REVISED DRAFT OF

REPORT

TO

AEC REGULATORY STAFF

SEISMIC EFFECTS ON BODEGA BAY REACTOR

BY

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INTRODUCTION

This report concerns the ability of the reactor facility proposed by the Pacific Gas and Electric Company to resist an earthquake opposite Bodega Head of the intensity postulated by the U. S. Geological Survey and the U. S. Coast and Geodetic Survey, including the faulting or relative displacements. Reference is made in this report to the application by the Pacific Gas and Electric Company concerning this reactor, particularly Amendment No. 8.

The general description of the postulated earthquake involves a pattern of ground motions similar to that recorded by the Coast and Geodetic Survey in the El Centro Earthquake of May 18, 1940, but with approximately twice the intensity, corresponding to a maximum acceleration of two-thirds gravity, a maximum velocity of 2.5 ft/sec., and a maximum ground displacement of 3 feet, and with occasional intermittent pulses of acceleration up to 1.0 times the acceleration of gravity. The response spectrum for the earthquake without the additional acceleration pulses up to 1.0g will be similar to that of the El Centro Earthquake. With the additional accelerations, the high frequency part of the spectrum will be increased somewhat.

In addition, the structures are considered to be subjected to simultaneous shear displacements ranging up to 3 feet, along lines extending under the containment structure or other parts of the plant, with motions in either horizontal or vertical directions along the fault. It is assumed also that after-shocks of intensity equal to the El Centro quake might be suffered before remedial action could be taken.

Under these conditions, and with the design considerations described in Amendment No. 8 and in previous application amendments, it is my conclusion, after study of the matter, that the structural integrity and leak tightness of the containment building can be maintained under the conditions postulated. However, certain precautions must be considered especially in the design of umbilicals and of penetrations to the containment building. These are described below.

Similarly, the ability to shut down the reactor and maintain it in the shut-down condition would not be impaired, provided that the intensities of motion and the magnitudes of fault slip do not exceed those postulated. Again, certain precautions are required as described more fully below.

The primary system, being contained in the massive reactor containment structure, would remain intact up to fault movements not exceeding 3 feet, and under earthquake motions as described above, provided that the piping system carrying the main steam lines from the dry well to the turbine inlet is made sufficiently flexible to accommodate a relative movement of 3 feet without failure, and at the same time is damped to reduce its dynamic response to earthquake oscillations. All attachments and umbilicals must be arranged to prevent failure by shearing or crushing due to contact with walls, rock, earth, etc. in the event of major earthquake motions. Further comment on these matters is made below.

The supply of power to the facility, from power lines crossing the major fault, might be interrupted, although the probability of such interruption is probably fairly low. In the event of such interruption, auxiliary power supplies are required. The sources of auxiliary power described appear to have adequate capability to resist the postulated earthquake effects.

In general, the provisions for meeting the various requirements are based on methods which in the light of analysis and study appear to be reasonably adequate.

The earthquake motions, including acceleration and velocity as well as displacement, appear to be 2 to 3 times more intense than any that have been recorded in the United States, and probably about twice as intense as those experienced anywhere else in the world in the recent years for which we have fairly good records. Nevertheless, it appears that the design objectives can be accomplished.

A more detailed discussion of the various points described in Amendment No. 8 is contained in the following material. In addition, consideration is given to several points not specifically discussed in the amendment.

EFFECTIVENESS OF SAND LAYER IN SHOCK ISOLATION

The sand layer under the containment building is intended to act in two ways: (1) to isolate in part the containment structure from the high peaks of acceleration that might be transmitted to it from the ground beneath it; and (2) to permit either horizontal or vertical faulting to take place in the rock beneath the containment structure without damaging the structure. It will be shown in the following discussion that the effectiveness of the sand layer in reducing the peak accelerations may be questionable, but its effectiveness in reducing the effects of faulting is substantial.

In the study of this problem I have had the benefit of discussion of the current state of knowledge of this aspect of the problem with Mr. R. A. Williamson of Holmes and Narver, a consultant to the AEC staff. The statements made herein reflect in general his views, as interpreted by me, and the final conclusions are based on my views as well as his.

Vibratory Effects

The properties of sand under static loading have been studied for many years and are well understood. The frictional resistance in natural beds of sand has been measured and compared with behavior of such beds under various conditions. Within recent years dynamic tests of the behavior of sand have been made by Dr. R. V. Whitman of MIT, Dr. H. B. Seed of the University of California at Berkeley, and by others. The results of these tests, and of the engineering experience for many years, indicate that the frictional resistance of sand, as measured by the angle of internal friction, changes very little for velocities of the order of 2 ft/sec., and the change is not greater than about 20% for velocities slightly greater than 3 ft/sec. The coefficient of friction, as measured by the tangent of the angle of internal friction, corresponds to values ranging from about 0.5 or slightly greater up to about 0.9, and in general there appears to be no increase in the coefficient of friction for high contact pressures or for high loadings.

The constancy of the angle of internal friction is dependent on the relative density of the sand. If it is in a condition corresponding to a density of the order of 90 to 95% of its maximum possible density, the friction angle does not increase with motion. For very low relative densities, or for loosely packed sand, the friction angle of dry sand will increase with loading. On the other hand, this increase in friction angle of loosely packed sand is accompanied by a reduction in volume, and this reduction in volume, under conditions of saturation, corresponds to a great increase in the pressure carried by the inter-granular water. This results in a temporarily decreased effective frictional resistance, and therefore it is quite reasonable to expect that under the conditions of deposition of the sand layer, the frictional resistance will not effectively be increased over the value corresponding to the density achieved in placement, over a long period of time. However, after an earthquake has occurred, the conditions prior to the next earthquake will have been slightly changed, if the sand is in a very loose condition to begin with. Nevertheless, a change in density of the sand would not be expected to occur unless relatively larger motions take place than those postulated.

The skin friction angle between relatively smooth concrete and sand is generally slightly less than the friction angle in the sand itself; hence the resistance to sliding of a properly constructed structure on a sand bed can be made as low as that which corresponds to a coefficient of friction of the order of 0.6 to 0.8, and it can be expected with confidence that this coefficient of friction will not increase with time provided that the sand is clean and the water inundating it does not contain cementing compounds.

Earthquakes having accelerations less than that required to overcome the frictional resistance would not affect the behavior of the sand at all.

It appears from the foregoing that the containment structure will move with the ground for accelerations less than about 2/3g and possibly even for accelerations as high as 0.9g to 1.0g. Only the very largest peaks of acceleration, greater than the frictional resistance, can be attenuated by the sand layer. Moreover, if the sand layer were to slip at an acceleration of about 2/3g, a ground acceleration of 1.0g would involve a slip of the containment structure on the sand bed of the order of 2-3 inches, which could reduce the gap provided for isolation purposes by this same amount.

Faulting Effects

The rock beneath the containment structure may suffer a postulated fault displacement of magnitude up to 3 feet in either the vertical or horizontal direction. Whether or not the sand has become partially cemented, it will be much weaker than either the rock or the concrete and will, therefore, not change or influence the fault motion immediately beneath the structure. If the rock faults vertically, the structure will tip. The greatest angle of tipping would be that corresponding to a vertical fault occurring at the center of the structure, in which case the angle would be approximately equal to the fault displacement divided by the radius of the containment building. Such tipping would partially close the gap left between the containment building and the surrounding rock and/or earth. This must be considered in evaluating the available space in which to accommodate concurrent horizontal fault motions. Both horizontal and vertical motions must be taken into account in considering the integrity of the containment building, other vital structures or any attachments or connections thereto.

When horizontal faulting takes place under the containment structure, there can be a tendency to rotate the containment structure. This rotation can result in somewhat larger movements of points on the circumference than the fault motions themselves, and must be taken into account in evaluating the effects on both the structure and attachments thereto.

If proper provision is made for the tipping and rotation, and possible sliding, the containment structure and its associated attachments can be designed to resist successfully a major earthquake with maximum effects as postulated. However, if such an earthquake brings the structure nearly into contact with the sides of the cavity in which it is placed, a second major earthquake may involve the possibility of damage to the structure or the attachments thereto, since the gap providing isolation against fault motions will have been nearly closed. In other words, the amount of faulting in successive earthquakes cannot involve a greater combined fault motion than three feet in any one direction, and the amount of gap left after faulting must not be so small as to permit battering of the structure or of vital attachments against rock, earth, etc. adjacent to the structure, in after-shocks, or in the remainder of the earthquake following the faulting.

DESIGN OF PIPING, ETC. TO ACCOMMODATE RELATIVE MOVEMENT AND VIBRATORY EFFECTS

The amendment indicates that adequate anchors and bracing will be provided to prevent large relative motions of the piping connecting the dry well to the wall of the reactor building. Beyond the anchor at the wall, and extending to the anchor near the turbine generator foundation, the piping will be subject to the differential motions corresponding to fault displacements ranging up to three feet, as well as the vibratory motions induced by the earthquake accelerations. Since the time sequence of the assumed faulting and the oscillation is entirely a random matter, both of the effects must be considered as occurring at any time, even simultaneously.

The precise strains in the pipe due to relative motions or due to earthquake vibrations are functions of the length of the pipe runs in the various directions and the method of anchoring. The curvatures in the pipe, and hence the maximum strains in it, due to a slow relative motion of the ends of a pipe run, are primarily a function of the geometry of the system, and are nearly independent of the thickness of the pipe shell. The diameter of the pipe and the length of the runs in the various directions, as well as the conditions at the support, namely whether these are fixed or hinged to provide rotation, are the primary influences affecting the strains accompanying a given relative motion of the ends of the run. The maximum strain is in general of the order of 4 times the diameter of the pipe times the relative displacement divided by the square of the component of length of the run in the direction perpendicular to the displacement. This value of the strain corresponds to a condition of fixity at the ends of the run. If the ends are hinged, which is an extremely favorable condition that cannot be obtained except with flexible connections, then the strains are reduced to possibly two-thirds as much as those corresponding to fixed ends. Therefore, the higher value will be used in the estimates made herein.

Both the horizontal and vertical components of the pipe runs of the 20-inch main steam lines are approximately 80 feet. Since the pipe is 20 inches in diameter, the corresponding strain is approximately 0.003 in/in. This is about twice the strain at the yield point. Therefore, without flexible connections, the strain in the pipe due to the postulated relative motion of slightly more than three feet would exceed the yield point, but only slightly, and by an amount that should not cause failure. To reduce the strains to yield point values would require the introduction of flexibility at possibly two of the joints or elbows in the pipe, or one or more bellows connections at the ends of the pipe run. It does not seem necessary to increase the length of the pipe run from 80 feet to 115 feet, which would be the requirement to reduce the strain to the yield point value merely by increasing flexibility of the pipeline itself.

The dynamic response of the piping depends on its fundamental period of vibration and can be obtained from the shock response spectrum. Since both the weight of the piping and its stiffness depend linearly on its wall thickness, the deflection of the piping due to a given acceleration, which is proportional to weight divided by stiffness, is independent of the wall thickness. Only the diameter of the pipe and the length of the pipe runs determine the frequency of a pipe not carrying additional load. For several different configurations of pipe a fairly consistent relationship between maximum dynamic strain due to earthquake vibration and maximum strain due to movement of the supports can be obtained.

The ratio of the maximum strain due to a spectral displacement, D, for vibration at a given frequency, compared with the strain due to a relative static displacement at the ends, Δ, is approximately $2\frac{D}{\Delta}$. Hence, the earthquake strains which accompany earthquake motions will be of the same order as the strains for the three foot movement of the ends if the earthquake displacement is approximately 1.5 feet. For the pipe runs considered, Mr. Williamson estimates a period of vibration of the order of 1 to 2 secs. assuming hinged ends. My calculations indicate a period of about 0.5 sec. for two fundamental modes, one primarily vertical and the other primarily horizontal, when the ends are fixed. These periods are about twice as long, or one sec., for hinged ends. The maximum combined stress when both modes are excited is only slightly greater than the maximum stress for one of the modes. For a period of 0.5 sec., and for the PG&E spectrum in Figure 1 of Amendment 8, for 0.5% damping, the displacement is of the order of 0.25 feet, and for twice this earthquake the displacement will be about 0.5 feet. On this basis, it can be estimated that the strains due to the earthquake response are about one-third as great as those due to the 3 feet relative displacement of the supports. Hence, under combined earthquake and relative displacement due to faulting, the pipe would be overstressed, but not beyond three times the yield strain.

It should be noted that the dynamic displacement due to the postulated earthquake varies almost directly as the natural period in the range from about 0.4 sec. to more than 3.0 secs. In other words, if the period of the pipe can be reduced, its displacement will be decreased in the same proportion. However, reducing the period of the pipe would, in general, require an increase in stiffness which would cause difficulties in resisting the relative displacement of the ends. Conversely, introducing flexible connections will in general increase the period of the pipe which will increase the dynamic earthquake strains.

The final design of the piping should take the foregoing considerations into account to insure that the piping can sustain both the earthquake vibrations and the relative fault motions without being overstrained.

It might be pointed out in this regard that the maximum displacement of the pipe, should it become inelastic in an earthquake, would probably not be different from the maximum displacement were the pipe to remain elastic. Hence the pipe, under the most serious combination of conditions, will be strained to about 3 times the elastic limit strain at yielding for the proposed material (under the combined effects of the fault motion and earthquake motion). Whether this is acceptable depends on the details of the final design. A possible means of reducing the stress involves introduction of damping by artificial means. If dampers are used, care must be taken to avoid introducing additional disturbing forces in the pipe when relative motions of the ground or the containment structure take place.

All umbilical connections to the reactor containment structure, including the main steam lines, should be designed to assure freedom from contact with other structures, walls, or earth and rock, by such a distance as to provide for the possibility of a three foot fault motion under the containment building and, in addition, the vibratory motion of the element considered. Also, all vital piping and other connections must be arranged in such a way that a three foot fault motion occurring elsewhere in the area will not cause a failure of the vital element. The actual relative displacement in piping and other umbilical elements may exceed three feet because of rotation and/or tipping of the containment structure caused by the fault motion.

The main steam lines and similar important lines should be designed to be locally stiffened by sleeves or doubler plates, at points where isolation valves or where anchors are attached, to prevent ovalling or distortion of the lines that would impair their behavior.

SAFETY OF AUXILIARY EQUIPMENT

The auxiliary equipment contained within the reactor containment building will, in general, move as a unit within the containment structure. The fault displacement of three feet for which provision is made does not produce a similar displacement within the structure, although it may produce a rotation or tilting of the containment structure. However, the equipment described in Amendment 8 and elsewhere in the application can certainly be designed for the slight tipping or tilting and rotation, provided it is not rigidly attached to items which move either a different amount or do not move at all.

It is stated in Amendment 8 that "where vital components of the emergency systems are located within the turbine generator foundation of the control building, the inner-connecting piping and cable will be designed to withstand up to three feet of relative displacement between the reactor containment structure and the turbine generator foundation, or control building." The provision of resistance to large relative displacement combined with resistance to oscillations seems capable of achievement for relatively small diameter pipes, or for wires, although it is more difficult for the 20-inch main steam lines.

SAFETY OF PRIMARY SYSTEM

Comments have been made previously in this report regarding the main steam lines and the difficulties involved in providing the necessary resistance to relative motion and to earthquake vibrations. The statement is made in Amendment 8 that "accelerations experienced by the primary system during such a displacement would be less than the accelerations used in the design of the equipment". It is not clearly stated that the accelerations experienced by the primary system during the maximum earthquake would be less than the acceleration used in the design of the equipment. Moreover, it is not clear, if the relative motion of faulting should exceed three feet, whether there will not be a greater maximum acceleration than that provided during the earthquake, owing to a possible crashing or battering of the retaining walls outside the gap against the reactor containment structure. These could induce fairly large, but high frequency, accelerations. Because of the large mass to be moved, the inertia of this mass, and the possible weakness of the walls of the reactor containment structure against a localized line loading from outside, it is not clear at all that a relative movement of more than three feet could be sustained without producing serious damage to the reactor containment structure or serious accelerations to the primary system within it. Nevertheless, since fault motions greater than three feet are not considered credible, questions of this sort need not be considered.

POSSIBLE INTERRUPTION TO SUPPLY OF POWER

The vulnerability of the overhead transmission lines has not been established. These lines cross the San Andreas fault, and although they are supported on widely spaced towers, there is a possibility that one or more of the towers may be displaced by as much as 20 feet relative to a neighboring tower. It is possible that the towers can sustain such a motion without loss of all of the lines. However, further study of this problem is desirable if it is necessary to depend on this source of power. Amendment 8 states, however, that if the external sources are unavailable, the engine generator, located within the reactor containment structure, will be capable of handling the load required to shut down the plant safely. A further supply of power is available in the battery contained within the reactor containment structure and control building.

It must be regarded as possible that the main overhead transmission line would be severely impaired in its functioning where it crosses the main fault.

ABILITY OF STRUCTURES AND EQUIPMENTS TO RESIST EARTHQUAKE OSCILLATIONS

The procedure described for the design of critical and non-critical structures, on pages 19-25 of Amendment 8, appears in general to be satisfactory, with minor exceptions. On page 21, the second paragraph indicates that "the design of the plant will be checked to assure that all critical structures, equipment and systems will be capable of withstanding earthquake ground motions corresponding to spectrum...(values)... <u>two</u> times as great as shown on Figure 1 without impairment of functions..." This means an earthquake of maximum acceleration of 0.67g, but not with acceleration spikes ranging up to 1.0g. The difference is not important for items having periods of vibration greater than about 0.5 sec., but it can be substantial for elements having shorter periods or higher frequencies, and the discrepancies become progressively larger as the frequency becomes higher or the period becomes lower. A clear and unequivocal statement about this point would be desirable.

In general, there is a reserve margin in almost every element beyond the point at which yielding begins, even in items of equipment, control rods, fuel assemblies, etc. Dr. Housner's study of the reserve capacity of structural elements, in Appendix II of Amendment 8, is sound. Nevertheless, for items of equipment which are not designed for yielding at all, but which have to satisfy certain criteria such as clearance or magnitude of displacement, it is essential to consider the higher spikes of acceleration in their design in order to provide the necessary reserve margin to assure operation of these items under the extreme maximum conditions.

In this regard, it should be noted that the design spectrum in Figure 1 is not quite as large as the values that correspond to the extreme peaks of the El Centro spectrum. The values in Figure 1 are in general those that correspond to the mean of the oscillations for the rather jagged peaks in the individual response spectrum curves for various earthquakes, especially in the high frequency region. An envelope through the spikes would generally lie about a factor of 2 above the smoothed spectrum, particularly for the low values of damping. This is not regarded as an important discrepancy, however, as there are indications that the mean of the oscillations in the spectrum is a much more significant value than the magnitude of the spikes. Calculations and measurements that have been made and that are reported for equipment mounted on submarines, and calculations for response of buildings to earthquakes, in general indicate that the measured responses are more nearly consistent with the mean of the oscillations of the spectral values rather than with the peaks. Hence appropriate smoothing of a design spectrum is a rational and reasonable procedure.

The accelerations transmitted to the reactor containment structure will not exceed the acceleration that will cause sliding on the sand layer, which may be from 2/3g to 0.9g, depending on the characteristics of the sand, until first contact is reached with the side of the cavity. Since this contact will occur after a three foot fault movement, or possibly slightly less if some sliding occurs on the sand, a design level of 1.0g for proper functioning of equipment should be used.

SUITABILITY OF PROPOSED DAMPING COEFFICIENTS

The damping coefficients listed on page 23 of Amendment No. 8 appear in general to be reasonable. The degree of precision implied in the selection of damping coefficients to two significant figures seems somewhat unwarranted. However, the values are in general reasonable for the stress levels implied in the design of the individual elements, or for the conditions which are involved in their behavior. The damping for the reinforced concrete reactor containment structure would be considered high for a structure supported directly on the rock, but appears to be reasonable considering the fact that the structure is supported on a sand bed.

EFFECTIVENESS OF SAND LAYER IN CLIPPING PEAK ACCELERATIONS

In view of the comments on the behavior of the sand layer, it can be concluded that the sand layer will act to clip high peaks of horizontal acceleration that exceed its frictional capacity to transmit force to the reactor containment structure. It will not clip vertical acceleration peaks.

DETAILED DYNAMIC ANALYSIS OF EQUIPMENT

The method described on pages 23 and 24 for handling the response of equipment within the building appears reasonable, although for sensitive items near the upper part of the building, the approximate method may not be adequate. A detailed dynamic analysis, such as described near the bottom of page 24, will be desirable for all extremely sensitive and critical items of equipment. The method of analysis described can take into account the interaction with the reactor containment structure itself. However, the ground accelerations or ground input motions considered should correspond to the maximum postulated earthquake, and not the 0.33g earthquake for which Figure 1 of the amendment is drawn.

The statement on page 34 implies that double the seismic loads corresponding to Figure 1 will be considered, but this does not take into account the spikes of acceleration ranging up to 1g for the higher frequency components. A further clarification of this point is desirable.

ADDITIONAL COMMENTS

The effect of the water in the annulus surrounding the reactor containment structure should not, in general, cause accelerations to be transmitted directly to the structure through the water because of the fact that the water has a free surface. However, it would be desirable to have a study by the applicant of this problem to insure that the surging of the water will not introduce additional oscillations within the structure. This does not seem likely and it appears most reasonable to expect that the water contained in the annular space will damp the motion of the structure. Nevertheless, no specific data on this topic are available.

In general, although questions have been raised about the treatment in certain aspects of the amendment, it is not believed that any of these questions involve problems that are not possible of solution within the range of currently available engineering knowledge. It is my considered opinion that the structure and its equipment can be designed essentially as proposed to resist the effects of the maximum earthquake postulated.