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SEISMICITY AND TSUNAMI REPORT

BODEGA HEAD, CALIFORNIA

The Division of Licensing and Regulation of the Atomic Energy Commission, Washington, D. C., requested the U. S. Coast and Geodetic Survey to report on the seismicity and tsunami condition of Bodega Head, California. This report contains an evaluation of the seismic condition of Bodega Head as defined by the Pacific Gas and Electric Company in numerous documents submitted to the AEC.

In addition, comments are made on documents submitted by the U.S. Geological Survey as the material pertains to seismic hazards, and by Dr. Pierre Saint-Amand who prepared a geologic and seismologic study of Bodega Head under the auspices of the Northern California Association to Preserve Bodega Head and Harbor. The Survey also presents an independently determined earthquake frequency pattern along the San Sndreas fault, the most probable ground motions measured in acceleration and displacement for a magnitude 8.2 on this fault near Bodega Head, and finally, an evaluation of the tsunami hazard at the same location. The Survey is in a unique position to perform this service because it has either the original documents or a complete file of historical data for earthquake seismology, engineering seismology, and tsunamis, and has made studies in these fields for approximately 30 to 40 years.

In this report and all other geologic and seismic reports, submitted to the AEC relative to the proposed reactor at Bodega Head, frequent reference is made to geological faults and in particular, the San Andreas fault. This

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is necessary in describing earthquakes because a fault is the only surface manifestation of previous earthquake occurrences. Geologists refer to these faults or earth fractures as active or inactive, depending upon the recentcy of movements. Active faults are associated with recent earthquake activity, such as the earthquake belt around the perimeter of the Pacific Ocean and across Asia and along the Mediterranean Sea to the Atlantic Ocean. An example of an inactive or relative inactive belt is the Appalachian system in eastern North America where there are extensive fault systems but only minor and infrequent tremors.

The San Andreas fault, which is of principal interest due to the proximity (within 1100 feet of the limits of the western zone) to the proposed site of Bodega Head reactor, is considered by geologists and seismologists to be an active earthquake source. The fault extends southeasterly from a point under the ocean about 300 miles from the Oregon coast (approximately 45° north latitude and 130° west longitude) to the lower limits of the Gulf of California. It intersects the California coastline at Point Arena and continues in a nearly straight line (southeast) to the vicinity of Gorman where it curves somewhat eastward. A few miles south of Gorman the fault curves westward slightly to become parallel to its original direction. Southward there is some doubt as to whether the observed faults are geologically extensions of the San Andreas, but the seismicity of southern and Gulf of California leaves no doubt about its lower extension.

The San Andreas fault, which is a right hand strike slip fault (i.e., motion is predominately horizontal) has been associated with two great in recent times

earthquakes in 1857 and 1906. Other faults trending nearly parallel to this master fault show evidence of right hand displacement. Faults with trends crudely at right angles to the San Andreas are predominately left hand type. In California the chief left hand fault is the Garlock which exhibits topographic evidence of activity without clear indication of displacement in historic time. The White Wolf fault, associated with the 1952 Kern County earthquakes, is roughly parallel to the Garlock fault. The evidence indicates principally dip slip displacement on the fault in 1952, but some left hand strike slip motion was also established.

In southern California there is evidence for accumulated shift of about 25 miles along the San Andreas fault since mid-Tertiary time. Some investigators believe much more horizontal motion has taken place. The fault is easily followed between 35° and 40° north latitude. Beyond these limits it is deflected and complicated by the Mendocino fracture zone to the north and the Murray fracture zone to the south. Movements measured along certain areas of this fault by the Coast and Geodetic Survey are approximately 2 inches per year. The relative motion indicates the west side of the fault is moving northward and the east side southward. The maximum horizontal shift observed after the 1906 earthquake was 21 feet at _

. The vertical motion during the same earthquake was no greater than 3 feet. This is typical of the earth motions resulting from California earthquakes, i.e., much greater horizontal than vertical displacements.

Even though California and specifically, the San Andreas fault, are considered earthquake prone areas, they experience a surprisingly low number of magnitude 6 and greater earthquakes. According to Richter, there have been two "great" earthquakes (1857 and 1906) on the fault and approximately 15 earthquakes from 1800 to 1950 with magnitudes 6 to 7 plus within 75 miles of this fault. Under magnitude 6 earthquakes are quite numerous and their distribution is shown on the earthquake history map of California.

As noted in the report submitted by Tocher for earthquakes felt at or near Bodega Head, 1838-1960, nome of them were located at Bodega. Of the 58 listed earthquakes, 14 were positively reported felt at Bodega or in Bodega Bay; two caused little or no damage and one in 1906 caused appreciable damage and some surface fissuring.

Studies of the seismicity along the San Andreas fault for the past 57 years show that a magnitude 6 to 6.9 earthquake occurs every 7 years on the average and only one magnitude 7-7.9 earthquake occurs during this period. This fits the pattern determined by Gutenberg in Seismicity of the Earth which predicts a magnitude 8 earthquake about once every hundred years. In discussing the frequency of high magnitude earthquakes, it should be noted that many reoccur in the same epicentral areas. Richter mentions three Honshu, Japan earthquakes of 1897, 1898 and 1905 with magnitudes from 7.9 to 8.3. A number of zones in Italy, for example, Girifaleo (1626, 1659, 1783, 1905); Monteleone (1659, 1783, 1905); Gerace (1720, 1784, 1791, 1907); experienced damaging earthquakes. According to Davis, Valparaiso, Chile was destroyed in 1822 and again in 1906. Skopje, Yugoslavia, of recent memory, was totally or partially destroyed in 1963, 1921, 1555 and 518.

In order to design and construct earthquake resistant structures it is necessary to know not only the above mentioned seismicity information about destructive earthquakes, but also the displacement, velocity and acceleration of ground motions and the response characteristics of structures to these motions. Since 1933 the Coast and Geodetic Survey has made these measurements of strong earthquakes in the Western United States and in Latin America. All interested parties in this investigation are aware of this work and the data collected have been used extensively by all. There is general uniformity in the interpretation of the direct recorded strong motion data at El Centro, San Francisco and Seattle. However, there is some dispersion in the computed results when attempts are made to extrapolate from magnitude 6-7 earthquakes to magnitude 8.2 (San Francisco, 1906). Computations are necessary since no magnitude 8 earthquakes have ever been recorded by strong motion seismographs. It was hoped that such equipment might record at least one high magnitude earthquake aftershock in Alaska (1964) but to date, not one has occurred. Such information, if available, would have been invaluable for this report.

Using the seismicity and strong motion information available for earthquakes along the San Andreas fault and near Bodega Head, it is possible to define the vibratory motions produced by these earthquakes. The surface geology of Bodega Head is well defined due to the careful excavation that has been performed by the applicant and his excellent cooperation with all parties studying the structure. The quartz diorite bedrock, even though fractured and crushed during geologic time, (probably more than 40,000 years ago) is acceptable as good foundation rock for reactor support. The faulting evidenced in the lower limits of the pit is a matter of some concern; however, according to geologists who have studied its character there is general agreement that it is not of recent origin.

In determining ground vibrations generated by a magnitude 8.2 earthquake on the San Andreas fault in the vicinity of Bodega Head, it is necessary to evaluate (1) the intense shaking of the ground at the proposed reactor site caused by seismic waves propagated outward from the fault and also, from the actual permanent displacement (fling) along the fault of the site and (2) possible dislocations within the site due to rupture by the main fault, a branch of the main fault, a minor auxiliary fault, or other sources such as landslides, etc.

The Modified Mercalli Intensity Scale has frequently been used to define earthquake motions. At best and only when the intensities are associated with estimated ground wave periods can these scale ratings be used for estimating accelerations. Considering a magnitude 8.2 earthquake, Tocher and Treaide estimate intensity VIII on the quartz diorite bedrock at the site and an intensity X in the fault zone. They recommend the power plant structures should be designed to resist an earthquake of MM-VIII, or to provide a margin of safety MM-IX.

Saint-Amand suggests a minimum intensity of MM-IX on Bodega Head for a similar earthquake; MM-X if significant landslides occurred during the main earthquake; MM-XI if major faulting occurred on Bodega during the main earthquake. His findings agree well with Richter's table of published relations of magnitude and intensity. However, it should be noted that Richter states that the correlation is rough and applies to intensities on "ordinary ground." According to Neumann, who has made exhaustive studies of intensity ratings, magnitude determinations and strong motion seismogram intensities on granitic basement rock (same as at Bodega Head) would be approximately one grade lower or a maximum of MM-X.

Eaton gives MM-IX as a reasonable estimate of the 1906 intensity at the site based on tha fact that the reactor would be sited on quartz diorite bedrock and that recorded maximum intensities of the 1906 earthquake near Bodega appear to be somewhat smaller than Richter's averages would suggest. Using the Gutenberg and Richter (1942) semi-empirical relationship MM-VIII, IX, and X yield accelerations of .15 g, .32 g, and .69 g, respectively.

Neumann after exhaustive consideration of intensity and recorded strong motion data gives a range of .67 g to 1.0 g for a magnitude 8.2 earthquake on the San Andreas fault near Bodega Head.

Housner (Benioff and Tocher agree)employed the response spectrum technique to determine the destructive action of the ground motion. Although this method is generally preferred to the intensity analysis, it has specific limitations as the spectrum assumes a recorded earthquake acceleration. Since no magnitude 8 shock has ever been recorded, the data must be extrapolated from a lower magnitude recording such as El Centro (1940), Olympia (1949), etc. ?

Benioff in describing the motion at the fault states that it is effectively an uni-directional fling or pulse which radiates outward from the fault. "Although the waves begin in the form of a single uni-directional pulse they are quickly transformed into oscillatory forms by reflections, refractions and change of type owing to the layering of the crust and the variations of wave speed with depth. Although the vibratory wave amplitude is small at the fault it increases rapidly with distance from the fault so that from about 2 miles to 12 miles, it is approximately constant, if the geology is uniform......" This explanation does not agree with results of earthquake effects since the larger intensities are indeed observed for larger earthquakes. Moreover, as pointed out by Eaton from the very definition of magnitude and the seismologist's ability to compute magnitudes from relatively short period body waves, there is good indication that the amplitude of waves radiated from relatively small areas of the fault surface increases approximately ten times between magnitudes 6-7 and 7-8.

The Coast and Geodetic Survey having access to these reports and having evaluated independently the response spectrum and the intensity versus strong motion data, recommends ~~[illegible]~~ 2/3 g (.66) at periods from 0.3 sec to 0.7 sec for the level and ~~0.9~~ 1.0 g

Relative to the possible dislocations in the site or adjacent parts of Bodega Head during a major earthquake, there is a scarcity of data upon which to quote an accurate probable displacement. In considering the geology of the site, most of the observers (Schlocker, Bonelli, Tocher, etc.) believe that the site is "safe" because of the quartz diorite formation and the lack of evidence of recent faulting in the shaft. No major faults were found and the field evidence suggests that most, if not all, of the fracturing, shearing, and faulting in the quartz diorite is very ancient. This is confirmed by the examination of the terrace deposits overlying the quartz diorite which failed to reveal any faulting in the terrace deposits. Even thou such evidence (lack of recent faulting in the shaft) was observed in ex avating the shaft, it must be emphasized that this survey covered an infinitesimal segment of the geological structure associated with the San Andreas fault. Therefore, it is assumed if such concentrated surveys were extended to other areas even very close to the proposed site, that positive evidence of recent faulting could be found. Moreover, the fact that large earthquakes of offsets on a number of minor faults in sympathy with a large displacement on the causative fault cannot be disregarded. Certainly in the case of the Point Reyes Peninsula during the 1906 earthquake the displacements in bedrock indicate that faulting does occur outside of the San Andreas fault zone in sympathy with large displacements within the zone. Such an occurrence of offsets on Bodega Head during future earthquakes is a definite possibility. Based upon the very likely existence of such faults, the Survey believes that displacements of at least 2½ feet, similar to that experienced at Point Reyes, must be considered likely at Bodega Head.

Another factor for consideration in evaluating Bodega Head as a possible site for a reactor is the probability of a damaging tsunami. It is well established that the San Andreas fault extends into the ocean along the northern coast of California. Since 1898 there have been two submarine earthquakes along this fault that could have potentially generated a tsunami. Moreover, there is a possibility that the next great earthquake of magnitude greater than 8 along this fault could occur off-shore.

Now, it might be in order to digress briefly and say something about tsunami causes and propagation since neither the applicant (PG&E) nor the consultants have discussed this matter in their documents. For the most part, tsunamis are generated by submarine earthquakes or earthquakes located close to coastal areas. The causes of tsunamis are not well established because only a small percentage of submarine earthquakes generate measurable water waves. The most common explanation calls for the displacement of submarine blocks of the earth's crust. Since it has been observed on land that great earthquakes have caused uplifts of 30-50 feet and affected crustal blocks hundreds of miles long and up to a hundred miles wide, it is easy to conceive of such a crustal movement under the ocean generating a huge water wave.

Slides along the coasts are also throught to be the source of tsunamis.

Tsunamis frequently originate at great oceanic troughs where great masses of unconsolidated material which, disturbed by an earthquake, may slide into the depths, displacing a great amount of water. Dr. Benioff, some years ago, suggested a possible correlation between tsunamis and great surface waves with periods over a minute. This was remarkably confirmed during the recent Prince William Sound earthquake where waves of a few feet were generated in the Gulf of Mexico, in other large bodies of water and in many swimming pools throughout the United States.

It is not surprising that the tsunami peril was not mentioned by PG&E and others because with the exception of a wave, reported generated by a local earthquake on December 21, 1812, there is no record of a destructive tsunami generated along the coast of California. The 1812 wave reportedly reached land elevations of 50 feet at Gaviofa, 30-35 feet at Santa Barbara, and 15 or more feet at Ventura.

Inasmuch as historical records for locally generated tsunamis are so sparce, the dimensions of tsunamis that have been established through relatively frequent occurrences in Japan should be considered. Iida has done considerable work in establishing statistical relationships on the available Japanese data, using both earthquake magnitude and focal depth. His formulas show a small tsunami will be generated for a shallow earthquake of magnitude 6½-7. He shows disastrous tsunamis generated for shallow earthquakes with magnitudes of 7 3/4 or greater. The magnitude of 7 3/4 corresponds to a fault length of 120 km and a ground displacement of 5.4 meters.

Based on Iida's formulas, a tsunami classified as destructive will have a height of about 10 meters or greater. The earthquake of March 3, 1933, off the Sanriku coast of Japan had a magnitude of 8.3 and was of shallow focal depth; the wave rose to heights of 23 meters on the coast. The recent Alaskan earthquake had a magnitude of 8.4; maximum waves of 30-35 feet were reported at Kodiak and may have been exceeded elsewhere. Local waves of 15-20 meters were reported for the Chile tsunami of May 1960 (earthquake magnitude of 8¼ to 8½). These support Iida's formula as being reasonable (even though far from being rigorous evidence) and suggest that his conclusions for the Japanese area may apply approximately in other areas.

In confirmation of these facts, it is in order to tabulate some statistics for a few major tsunamis generated in different geographical areas.

Prince William Sound - March 28, 1964 - 61° N, 147.5° W, Magnitude 8.4.

Cordova	65 miles (Stat)	30 feet
Kodiak	210	35
Seward	85	30
Sitka	495	23
Crescent City	1,620	13
San Francisco	1,890	7

Chilean earthquake - May 22, 1960 - 38° S, 73.5° W, Magnitude 8½.

Talcahuano, Chile	90 miles (Naut)	16½ feet
Valparaiso	312	5½
Antofagasta	875	4½
Crescent City	5,529	10.9 feet
Hilo, Hawaii	5,704	35
Kanaisi, Japan	9,150	12.9 feet

Aleutian earthquake - March 9, 1957 - 51° N, 175° W, Magnitude 8.3.

Adak, Alaska	80 miles (Naut)	26(?) feet
Unalaska	355	4.5 feet
Kahalui, Hawaii	2,005	11.2
Valparaiso, Chile	7,384	6.7

Kamchatka earthquake - November 4, 1952, 52½° N, 159° E, Magnitude 8¼.

Attu, Alaska	460 miles (Naut)	8.0 feet
Adak	893	6.9
Hilo, Hawaii	2,893	7.9
San Francisco	3,265	8.1
Talcahuano, Chile	8,420	

Aleutian earthquake - April 1, 1946, 53½° N, 163° W, Magnitude 7.4.

Scotch Cap, Alaska	100 miles	80 feet
Hilo, Hawaii	2,280	35 (?)
San Luis Obispo, California	1,435	8½

Honshu, Japan earthquake - March 2, 1933, 39¼° N, 144½° E, Magnitude 8.9.

Sgoya, Japan	190 miles (Stat)	30 feet
Tanohata	140	27
Koyatori	130	40
Ryori Sirahama	140	63 (Plus)
Hirota Atumari	145	77 -

Even though little is known about tsunami generation and the propagation of the tsunami in open water where the velocities range up to 500 or 600 miles per hour and the wave lengths may be a hundred miles long, there is certainly positive evidence that a potential exists for a tsunami along the California coast, particularly along the San Andreas fault off the California coast. In reviewing the wave heights generated by these and other submarine earthquakes, it would not be unexpected for an earthquake approximately 250 miles from Bodega Head to produce a wave height of 25 feet above mean sea level. Therefore, the Survey recommends that adequate protection be provided for the proposed Bodega Head reactor site against a potential tsunami having a wave height of 25 feet above mean sea level.

Before summarizing the conclusions of this report it is order to comment on the trendous amount of work that has been performed by the PG&E Company, its consultants, the scientists and engineers of the AEC, etc., consultants and the interested public. Each one is aware of their great responsibility in the decisions to be reached in the near future relative to either licensing or refusing a license for a reactor at Bodega Head, California. This responsibility is explicitly emphasiced by the statement of the Honorable Chester Holifield of California - "I feel that one large reactor incident would cause such great loss of life that it might preclude any further development in the industrial field if it should occur...."

Neumann states, "While there can be no quarantee that an earthquake greater than the 1906 shock will not occur in the Bodega Head area, the history of earthquakes in active seismic areas leads one to believe that this is not lively.... Theoretical considerations lead one to believe that if certain tectonic processes are underway in the deep crustal rocks of th earth in a given region, these processes will be repeated over very long periods of time.....perhaps many centuries--before the pattern changes."

Eaton in his report succinctly and profoundly stated "Few places on earth are exposed to more certain earthquake risk than are those along the San Andreas fault in northern and southern California. Acceptance of Bodega Head as a safe reactor site well establishes a precedent that will make it exceedingly difficult to reject any proposed future site on the grounds of extreme earthquake risk."

The Survey, fully aware of the exhaustive and comprehensive studies made by all participants, believes that the conclusions reached by its scientists are adequate and sufficiently complete so that the AEC may employ them in rendering a judgment.

CONCLUSIONS

(1) The seismicity study of the San Andreas fault area near the propos Bodega Head reactor shows the possibility of a magnitude 8.2 earthquake abou once every 100 years. All actions relative to this site should be contingen upon the occurrence of a large magnitude earthquake during the lifetime of a reactor.

(2) The characteristics of the ground vibrations tolerable at this site are: acceleration of ground motions - ~~0.6-0.7~~ 1/3 g for periods of 0.3 to 0.7 seconds for which the structure and all of its elements should be designed; ~~0.9~~ 1.0 g for the same period range is the limit for which critical elements will fail but not release fission material.

(3) There is a definite potential for a tsunami to affect the Bodega Head site. It is therefore recommended that any proposed reactor be so constructed that tsunami wave heights of 25 feet above mean sea level will not impair its operation and the safety of the surrounding population

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