTECH for Sandia National Laboratory, and by EPRI at Wyle. Based on the above, an outline of the work to be carried out at BNL under the NPAR scope relating to identifying the aged components sensitive to seismic loadings is provided.

In order for an equipment to independently undergo severe inertial loading and possible failure as a result of seismic excitations, each component or assembly of components must have both significant mass so that the input acceleration produces a large inertial force, and the flexibility to premit large deformations. It is plausible that individual sub-components in equipment might not possess any of the above, however, as an assembled circuit the equipment can have susceptibility to earthquake-induced excitations. Within the context of age-related degredation, certain component material "weak links" will fail subject to insuitable levels of cyclic loads and hence, aging-seismic correlation of such equipment exists and has the potential to fail in the event of an earthquake.

2.0 REVIEW OF SQUG PILOT STUDY ON EQUIPMENT QUALIFICATION

REPORTS: "Pilot Program Report: Program for the Development of an Alternative Approach to Seismic Equipment Qualification", Peter Yanev, Sam W. Swan, Vol. I & II.

EQE Inc., sponsored by the Seismic Qualification Utilities Group (SQUG) has developed a data base on the performance of equipment in five fossil-fueled plants consisting of 24 units and a high-voltage DC-to-AC converter station. These plants have experienced four damaging California earthquakes of Richter Magnitudes 5.1 to 6.6. Peak horizontal ground acceleration (PGA) of these earthquakes ranged between 0.2g and 0.5g. The atual earthquake induced equipment effects were compared with equipment qualification data from three nuclear plants.

The objective of the pilot program was to determine the feasibility of establishing criteria for assessment of the seismic adequacy of equipment in nuclear power plants based on evaluation and application of data to be acquired on the characteristics and seismic performance of equipment in non-nuclear power facilities that have been subjected to strong-motion earthquakes. Application of the criteria would provide a valid basis for assessing the need for subsequent qualification efforts in the nuclear industry and for defining the extent of the effort.

The data base plants included in the pilot program are listed below:

Earthquake	Facility and Location	Estimated PGA*(g's)	Type of Equipment Present
San Fernando 1971	1) Sylmar Converter Station, Sylmar	0.50-0.75	Electrical & some mechanical
	2) Valley Steam Plant, San Fernando Valley (4 Units)	0.40	ALL
	3) Burbank Power Plant, Burbank (7 Units)	0.35	ALL
	4) Glendale Power Plant, Glendale (5 Units)	0.30	ALL
	5) Pasadena Power Plant, Pasadena (4 Units)	0.20	ALL
Imperial Valley 1979	1) El Centro Steam Plant, El Centro (4 Units)	0.51	ALL

* Peak Grand Acceleration (estimated except for El Centro)

All of the above plants are located in California. The general considerations guiding these particular selections were based on:

- density and number of candidate equipment items
- age of facility
- cooperation of owner
- possibility of field testing while facility was operating
- estimated PGA at the site
- location

The three nuclear plants selected for detailed study are:

Facility	Reactor Type	OL Date	SSE ZPA (g)
Dresden 3, ILL	BWR	1970/71	0.20
Pilgrim, Mass.	BWR	1972	0.15
Calvert Cliffs 1, MD	PWR	1975/77	0.15

Only the equipment required for safe shutdown were considered in the surveys. The basis for selecting these plants were:

- possibility of field testing while facility was operating or was in an outage
- age and type of reactor
- participation of the utility in SQUG

It should be noted that most of the equipment of interest in the data base plants is located at grade, in basements, or in the first two floor of the structures (upto the turbine decks).

2.1 SQUG Evaluation

The flowchart on the following page is excepted from the pilot program report. It is for the pilot program conducted by EQE in comparing the data base plant equipment with nuclear power plant components. Seven classes of equipment were selected for detailed study. Each class was reviewed to determine similarities between equipment in the two types of power plants. The following characteristics were examined to establish similarity: primary structural and functional characteristics; dimensions and name-plate data; and ranges of dynamic-response frequency. The response frequencies found during the testing were compared to determine whether the equipment in the data base plants and the nuclear plants could be expected to have similar dynamic response properties.

The seven generic classes of equipment selected in the pilot program include:

- motor control centers
- low voltage (48 V) switchgear
- metal-clad (2.4 to 4 KV) switchgear
- motor-operated valves
- air-operated valves
- horizontal pumps
- vertical pumps

This equipment represents a large portion of the safety related equipment in nuclear plants, and therefore numerous examples were found in the data base facilities.

Although the pilot program focussed on the six data base plants representing 24 fossil units and one converter station, the report included results from a total of 14 data base plants involving 4 different California earthquakes. The study has included a wide variety of mechanical and electrical equipment, beyond the seven classes indicated above. Appendix A provides short summaries of each earthquake event and the equipment affected in the 14 data base plants.

The performances of the seven classes of equipment from the six data base plants were compared with equipment in three nuclear power plants. About 2,600 items were studied in the program. With the exception of some relay chatter that caused plant trips in at least two instances, electrical equipment that was properly anchored withstood the earthquakes without damage and functioned properly during and after the event. The following is the summary of the equipment performance.

	Performance in Earthquake Environment Of At Least 0.2g Peak Ground Acceleration (Number of Items in Pilot Program Survey)	
	NO DAMAGE	DAMAGED
1. Motor control Center Cabinets	6	0
1a. Motor Starters	850	0
2. Low-Voltage Switchgear Cabinets	27	0
2a. Low-Voltage Circuit Breakers	350	0
3. Metal-Clad Switchgear Cubicles	185	0
3a. Door Mounted Relays	550	0
4. Motor-Operated Valves	45	0
5. Air-Operated Valves	370	1*
6. Horizontal Pumps	240	0
7. Vertical Pumps	160	0
TOTAL:	2,565**	1*

Notes:

* The one failed valve was damaged by impact with an adjoining girder, and not be inertial forces generated by the earthquake.

** The total excludes the cabinets.

1. The equipment count is approximate and probably low.

2. The data summarized inthe table is based only on six plants studied in detail. It is representative, however, of the nine other data base facilities visited.

3. Ceramic switchyard equipment is not included in this study.

4. Many of the items of equipment listed were exposed to peak ground accelerations exceeding 0.5g with no failures.

It is concluded that the equipment is very similar in both nuclear and fossil frcilities and is inherently rugged and highly resistant to inertial earthquake loads.

2.2 SQUG Conclusions

Based on the above SQUG has concluded the following:

1.) The above conventional power plant equipment has experienced earthquakes with intensities equal to or exceeding seismic loads that are associated with many NPP safe shutdown earthquake levels.

2.) Certain types of mechanical and electrical equipment found in NPPs are very similar to the types found in conventional plants.

3.) Seismic qualifications of nuclear equipment by conventional methods is not necessary for the classes of equipment evaluated for an SSE level of 0.3g.

4.) The equipment in the original seven classes are inherently rugged in order to withstand seismic hazards of 0.2g to 0.3g ZPA. Hence, seismic qualification by conventional methods are unnecessary for these classes of equipment.

2.3 SSRAP Review

A five member Senior Seismic Review and Advisory Panel (SSRAP) was formed by SQUG in agreement with NRC in July 1983. The NRC had spent a considerable amount of effort in assessing the validaties claimed by SQUG. The panel consisted of the following members:

Senior Seismic Review and Advisory Panel (SSRAP)

Robert P. Kennedy	Structural Mechanics Associates Newport Beach, CA
Walter A. von Riesemann	Sandia National Laboratories Albuquerque, NM
Paul Ibanez	ANCO Engineers, Inc. Culver City, CA

Anshel J. Schiff — Purdue University (currently on sabbatical at Stanford University)

Loring A. Wyllie, Jr. — H. J. Degenkolb Associates, Engineers San Francisco, CA

The panel has added an eighth class of equipment, unit substation transformers. Hence, the assessment is limited to the following eight classes of equipment:

1.) Motor Control Centers
2.) Low-Voltage (480 V) Switchgear
3.) Metal-Clad (2.4 to 4 KV) Switchgear
4.) Motor-Operated Valves
5.) Air-Operated Valves
6.) Horizontal Pumps and Motors
7.) Vertical Pumps and Motors
8.) Unit Substation Transformers

The review efforts of the SSRAP was limited to the following on the performance of these eight classes of equipment:

1.) Detailed reviews of Valley Steam Plant, Burbank Power Plant, Glendale Power Plant, and Pasadena Power Plant, the Sylmar Converter Station, and El Centro Steam Plant. The panel had extended their reviews to the pumping stations and petrochemical facilities subjected to the 1983 Colinga earthquake (magnitude 6.7).

2.) Limited reviews were conducted on other facilities reported in the previous section and also included literature reviews for reported failure of equipment as a result of other large earthquakes.

3.) Walk-throughs of some plants were made and the panel spoke to operators discussing the problems experienced during or shortly after the earthquake. The plant visits also included NPPs as well as vendor facilities to compare nuclear grade equipment with the commercial ones in fossil plants.

4.) Reliance was placed on the extensive collective experience of its five members with these eight classes of equipment.

In conclusion, SSRAP was in almost complete agreement with the findings of SQUG. Equipment installed in NPP's is generally similar to and at least as rugged as those installed in conventional plants. The equipment, within the eight classes mentioned before, has an inherent seismic ruggedness. They demonstrated capability to withstand significant seismic motion without structural damage during as well as after the seismic event. However, the data base is insufficient to preclude the possibility of relay chatter or breaker trips.

SSRAP has suggested three different seismic motion bounds shown in the Figure on the fillowing page. These bounds may be used for the equipment class as given below:

Equipment Class	Bound
Motor control centers Low-voltage (480 V) switchgear Metal-clad (2.4 to 4 KV) switchgear Unit substation transformers	Type B
Motor-operated valves those with eccentric operators and large lengths to pipe diameter ratios	Type C
Motor-operated valves (exclusive of those with eccentric operator and large lengths to pipe diameter ratios) Air-operated valves Horizontal pumps and their motors Vertical pumps and their motors	Type A

The qualification of equipment is not required provided the horizontal design spectrum (5% damping) lies below the appropriate bounding spectrum at frequencies greater than or equal to the fundamental frequency range of the equipment. This comparison is acceptable provided the equipment is properly mounted, less than about 40 feet above grade, and has moderately stiff structures. For equipment mounted above this height, comparisons of 1.5 times these spectra should be used.

2.4 BNL Comments

The major thrust of the SQUG and SSRAP efforts is to answer the NRC unresolved safety issue A-46 relating to seismic qualification of equipment in operating plants. Neither the NRC nor utility sponsored studies have addressed the question of aging of equipment. That is unless on considers the fact that the SQUG data base equipment was over 20 years old at the time of the earthquake exposure, and that some of this equipment is located in reasonably high thermal and corrosive environments.

The following is a summary of BNL's review:

1.) The aging of equipment was not emphasized in either the SQUG or the SSRAP efforts in evaluating its seismic capacitywith the exception that the equipment was 20 years old. The true age of the equipment from the maintenance records was not determined. It should be noted that the data base equipment was not exposed to radiation or harsh environment as could be the case for nuclear accident conditions inside the containment.
2.) Although, maintenance personnel have noted increased wear in bearings of vertical pump shafts subsequent to the earthquake event, no follow up studies have been conducted to ensure aging-seismic degradation of the bearing was not the cause.
3.) No functional parameters of age-sensitive components in equipment was monitored prior, during, and after the earthquake to establish if any aging-seismic degradation occurred.
4.) In spite of satisfactory functional capability of most data base equipment after the event, chattering relays caused many plant trips. The consequences of these trips for nuclear plants were not assessed.
5.) The quality of fossil plant records, (specifically many years after the seismic event occurred) is questionable. The event reports seemed to present all the plant operational activities without any specifics of any equipment malfunction after the seismic exposures.

6.) Larger sizes and sophistication of nuclear grade equipment could make them more susceptible to seismic induced malfunctions than the data base fossil plant equipment.

<u>Observations</u>

1.) Response spectra comparison between the design values in NPPs and the California earthquakes is valid. It is true that the design of current NPPs is very conservative.

2.) Proper mounting is, the most important aspect in evaluating the seismic resistivity of an equipment.

3.) SSRAP efforts were largely based on SQUG studies ith exceptions to selected plant visits and expert knowledge. The primary thrust of their study was related to seismic qualification of equipment in operating plants.

3.0 NUTECH STUDY FOR SNL

REPORT: "Aging-Seismic Correlation Study on Class 1E Equipment", A.C. Sugarman, Nutech Report.

Nutech Engineers have studied the aging-seismic correlation for NPP equipment under contract from Sandia National Laboratories for NRC. An analytical methodology was developed for evaluating potential aging-seismic correlation with the premise that equipment will fail during a seismic event when a "weak link" in the equipment mechanically fails by yielding or breaking. This is assumed on the presumption that the weak links in equipment are fabricated from organic materials such as elastomers, plastics etc., which degrade in strength with time and thus increase the potential for seismic failures. This method excludes failures resulting from poor electrical contact due to dust or dirt, human errors, operating or maintenance deficiencies, and other non-mechanical deficiencies.

To methodically evaluate the aging-seismic correlation in equipment, several sequential analyses are performed. These include:

- Preliminary Screening Evaluation to eliminate equipment in which no aging-seismic correlation would be expected.

- Weak Link Analysis (WLA) of equipment to identify those components made from material in which significant age-related degradation may occur. This includes aging mechanisms due to environmental, wear, and cyclic stressors.

- Failure Modes and Effects Analysis (FMEA) to define the failure modes in the equipment. Only those failure modes which have age degradable material will be of interest.

- Probabilistic Failure Analysis (PFA) of the components and the system based on the ultimate strength of the component and the total stress (from normal operation plus seismic loading) on the component.

The study included the following 18 safety-related electrical equipment items:

1.) Batteries
2.) Battery Chargers
3.) Transformers
4.) Cables
5.) Penetrations
6.) Switches
7.) Meters
8.) Motor (squirrel cage)
9.) Radiation monitor
10.) Terminal Blocks
11.) Recorder
12.) Temperature sensors
13.) Protection relays
14.) Motor starters
15.) Solenoid operators
16.) Electric equipment
    - amplifiers
    - signal converters
    - inverters
    - rectifiers
17.) Circuit Breakers
18.) Transmitters

With the exception of Terminal Blocks, all other components were identified as containing age-degradable organic materials which represent weak links. The most common degradation mechanism leading to seismic failures was thermal effects on electrical insulation and seal materials. In the case of electronic equipment components, the semiconductor devices were found susceptible to corrosion, intermetallic growth, and thermal and mechanical fatigue.

The report has summarized criteria for weak link components in typical electrical equipment. The weak link components include:

a) Electrical Insulation
b) Seals and Gaskets
c) Protective Envelopes (encapsulants, covers)
d) Lubricant
e) Battery
f) Terminals (eg. battery, circuit board, etc.)
g) Circuit Boards
h) Contacts
i) Springs
j) Bearings
k) Radiation Detector Materials
l) Thermocouples

The criteria that was used to characterize these components for age-related degradations are also included.

3.1 BNL Comments

1.) The method assumes that the predominant failure mechanisms for the equipment during a seismic event will be the mechanical failure of a weak link component that will cause the equipment to fail. This may not be the case for all types of equipment (i.e., relay chatters).

2.) A normal probability distribution of failure frequency with stress is assumed in which case the known breaking strength is the mean and one standard deviation is assumed to be 20 percent of this mean. This assumption requires justification based upon material characteristics.

3.) The method was applied to motors and batteries using engineering approximations when data was not available. The motor insulation and the polycarbonate cell wall, cover, and vent cap were considered as the weak links. Thermal aging was modelled using the Arrhenius equation. Based on these, it was established that aging-seismic correlation exists for motors and batteries. These two examples indicate that this analytical method provides a logical approach for screening equipment for aging-seismic correlation evaluation. However, it requires more than just simple calculations in order to establish the existence of this correlation.

4.0 WYLE STUDY FOR EPRI

REPORT: "Correlation between Aging and Seismic Qualification for Nuclear Plant Electrical Components", J. F. Gleason, Wyle Report.

Wyle Laboratories have performed seismic tests on certain components used in safety-related equipment in NPPs to demonstrate that no correlation exists between deterioration due to aging and the ability of the components to function during and after a seismic event.

Each class of components, prior to seismic tests, were either artificially aged or new. The aging included thermal (using Arrhenious equation), cyclic (operational), and both thermal and cyclic aging.

Both the aging and seismic stresses applied to the components were purposely more severe than typically required for qualification of safety-related equipment.

The seismic test was performed with a random multifrequency input to the table. The table input was applied bi-axially. Each seismic simulation duration was 30 seconds. After the initial series of tests, the test fixture was rotated 90 degrees and the test series was repeated. The frequency bandwidth spaced 1/3 octave over the range of 1 Hz to 40 Hz was used in the tests.

Primary test specimens:

1.) Resistors
   - wire-wound
   - carbon-composition
   - film
2.) Diodes
3.) Integrated Circuits
4.) Transistors
5.) Optical Couplers
6.) Relays
   - Printed Circuit (PC) Board-mounted
   - Panel mounted

7.) Capacitors

- Tantalum CSR-13 series
- Ceramics

8.) Terminal Block

In order to provide a prototypical test specimen, typical mounting and interconnecting components were also included in the tests. These are termed as secondary test specimen components:

1.) P.C. Boards
2.) I.C. Sockets
3.) Transistor Sockets
4.) Relay sockets
5.) Soldered Connections
6.) Wire-Wrapped Connections
7.) Teflon Hookup Wire

Critical component parameters such as resistance, voltage, capacitance, signal gain and current were monitored for each component to measure its health before and after the seismic tests.

Based on the test results it was concluded that a high level of statistical confidence on the absence of correlation between aging and seismic performance was obtained for all the above mentioned component types with the exception of relays. Artificial accelerated aging prior to seismic test should not be required for these components, as it is currently required in equipment qualification regulations. The report also rejected the notion that relays might have the aging-seismic correlation, based on the statistical significance (one out of twenty relays experienced contact chatter, hence failure).

4.1 BNL Comments

Out of 1944 components tests, only one instance of relay chatter was reported as an anomaly. Several other anomalies including disconnection of P.C. Boards, relays falling out of the sockets, other electrical spikes were observed during the seismic testings. However, these were apparently attributed to the deficiencies in the test procedures rather than the components itself.

4.2 Unpublished Wyle Test Program (Presented at the IEEE/ANS meeting held at Orlando, Florida in November 1984)

Similar tests on other components are being tested at Wyle under funding from EPRI. According to the test results the additional components which do not require aging prior to seismic testing are:

1.) Transformers (instrumentation and power)
2.) Terminal blocks (Nylon, Melamine, DAP, Polypropylene)
3.) SCR
4.) Inductors
5.) Integrated Circuits (Linear)
6.) Fuses (Fibre glass, ceramics, fibre, melamine, glass)
7.) capacitors (Aluminium, polyestic, polycarbonate, paper)
8.) P.C. Boards
9.) Motors
10.) Power Supplies
11.) Transmitters
12.) Circuit Breakers

Other components presently being investigated are:

1.) Pressure Switches
2.) Solenoid Valve
3.) Limit Switches
4.) Rotary Switches
5.) RTDs
6.) Contactors
7.) Relays
8.) Metals
9.) Electronic Alarms

5.0 BNL PROPOSED STUDY

This study is proposed in order to ascertain whether equipment utilized in nuclear power plants could have the potential of failure due to a seismic/dynamic loading at an age-degraded stage of that equipment. Because of the complexities involved it requires more than a simplified procedure or test. All of the earlier studies, as summarized in this report include either an analytical method with subjective assumptions, or physical testing in a simulated dynamic environment.

The proposed study is intended to combine both analytical and testing methods and will include all types and sizes of equipment used in nuclear plants. An analysis of the performance of equipment in nuclear or non-nuclear plants which have already experienced real earthquakes, part of the study. The following is a summary of the proposed investigation to be carried out by BNL:

Part 1: Real Earthquake Pilot Study

The SQUG studies revealed that there exists a wealth of data in plant equipment maintenance log sheets of some west coast power plants which have survived earthquakes of magnitudes comparable to NPP design basis levels. EQE, Inc. which performed the pilot studies for SQUG, has agreed to provide the age-related maintenance and performance record data of certain selected equipment. BNL will evaluated this data to determine whether this equipment has any aging-seismic correlation.

Part 2: Analytical/Testing Evaluation of NPP Equipment

Part 2 will be conducted in parallel to the Part 1 effort. It consists of three phases which are:

Phase A: Selection of Equipment Having Aging-Seismic Correlation
Phase B: Analytical Assessment
Phase C: Seismic Testing of Naturally Aged Equipment (if necessary)

The first phase of this part will evaluate all types of equipment generally utilized in the nuclear industry. The construction and use of age degradable material for the equipment will be summarized for the purposes of establishing the weak-links which might fail when subjected to seismic forces. This effort will include the following tasks:

- Collection of a list of all equipment utilized in NPPs for both safety and non-safety systems which will identify:
    - types and sizes
    - harsh and mild environment
    - operational and accident stressors
    - maintenance/surveillance requirement
- Identification of major manufacturers and significant design differences within the product.
- Establish "weak links" (NUTECH Approach)
- Evaluate the criticality of weak links
- Review published documents
- Recommend equipment which could have the potential of aging-seismic correlation.

The above screening process would define the next phase, which is the selection of equipment. Research activities and published materials relating to these components will be reviewed for the purpose of establishing the aging-seismic correlation. If necessary, the component will further be studied in phase B using analytical techniques and/or in phase C using seismic tests on some naturally aged components. The following is the summary of tasks which will be carried out in phases B and C of this study as necessary:

Phase B: Analytical Assessment (primarily mechanical components)

- Perform stress analysis of weak link components
- Develop the probabilistic methods to examine the possibility of age-degraded component to fail during seismic
- Establish failure modes and effect analysis
- Develop effect of failed components equipment performance
- Characterize the probable seismic load magnitude, frequency and duration

- Evaluate the dynamic characteristic of equipment under investigation
- Assess the potential for seismic induced failures of the equipment

Phase C: Seismic Testing of Naturally Aged Equipment

- Obtain aged components from NPPs
- Monitor pre-seismic operational parameters
- Simulate as-mounted condition in NPP
- Perform 3-D random excitation seismic tests
- Examine post-seismic operational parameters
- Establish aging-seismic correlation of the equipment

Appendix A

A.1 San Fernando Earthquake

The San Fernando earthquake of February 9, 1971 occurred at 6:01 am, with a richter magnitude of 6.6. The strong motion of the main shock lasted about 12 seconds.

(1) Sylmar Converter Station (1970)

The estimated peak ground accelerations for this plant location are 0.5g in both horizontal direction and 0.3g in the vertical direction.

Most of the anchored equipment in the station building was undamaged and was brought back on line without need of repair. Equipment in this category includes motor control centers, switchgear, relay panels, control panels, pumps and motors, air compressors, piping, HVAC ducting, and cable trays. Several motor control centers and switchgear units in the basement were inadequately anchored to the floor and moved a few inches. The motor control centers were prevented from toppling by the connected overhead cables. Nearby spare control cabinets that were unanchored toppled and were heavily damaged.

The entire suspended ceiling of the station control room collapsed. There was no reported failure of equipment or components of the main control panel or adjacent cabinetry that had been hit by the collapsed ceiling. According to the operators, the equipment in operation today is the equipment that survived the earthquake; no repair was required after the earthquake.

In summary, the Sylmar facility contains motor control centers, 480-V and 4 kV switchgear, relay boards, most other types of electrical cabinetry, conduit, cable trays, smaller pumps and motors, HVAC equipment, air compressors, and other light mechanical equipment and piping that survived very strong ground motion. Because of the very high accelerations at the site and the age of the equipment (1970), the station is one of the most valuable data base facilities. Its equipment can be used for comparison with nuclear power plant equipment in areas of low and high seismicity.

(2) Valley Steam Plant (1954, 55 and 56)*

At the time of the earthquake, units 1, 3 and 4 was on line. Unit 2 was down for scheduled maintenance. The earthquake with an estimated PGA of 0.4 g in north-south direction and 0.21g in the east-west direction tripped units 1 and 4 off line. The trip was attributed to the pressure relays associated with the high-voltage switchyard equipment. Unit 3 stayed on line throughout the earthquake; however the flow of gas fuel was interrupted by the closing of a control valve which was activated by a vibrating Mercoid switch. It should be noted that the plant was originally designed for a static load of 0.2g. the plant's trouble report notes the following damage to equipment.

- A lightning arrestor in the switchyard was broken.

- At unit 4, a few circulating water tubes in the condensor were ruptured. The damage was noticed when contamination began to appear in the boiler feedwater. This was the only reported failure of piping and tubing of any kind at the plant.

- The plant was operated manually following the earthquake because the operators were not confident of the automatic control systems. The linkages of certain meters were reported to have become disconnected; however, the plant operators indicated that no control components actually had to be replaced.

(3) Burbank Power Plant

The plant complex is made up of two different power plants: The two-unit Olive Plant (1961) and the five-unit Magnolia Plant (1-4 units 1940s and early 1950s, unit 5 (1960). The relatively newer plants were designed for an equivalent static force of 0.2g. The estimated PGA for the site was 0.35g in the east-west direction and 0.29g in the north-south direction.

Several relays in the control building tripped during the earthquake, taking both units off the line. Damage at the Olive plant was limited to:

* ( ) years correspond to the age of the plant units

- A broken valve and pipe at the demineralizer tank.

- A broken front center-line guide on the unit 2 boiler casing located at the top of the boiler structure.

Magnolia units 2 and 3 were on line at the time of the earthquake and remained on line throughout the earthquake. A fuel-oil gage line ruptured in unit 3, spraying oil on the front face of the furnace and on the surrounding floor. This caused a drop in the fuel-oil pressure to the burners. In addition the following damage was noted at the Magnolia Plant.

- The demineralized-water tank in the plant yard was not anchored and shifted, breaking attached piping connections.

- Six bolts at the base of the gantry crane were broken.

- The boiler brickwork on one of the furnaces cracked.

- A 2-inch-diameter pipe connecting to the unit 3 main cooling-water line cracked. (The plant operators thought this was probably a minor leak since it did not impair restarting the plant.)

- The plant's demineralizer cation tank shifted on its supports.

(4) Glendale Power Plant (1941, 47, 53, 59 and 64)

Units 3, 4 and 5 were in operation at the time of the earthquake and they continued to operate and to generate power during and after the earthquake. The estimated PGAs for the site were 0.3g in east-west and 0.25 in north-south directions. The newest unit (unit 5) was probably designed for an equivalent static shear force of 0.2g. The equipment seem to be well anchored. The reported damage consisted of two broken water lines, one on the cooling-water line to the induced-draft fan and air preheater of the unit 3 boiler, and the other on the no. 2 influent water line to the demineralizer tank. No other structural or equipment damage was reported.

(5) Pasadena Power Plant (1955,57, 65 and 49)

At the time of the earthquake, units 1 and 3 were in operation while the other two were on hot standby. The estimated PGAs for this plant location were 0.22g (NS), 0.18g (EW), and 0.12g (V). The newest plant was probably designed according to 0.2g UBC requirements. The two operating units did not trip but continued to operate throughout the earthquake. The only damage reported was to linkage in an air-flow monitor that records the Unit 3 furnace intake air. It became disconnected, indicating erroneous readings in the control room.

(6) Vincent Substation (1968)

Since the plant was built in the late sixties, the buildings, steel structures and the electrical apparatus were designed according to the current seismic design criteria. The estimated PGA is 0.2g. The following information is applicable to this plant.

- The initial earthquake shock caused a sudden pressure relay on the #1 AA 500/220 KV transformer bank to operate, thereby tripping the south 500 KV bus.

- The no. 2 Midway north bus Westinghouse 500 KV PCB (power circuit breaker) sustained major damage. Three porcelain columns were broken. Five of the nine heads has twisted clockwise when viewed from above. Twisting of the columns occurred at the bottom of the lower porcelain. This PCB was out of service forty-one days before parts could be obtained and repairs completed.
- The no. 1 Midway north bus Westinghouse 500 KV PCB suffered damage to four support struts. The no. 1 Midway south bus Westinghouse 500 KV PCB suffered damage to seven support struts. These two PCB's were repaired and returned to service within 48 hours.

- Two 500 KV bus insulators were broken at the bases but did not fail. One 500 KV insulator in a disconnect switch was broken and threw the disconnect out of alignment.

- The 500 KV lightning arrester on the spare 500/200 KV transformer broke off and fell to the ground. In falling it damaged the discharge counter, some transformer cooling fans, and a radiator flange which sprung a leak.

- A corona ball shook off the external bypass 500 KV disconnect on the no. 2 Midway 500 KV line series capacitors. No damage resulted.

- Thirty-two plastic ceiling panels fell to the floor in the operating room.

The control room houses relay panels, control panels, battery racks, and battery chargers. No physical damage had been found and no electrical components had been repaired or replaced after the earthquake.

(7) Rinaldi Receiving Station (1968)

This plant was built identical to the previous substation. The estimated PGA for this plant site is 0.5g or more, on the basis of the site's proximity to the fault. Two air-blast circuits breakers in the yard were badly damaged. The control building containing relay panels, battery racks and chargers, control panels, and instrument racks exhibited no physical damage.

(8) Saugus Substation (1920's)

A nearby record had indicated a horizontal acceleration of 0.37g (N21E) and 0.28g (N69W) and a vertical acceleration of 0.18g.

The station is one of the SCE facilities most severely damaged. All reported damage was concentrated in the switchyard and was experienced by switchyard equipment. The following information is related to the substation damages due to the earthquake.

- The A-phase 220 KV lightning arrester on the Santa Clara line broke off from its base and fell, pulling two line sided 220 KV disconnects down and damaging seven tripod insulators, and chipping a type A potential device.

- One 220 KV post insulator on the PCB side of the no. 3 Magunden A-phase 220 KV south bus disconnect broke and fell to the ground. In falling it pulled the disconnect bayonet and corona ring which burned the operating rod. The control rod and the post insulator units were replaced.

- Four transformer tanks in the no. 1 and 2A 220/66 KV transformer banks shifted from one to two-inches shearing hold-down bolts on the east side to the transformers. The spare 220/66 KV transformer sitting on its transfer car, slipped its rail checks about six inches. All hold-down bolts have been replaced with hardened steel bolts.

- A crated 66 KV oil-filled bushing on the transformer pad fell over and broke the glass bowl on its top.

- A fitting broke on the no. 2A 220 KV jack bus allowing one end of the jack bus to fall.

- Sudden pressure relays operated to remove the no. 3A 220/66 KV transformer bank from service. Alarms only were received on the no. 1A and no. 2A transformer banks.

The control building contains most of the equipment of interest to the pilot program. The building houses panels with numerous relays (mostly manufactured by General Electric and Westinghouse), control panels (in the control room), battery racks, and battery chargers. No physical damage had been found and no electrical components had been repaired or replaced after the earthquake.

A.2 Imperial valley Earthquake

The Imperial Valley earthquake occurred at 4:16 pm on October 15, 1979 in the general area of the town of El Centro. The earthquake had a Richtor magnitude of 6.6 and lasted about 15 seconds.

(1) El Centro Steam Plant (1949, 52, 57 and 68)

At the time of the earthquake, units 3 and 4 were in operation. The other two units were shut down for scheduled maintenance. The recorded PGAs for the site were 0.51g (NS), 0.37g (EW), and 0.93g (Vertical). The seismic relays in the 240 V switchgear tripped both units off line. Circuit breakers on the outdoor 480 V switchgear serving the cooling towers was also tripped.

Unit 4 experienced the following damage:

- Several three-inch and four-inch generator exciter cooling water and hydrogen cooling water lines cracked. The cracking apparently occurred at points where the lines had corroded or where previous weld repairs had been made. Leakage from the cracks was minor; however, restart of the plant was impeded.

- A two-inch component cooling-water line cracked at a Victraulic coupling.

- The yoke of an air-operated valve on a steam-supply line to the evaporator failed. The valve was located on the mezzanine above the turbine deck. The yoke failure was attributed to repeated impacts of the operator and an adjacent girder.

- Swaying of the main steam lines was sufficient to cause impact on adjacent girders and walkways, which indicates deflections of at least 2 or 3 inches. Many dents in steam-line insulation, caused by contact with adjacent steel work, were observed. No leakage from any high-pressure, high-temperature lines occurred.

Unit 3 experienced the following damage:

- Cracks occurred in the hydrogen cooling-water lines, as in unit 4.
- An unanchored turbine oil cooler slid slightly on its pedestal.
- A feedwater heater on the roof slid a few inches; no damage occurred.

Unit 2 experienced the following damage:

- A filter in the pumphouse located in the plant yard slid because of lack of anchorage. The sliding caused the failure of a small line attached to the filter.

- Guide bracing on the unit 2 mud drum was bent.

- The steel supports of a roof-mounted feedwater heater were bent.

Unit 1 experienced the following damage:

- A lightning arrestor in the switchyard was broken.

The following damage throughout the plant at large was reported:

- Some damage occurred in all but one of the large oil-storage tanks located in the plant yard. Leakage occurred at the interface of the roof and wall of each tank. The wall of one tank also buckled.

- Asbestos panels on the cooling towers were knocked off.

- Anchor bolts for the large transformers in the switchyard were stretched; one transformer slid about 2 inches.

- Two grounding insulators in the switchyard failed. The insulators are ceramic columns about 9 feet high. They snapped at the base.

- The anchor bolts on the stacks for units 1, 2, and 3 were stretched.

The following structural damage was reported:

- Cracked and spalled concrete was generally observed at the interfaces of the units. A steel plate that covered the gap between the turbine decks of units 1 and 2 buckled because of differential movement of the two buildings.

- Buckling and yielding was observed in the unit 4 boiler structure. The seismic stops that were mounted on the structure to limit excessive movement of the suspended boiler were bent. Diagonal bracing in the boiler structure buckled at three locations.
- A concrete support pad for the unit 4 air preheater was crushed.
- Cracking in the walls of the chemical laboratory was observed.

(2) Magmamax Geothermal Plant (1979)

The nearest strong-motion instrument recorded maximum horizontal accelerations of 0.26g and 0.22g and a maximum vertical acceleration of 0.31g. There are many horizontal and vertical pumps and motors, and they are of the same vintage as in recent NPPs. There was no damage to this plant due to the earthquake.

A.3 Point Mugu Earthquake

The Point Mugre earthquake occurred at 6:46 am on February 21, 1973. It had a richter magnitude of about 5.75 and lasted for about 6 to 8 seconds.

(1) Ormond Beach Generating Station (1970, 1973)

The station has experienced a PGA of 0.13g. Unit 1 was operating at the time of the earthquake and was tripped off line by the earthquake. The following is the list of damage to the equipment:

- The unit one generator differential relay tripped while carrying 600 MW. The shaking of this relay's support panel was the apparent cause for the closing of the relay contacts. A CFVB voltage balance relay also tripped due to the earthquake. The closure of the generator differential relay was the main cause for the station to remain off-line until 3:46 am.
- A small fire also started next to the windbox of unit one. The fire was the result of the down-comer pipe partially breaking away from the windbox. The fire was quickly extinguished. Minor repairs to the insulation and other related items of the downcomer pipe were required.

- A 10-inch support rod on one hydraulic snubber at approximately the 150 ft. level was buckled at about a 20 degree angle. The support rod on this particular snubber was the longest one observed out of the many snubbers at the plant. The longer-than-normal length of the support rod could have been the cause of this buckling failure. The location and size of these snubbers indicate that they were ambient noise snubbers and not seismic snubbers.

- Four 75 foot vertical steam pipes and four 100 foot vertical steam pipes on the south and north sides of units 1 and 2 collided with nearby catwalks and structural steel members. Consequently, dents were formed at various levels in the insulation covering of these pipes. From these dents it was determined that some of these pipes deflected over 13 inches. However, the dents in these steam pipes lines were not serious enough to warrent replacement or repair.

Other studies had indicated several other problems relating to excessive bearing accelerations of the turbines and recirculating fans, buckled snubber supports, many large pipe insulator damages and collision of large pipes without any significant structural damage. This plant contains numerous MOVs with limitorque operators, but no failures of this equipment were reported.

(2) Santa Clara Substation (1957)

The PGA estimated for the site is about 0.1g. The control building houses relay panels, control panels, battery racks, battery chargers, etc. No reportable damage was found from the plant record. The station was operating at the time of the event and remained on line.

A.4 Santa Barbara Earthquake

The Santa Barbara earthquake occurred at 3:45 pm on August 13, 1978. Its richter magnitude was 5.1 and the strong motion of the shock lasted 6 to 7 seconds.

(1) Goleta Substation (1968)

The accelerometer installed at the station had indicated the PGAs of 0.28g (NS), 0.24g (EW), and 0.09g (V). Neither physical nor electrical damage had been found or the need to repair or replace any equipment after the earthquake.

(2) Elwood Peaker Power Plant (1972)

The estimated peak ground acceleration was found to be about 0.3g to 0.4g. There was no damage to the plant.