SEISMIC CAPABILITY OF NUCLEAR PIPING

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INTRODUCTION

There are several types and classes of piping in a modern nuclear power plant and the seismic design requirements of the different classes vary considerably. Further, if the historical evolution of seismic design requirements is considered there is even more variability. Before the development of the ANSI B31.7 code for Nuclear Piping in the late 1960's and subsequently the piping provisions of ASME, Section III, all nuclear safety class piping was designed to meet the requirements of the ANSI (formerly USAS) B31.1 code for Power Piping. As a result many of the operating nuclear power plants in the United States today were designed and built to meet the provisions of the B31.1 code.

A general review of the methods applied to the seismic analysis of B31.1 safety class piping is given including reference to the historical evolution of these methods. Then the B31.1 code itself is discussed and it is shown that contrary to the belief of many, the B31.1 code rests on an advanced technical base, sufficiently advanced, in fact, that very few changes had to be made, other than notation, to upgrade it to the B31.7 nuclear code and then to ASME Section III. The older piping code, unlike those for vessels, contained all the main features of current codes. Piping designed to B31.1 is not outdated and performs very well in earthquakes. The available data on performance of piping in seismic events are reviewed, and it is shown that well designed piping is very difficult to damage as a result of its natural controlled flexibility.

and taking the response directly from the ground spectrum. This approximation was an improvement over purely static methods, but is quite simplified compared to later methods.

Subsequently in the 1960's the effect of building motion on piping systems was incorporated into the design process on an industry wide basis although the concept had been developed much earlier (2). Conceptually, this is done by analyzing the building for the effect of ground motion and developing new spectra at the floors and walls of the building where piping is supported. In practice this was done at first using records of actual earthquakes, Taft, El Centro, etc., normalized to the design acceleration level chosen for the site. The accelerations were applied to lumped mass building models in a time history fashion. At first, very few masses would be used for the building, say less than 10. Also approximate methods were devised to obtain the effect of building amplification on the design spectra (3) directly without a time-history analysis of the building. Design floor spectra were developed by these means and used for several plant designs.

In the 1970's several major changes in methods of nuclear plant seismic analysis were made. The key changes were a standardization of design ground spectra, a requirement for 3 directional analysis and use of increased damping values. The net effect was a more rational approach to seismic analysis, but in any given case, computed seismic stresses tended to be comparable to those obtained by the more approximate

Some analyses have been done by analyzing each of three directions separately and combining contributions from each direction. In many cases the horizontal direction that causes the worst stress is combined with the vertical and a planar response is the basis for evaluation.

The directional combinations have also been made in different ways. Since the various response quantities are signed, algebraic summation of responses from each direction within each mode has been done. Analyses have been completed using the other options, SRSS and absolute sum also. The latter is definitely conservative.

After combinations have been made so that the response for each mode is complete, the sum of all the modal responses must be obtained. Analyses have been completed using several different ways of combining these responses. The methods include a straightforward "square-root-of-the-sum-of-the-squares" of SRSS, the absolute value of the single maximum modal response plus the SRSS of the remainder, and other combinations of absolute values of response closely spaced modes plus the SRSS of the remainder.

The general impetus for the advance of seismic analysis and evaluation methods came from a widely felt need both within the industry and regulatory agencies to understand seismic behavior of piping. As results became available from development activities they would be used for specific plant analysis. The instigation for doing so would come as often from the utility or the manufacturer as

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.

"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 in a single nuclear plant the safety class piping might resolve down to as much as 90 to 100 piping problems. It can be seen the simplifications are not only desirable, they are necessary.

Although an evidently straightforward 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 principle stress up until 1964.

The Code has a brief paragraph that states earthquake loads, when applicable, must be considered. No explicit guidance is provided however.

Usually, one amplified floor response spectra is used as an input acceleration at each point of support or connection to the building. This simplification can be an important conservatism especially for piping systems traversing different vertical levels or different buildings. The model of the piping system is passed through the computer several times to account for all directions of motion and both the operating and design bases earthquakes.

The inertial forces in the piping system are combined with the gravity forces (weight) of the piping with contents and the pressure forces. This is done first for all directions within each mode of vibration, then the contributions of each mode are combined to obtain the total force. A current controversy lies in the fact that force combinations within each mode were in some cases combined algebraically so that some loads would subtract from the total. The alternative would be to combine forces in such a way that subtraction could not occur which is the case if a SRSS approach is used.

When load combinations are complete, bending moments and stresses in the piping system are computed according to B31.1 equations. Basically twice the maximum shearing stress in the pipe due to bending and tension is computed and limited 1.2 S_h for the OBE and 1.8 S_h for the DBE in a manner very comparable to ASME III today. S_h is the tabulated value of allowable stress in the hot condition. In B31.1, S_h is based on the lower of 5/8 Yield Strength or 1/4 Ultimate Strength

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 foreword 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 (6,7). Subsequently, a new edition was published in 1967, 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 essential point of the preceding discussion has been to make clear that safety class piping designed to meet the requirements of the older ASA B31.1 Code would almost without exception also meet the requirements of the latest version of the ASME Code. A little more needs to be said about seismic design however. The B31.1 Code of 1967 and 1955 clearly spells out that seismic stresses are to be considered but does not say exactly how. For nuclear plants built to those codes, however, this is not significant for present purposes since rigorous seismic analysis was completed for these plants to satisfy licensing requirements.

SEISMIC PERFORMANCE OF POWER PIPING

Although there appear to be no controlled experiments of seismic performance of actual piping systems, there is, nevertheless, a surprising amount of very interesting data on the response of power piping to actual earthquakes. In the following, power plant behavior in several recent earthquakes, Managua 1972, San Fernando 1971, Alaska 1964, Kern County 1952, Long Beach 1933 is discussed. No attempt has been made to sort or classify the observations; rather all significant data that could be found in a short time are reported.

Possibly the most interesting of the observations are those pertaining to the Kern Steam Station in the Kern County earthquake, and the Enaluf Steam Plant in the Managua earthquake. Both these

designers and builders of the plant. For other reasons it was necessary to reexamine 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 five 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.

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, than applying the appropriate lateral g force. Based on the dynamic analysis of the main piping, pseudo-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 (9).

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 very substantial 0.259 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 very clear and graphic 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 greather inherent reserve in the piping systems due to their natural controlled flexibility.

The significant finding of the observations of reference (11) is that two power plants rode out the Alaska Earthquake with no failures of the power 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" (11).

A brief mention is made in reference (10) 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 nonstructural 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 (12) 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.

Lake Hughes, 25 km from the epicenter. Figure 1 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 two hours (13). There was significant motion of the piping and seismic hold-down bars came into play (14), 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. Piping designed to nuclear standards is that much more resistant.

There were other power plants in the area at Playa del Rey, San Pedro and Seal Beach that were no 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 power piping failures in the San Fernando Earthquake.

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 seismic design applied, but certainly less rigorous than used for nuclear plants, the piping sustained accelerations on the order of 0.6 g with no failure. Modern welded steel piping with built in controlled flexibility is inherently highly resistant to earthquake damage.

specifically scrutinized. Contrast this situation with say the Kern County plant where 0.25 g was actually experienced and explicit analysis was performed only on the steam and feed lines; or the ENALUF plant which was probably designed statically and experienced perhaps 0.6 g. The contrast is simply too great; piping failures will not result from earthquakes in United States east coast nuclear plants.

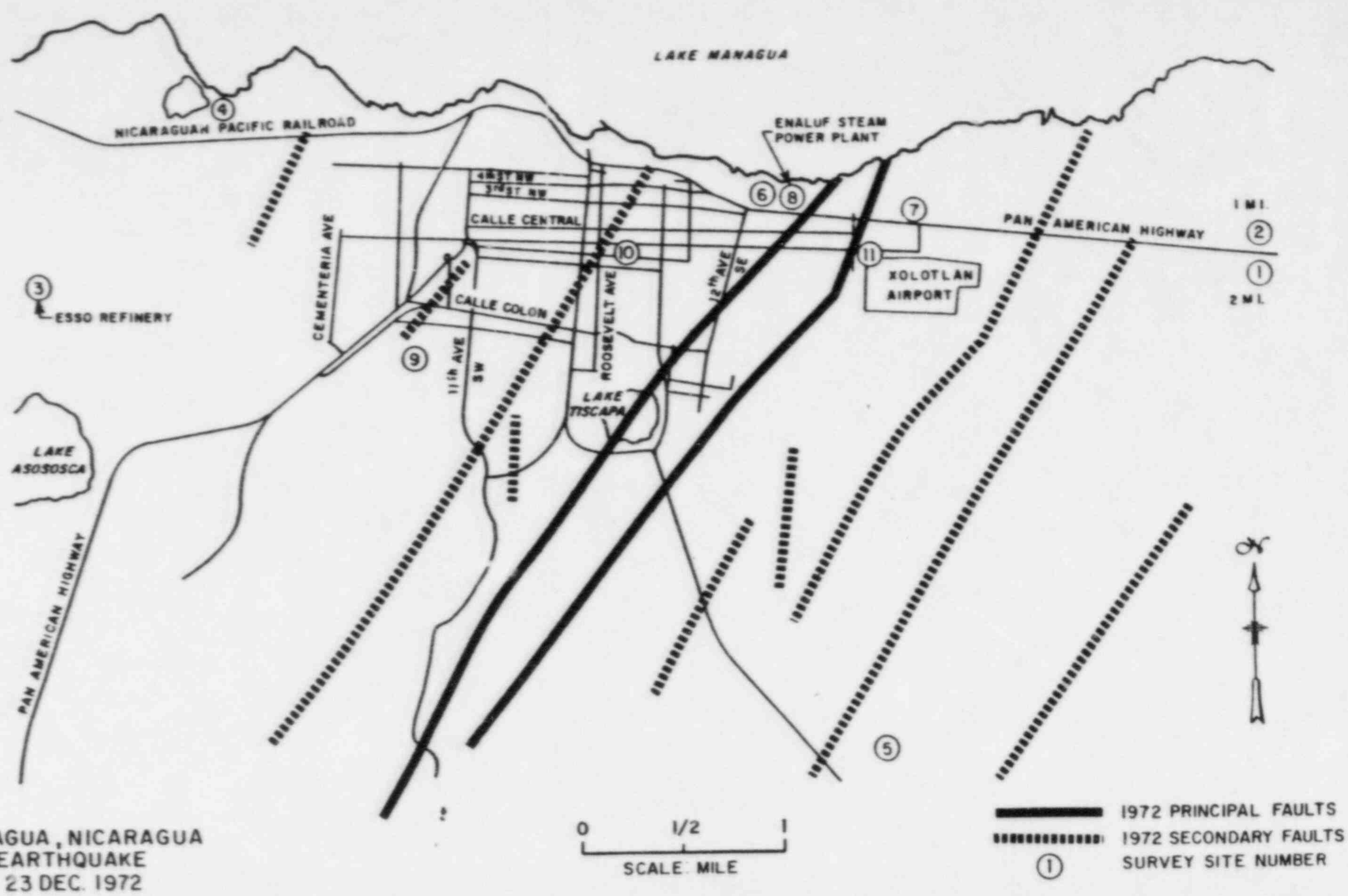

FIG. F-2

MAP OF MANAGUA, NICARAGUA SHOWING THE LOCATIONS OF FACILITIES AND BUILDINGS REFERRED TO IN THIS REPORT
SEE TABLE I FOR A LIST OF THE FACILITIES

TABLE 1

SEISMIC ANALYSIS OF NUCLEAR PLANTS

1955	Static Methods
1960	Introduction of Ground Spectra Buildings Considered Rigid
1965	Building Motion and Amplification of Spectra Considered Dynamic Analysis and Amp. Res. Spec. First Applied to Piping Ground Spectra Change
1970	Soil Structure Interaction Considered Ground Spectra Change 3 Directional Earthquakes R.G. 1.92, 1.6., 1.60 Damping Changed
1975	Higher Site G Levels Considered Systematic Reevaluation Program Seismic Safety Research
1980	

TABLE 3

DAMAGED EQUIPMENT AT THE ENALUF POWER PLANT

Unit 1

1. The forced-draft fan was out of alignment.
2. The induced-draft fan was out of alignment.
3. The bearings of the condensate pump burned out.
4. A 440 v ac panel fell.
5. The condensate-pump intake valve was broken.
6. Some tubing and the refractory walls of the boiler were broken.
7. Deaerator No. 1 fell from its base.
8. The stack suffered broken splice bolts at mid-elevation.

Unit 2

1. The forced-draft fan was out of alignment.
2. The induced-draft fan was out of alignment.
3. The refractory walls of the boiler were damaged.
4. Deaerator No. 2 fell from its base.
5. The condensate-pump intake valve was broken.

Unit 3

1. One 440 v ac control center fell.
2. The main-transformer bushings were broken.
3. The starting-transformer bushings were broken.
4. Some preheater seals were damaged.
5. Four turbine bearings burned out when the depowered emergency lube oil pump batteries broke.
6. A 69 kV switch bushing was broken.
7. The boiler support tubes over the preheater were broken.
8. The forced-draft fan control linkage was damaged.
9. Miscellaneous air tubes and other tubing were broken.
10. An evaporator drip valve was broken.
11. Three recirculating-valve bodies were broken.
12. The batteries in the battery room fell from their supports and broke.

Miscellaneous Damage

1. The turbine-bay-crane rails were bent and the electrical supply conductors were broken. The crane remained in place.
2. One 138 kV substation fell.
3. Several transformer bushings were broken.
4. Five lightning rods (69 kV to 138 kV) were broken or damaged.
5. One capacitor transformer was broken.
6. Miscellaneous insulators were broken.
7. Water softener units fell from their supports and were damaged.
8. One end of the bridge crane in the building that housed the diesel-electric generators fell from the crane girder.
9. Other miscellaneous minor damage

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D

EARTHQUAKE: 1933 LONG BEACH
MAG. 6.3 (EST.)

FACILITY: LONG BEACH STEAM STATION

5 UNITS: 2 Built in 1922
3 Built in 1928

DESIGN BASIS: 0.2G Static

SITE ACCELERATION: 0.25G Estimated

SITE LOCATION: About 4 Miles from Causative Fault

DAMAGE: Lighting Fixtures, etc.
No Significant Damage; No Failures of Structure or Equipment

EARTHQUAKE: TEHACHAPI 1952 (KERN COUNTY) MAG. 7.7

FACILITY: KERN COUNTY STEAM STATION

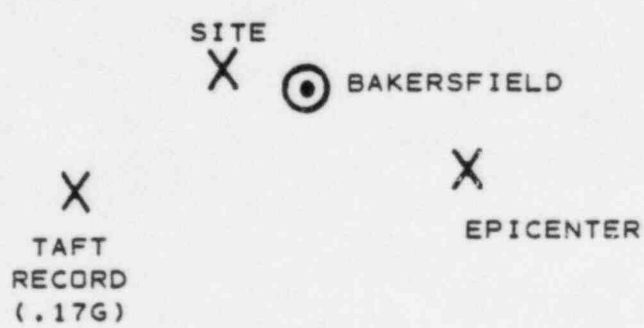
1 60 MW OIL FIRED UNIT - 1948

DESIGN BASIS: 0.2G Static +
Steam and Feedwater Lines Analyzed with Biot Spectrum; 0.1 to 0.3G

SITE ACCELERATION:
0.25G (Est.)

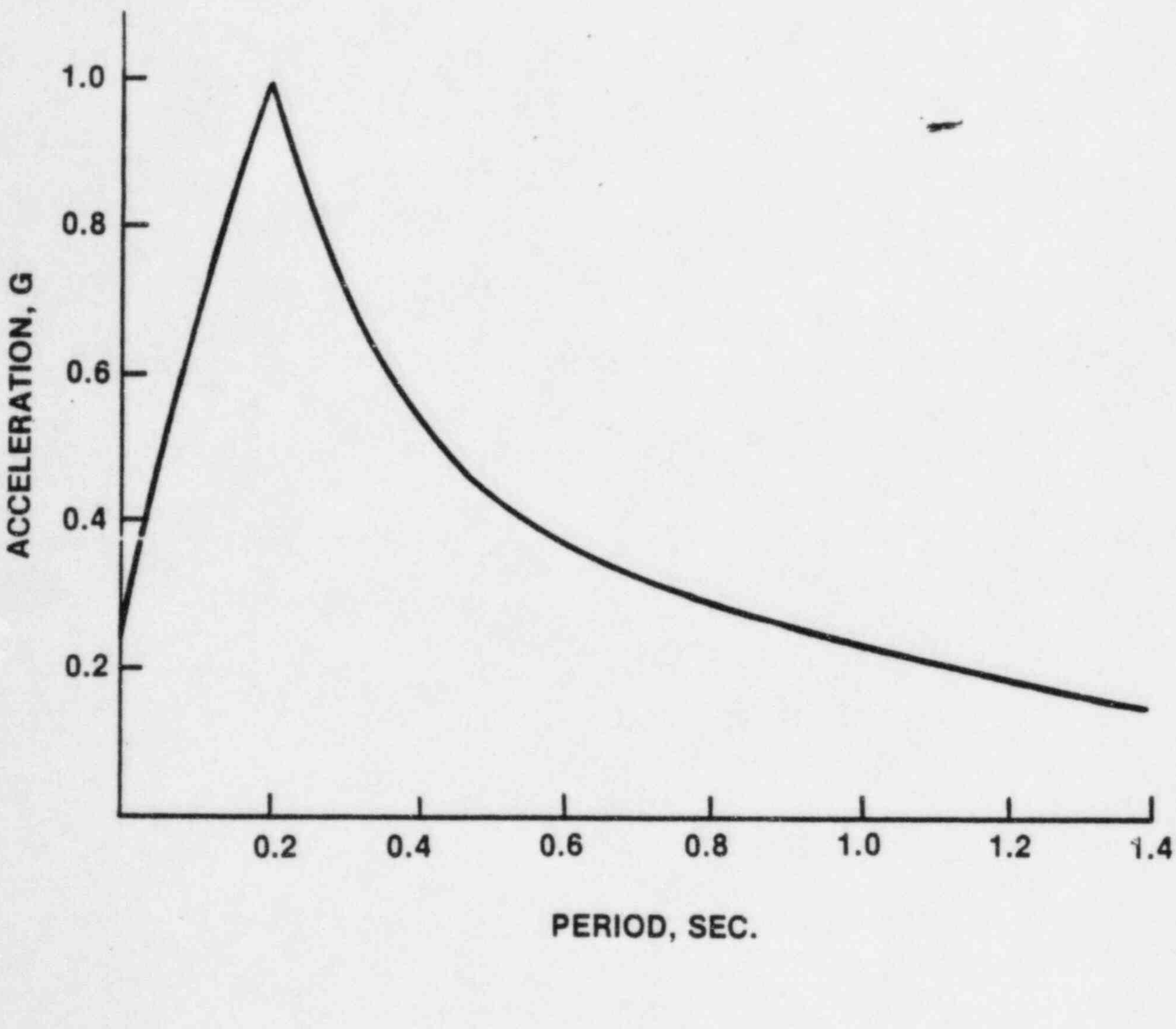
Site was nearer epicenter than Taft record (.17G) location

DAMAGE: Oil Tank Seals, Small Turbine Thrust Bearing.
No Damage to Structure, Piping or Generation Equipment



July, 1979

STANDARD SPECTRA
PROPOSED FOR DESIGN
M.A. BIOT 1941



July, 1979

EARTHQUAKE: ALASKA 1964
MAG. 8.4

TWO POWER PLANTS REPORTED TO HAVE BEEN SEVERELY SHAKEN WITH NO PIPING FAILURES

The Chugach Power Plant at Anchorage experienced about 0.2G. It was designed for 0.1G static. There was minor damage but no failure of piping, structures or generation equipment.

EARTHQUAKE: SAN FERNANDO
1971 MAG. 6.1

FACILITY: VALLEY POWER PLANT
3 UNITS

This Plant was Located About 2.8 Mi. from Line of Rupture and About 5 Mi. from Epicenter. Based on the Locations of Various Recordings, the Site is Estimated to Have Seen More Than 0.25G.

DESIGN BASIS: .2 or .25G

DAMAGE: No Damage to Plant - Operating at Full Power 2 Hours After Event

EARTHQUAKE: MANAGUA 1972
MAG. 7.5

FACILITY: ESSO REFINERY

DESIGN BASIS: 0.2G UBC

SITE ACCELERATIONS:

.39G E-W	Measured
.34G N-S	

DAMAGE: Essentially None;
Some Piping Jumped from Saddle Supports and Was Lifted Back.
Plant was Operating at Full Capacity 24 Hrs After Event

EARTHQUAKE: MANAGUA 1972
MAG. 7.5

FACILITY: ENALUF POWER
PLANT 3 UNITS

DESIGN BASIS: ?

SITE ACCELERATION: 0.6G Estimated

Site is Right Next to One of Main Faults

DAMAGE: Minor -
No Piping or Structural
Failures