DIABLO CANYON POWER PLANT

UNITS 1 AND 2

THREE-DIMENSIONAL STUDIES

OF HIGH DENSITY SPENT FUEL RACKS

(ACORN 10 AND ACORN 12)

Pacific Gas and Electric Company

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1. BACKGROUND

The analytical methodology used for obtaining rack interaction impact loads for the high density racks at Diablo Canyon was described in the Reracking Report, submitted by PGandE on September 19, 1985 (Reference 1). The methodology, in general, utilizes conservative inputs in a three-dimensional (3-D) single-rack model that lead to conservative impact loads. PGandE determined that these conservatively determined loads, combined with use of ample design margins, provide an adequate design basis to accommodate the effects of multi-rack impacts. This determination was further confirmed by the results of recent two-dimensional (2-D) parametric studies using both multi-rack and single-rack models (Reference 2) which showed that the conservative models, in general, predicted conservative results. Furthermore, the calculated loads in all cases were found to be substantially less than the loads used for rack qualification.

Following a technical meeting on March 26, 1987, to review the 2-D parametric studies, the NRC Staff requested (Reference 3) that PGandE perform further 3-D single-rack studies which would incorporate the realistic assumptions used for some of the 2-D parametric studies. Specifically, the NRC Staff requested that computer runs ACORN 10 and ACORN 12 (Table 6.8.2 of the Reracking Report) be rerun with these assumptions. In addition, the NRC Staff requested that the results of these studies be summarized in a table similar to Table 6.8.2 of the Reracking Report, including the stress ratios (R_1 through R_6).

2. DESCRIPTION OF THE NRC-REQUESTED 3-D STUDIES

Computer runs ACORN 10 and ACORN 12 analyzed the behavior of a fully loaded 10x11 rack located at a corner of the spent fuel pool for friction coefficients of 0.8 and 0.2, respectively. Based on a review of the results of numerous cases reported in the Reracking Report and the Seismic Analysis Report (Reference 4), it was determined that the case analyzed by ACORN 10 resulted in the highest stresses in the rack, and hence ACORN 10 was selected for this study by the NRC. Computer run ACORN 12 was selected to facilitate comparisons with ACORN 10 in order to study the behavior of the same rack assuming a lower friction coefficient.

The model used in these NRC-requested 3-D studies was the same as the model used in the design basis analysis reported in the Reracking Report (Figures 6.2.1, 6.2.2, and 6.2.3) except for the following assumptions:

- Spring constants: The design basis analysis used spring constants significantly higher (over 10 times) than the calculated values. The parametric studies used spring constants consistent with those used in the recent 2-D parametric studies (e.g., 1.5 times the calculated values for the fuel assembly to cell wall impact spring).

- Hydrodynamic coupling: In the design basis analysis external hydrodynamic coupling effects were assumed to be a function of only the horizontal translational motion of the rack centroid. The forces developed due to these hydrodynamic effects were located at

the rack mid-height and directed through the rack centroid. This assumption conservatively neglected the hydrodynamic coupling effects induced by the rocking and torsional motion of the racks.

Consistent with the 2-D parametric studies, the hydrodynamic coupling terms due to rocking and torsion were included in these NRC-requested 3-D studies to more realistically represent rack motion.

- Gap values for hydrodynamic coupling: The design basis runs were performed by assuming conservative (higher) values for the effective gap used in calculating the hydrodynamic coupling effect. The effective gap, as derived based on continuity and energy principles, is given by the following expression:

$$\frac{1}{g_e} = \frac{1}{g_L} + \frac{1}{g_R}$$

where g_e is the effective gap, and g_L and g_R are the fluid channel widths on the left and right side of the rack, perpendicular to the direction of rack motion. A value of $g_e = 2.0$ inches was assumed in the design basis analysis for the x and y directions. In the NRC-requested 3-D studies, the effective gaps were calculated to be consistent with realistic situations. The corresponding effective gaps were $g_{ex} = 1.0$ inch and $g_{ey} = 0.884$ inch. Use of

the realistic gap values is appropriate and consistent with the 2-D parametric studies. The hydrodynamic coupling coefficients for translational motions were developed using an equivalent lateral gap (h_0) of 7.5 inches.

- Support foot construction: The design basis analyses were originally performed using a smaller support foot geometry than the final foot configuration selected for use in the racks. The computer results were subsequently modified to account for the substantial increase in foot cross-sectional area and inertial properties. During the NRC structural audit of March 24-25, 1986, the NRC Staff noted that the final configuration resulted in lower stress ratios, thereby improving design margins (Section 4.4g of Reference 5). These modified stress ratios are included in Tables 4.1 and 4.2. The results of the NRC-requested 3-D studies reported herein reflect the final configuration of the rack support feet.

3. DESIGN ALLOWABLES

3.1 GROSS SECTION STRESSES

The acceptance criteria for the Hosgri load combinations are the Level D Service Limits as specified in Section III of the ASME Boiler and Pressure Vessel Code. Section F-1370 (Section III, Appendix F) states that the limits for Level D Service are the minimum of 1.2 (S_y/F_t) or $(0.7\ S_u/F_t)$ times the corresponding Level A Service Limits. Substituting the appropriate value for F_t, the corresponding multiplying factor is 2.0 for the rack material and the upper portion of the rack feet. For the lower part of the support feet, the multiplying factor is 1.67. Table 3-1 summarizes the acceptance criteria for stresses.

Using the criteria described above, PGandE examined nine critical sections of the rack, including:

- The rack body immediately above the baseplate where maximum shear and moment will occur.

- The upper portion of each of the four rack support feet where compression, shear, and moment will be the highest.

TABLE 3-1

DESIGN ALLOWABLES

	Rack	Support Feet: Upper Component	Support Feet: Lower Component
Material	ASTM A240-304L	ASTM 479-S21800	SA 564-630
S_y	23,150 psi	44,900 psi	94,350 psi
S_u	68,100 psi	101,040 psi	145,000 psi
ASME Code, Section III Reference	Table I-2.2 Table I-3.2	Table I-2.2 Table I-3.1	Table I-2.2 Table I-3.1

- The lower portion of each of the four rack support feet where shear and compressive stresses will be the highest due to the reduced cross-sectional area.

Consistent with the original design methodology, the stresses in the above locations were computed at each time step of the analysis for each critical section, and their maximum values are reported in the form of stress ratios. These ratios are defined (Reference 1) as follows:

R_1 = Ratio of direct tensile or compressive stress on a net section to its allowable value (note: support feet only resist compressive loads)

R_2 = Ratio of gross shear on a net section to its allowable value

R_3 = Ratio of maximum bending stress about the x-axis to its allowable value for the section

R_4 = Ratio of maximum bending stress about the y-axis to its allowable value

R_5 = Ratio of combined flexure and compression

R_6 = Ratio of combined flexure and tension (or compression)

3.2 LOCAL STRESSES

Impact loads were examined for local effects on rack components. Areas examined included contact areas between the fuel assembly and cell wall, and contact areas (girdle bar and baseplate) which are subjected to rack-to-rack and rack-to-wall impact loads. Standard Review Plan 3.8.4, Appendix D, Table 1, states that "... deformation limits should preclude damage to the fuel assemblies." Local effects on Diablo Canyon racks were conservatively evaluated to ensure that no permanent deformation will occur.

3.2.1 Fuel Assembly to Cell Wall Impact

Using the principle of virtual work, it was determined that the cell wall limit load for fuel assembly impact is approximately 16 kips per cell or 1,766 kips for a 10x11 rack. Allowing for a factor of safety of 2, the corresponding values are approximately 8 kips and 883 kips, respectively.

3.2.2 Rack Impact

The local effect on girdle bars due to rack-to-rack impact was evaluated for a corner impact and for a line load impact. It was determined that for a corner impact, the impact load on the girdle bar would need to exceed 175 kips before any local deformation would occur. The corresponding load necessary to cause deformation for a line load impact is higher.

Impact loads on rack baseplates are resisted by the in-plane load bearing capacity of the baseplates. The impact capacity of the baseplate is substantially higher than 175 kips.

3.3 FUEL ASSEMBLIES

Each fuel assembly contains 264 fuel rods in a 17x17 array. The rods are supported by eight fuel assembly grids spaced along the length of the fuel assembly. During rack movement, some of the fuel assembly grids will impact the storage cell walls. The fuel assembly manufacturer, Westinghouse, has determined that fuel assembly integrity will be maintained for an impact force in excess of 3,400 pounds per fuel assembly grid.

4. RESULTS OF ANALYSIS

4.1 NRC-REQUESTED 3-D STUDIES

Tables 4-1 and 4-2 show a comparison of the results for the design basis analysis (ACORN 10 and ACORN 12) and the NRC-requested 3-D studies performed using realistic assumptions. In order to establish a common basis for comparison, the stress ratios reported in the Reracking Report (Table 6.8.2) for the design basis analyses were revised to account for the larger support feet. The results of the comparison indicate the following:

a. All stresses obtained from the NRC-requested 3-D studies are enveloped by the maximum stresses as reported for the design basis analyses (ACORN 10). The stresses from the NRC-requested 3-D studies show that the rack and supporting feet have factors of safety in excess of 2.5 over the allowables.

b. The fuel-to-rack impact load is reduced significantly. The revised load corresponds to approximately 600 pounds per fuel assembly, thus providing significant factors of safety and ensuring cell wall and fuel assembly integrity (see Sections 3.2.1 and 3.3).

c. As indicated in Table 4-1, the maximum stress ratio (1.436 from ACORN 10) occurs in the upper component of a support foot. The

TABLE 4-1

SUMMARY OF RESULTS - RACK TYPE 10 x 11 ($\mu = 0.8$)

Run No.	Case	Rack/ Rack Impact	Impact Loads (kips): Cell/Fuel Assemblies	Impact Loads (kips): Rack/ Rack (Note 2)	Impact Loads (kips): Rack/ Wall (Note 2)	Impact Loads (kips): Support Foot (Note 2)	Stress Ratios - Base/Support (Note 1): R_1	R_2	R_3	R_4	R_5	R_6
ACORN 10	Hosgri earthquake (HE); corner rack; full fuel load; design basis analysis	Yes	250	76	No impact	296	.122	.156	.231	.134	.323	.364
							.305	.347	.737	.506	1.265	1.436 (Note 3)
3D28	HE; corner rack; full fuel load; realistic spring constants and hydro-dynamic coupling	Yes	59	85	48	202	.117	.080	.126	.089	.238	.265
							.215	.199	.362	.235	.657	.743

1. The upper set of values in each row are load factors for the rack base (2.0 allowable); the lower set of values are similar maximum load factors for the support feet (2.0 allowable). (The upper part of the support feet have the more critical load levels; the lower support foot locations have much lower load factors which meet the limiting HE load factor of 1.67 with significant margin.)

2. Loads represent the maximum value for an impact spring.

3. Stress ratios for the support feet are revised from the Reracking Report to reflect the as-built condition of the support feet.

TABLE 4-2

SUMMARY OF RESULTS - RACK TYPE 10 x 11 ($\mu = 0.2$)

Run No.	Case	Rack/ Rack Impact	Impact Loads (kips): Cell/Fuel Assemblies	Impact Loads (kips): Rack/ Rack (Note 2)	Impact Loads (kips): Rack/ Wall (Note 2)	Impact Loads (kips): Support Foot (Note 2)	Stress Ratios - Base/Support (Note 1): R_1	R_2	R_3	R_4	R_5	R_6
ACORN 12	Hosgri earthquake (HE); corner rack; full fuel load; design basis analysis	Yes	213	27	No impact	126	.051	.023	.081	.065	.147	.164
							.133	.045	.098	.083	.273	.298 (Note 3)
3D22	HE; corner rack; full fuel load; realistic spring constants and hydrodynamic coupling	Yes	61	45	37	261	.173	.064	.102	.080	.244	.262
							.277	.093	.169	.168	.507	.551

1. The upper set of values in each row are load factors for the rack base (2.0 allowable); the lower set of values are similar maximum load factors for the support feet (2.0 allowable). (The upper part of the support feet have the more critical load levels; the lower support foot locations have much lower load factors which meet the limiting HE load factor of 1.67 with significant margin.)

2. Loads represent the maximum value for an impact spring.

3. Stress ratios for the support feet are revised from the Reracking Report to reflect the as-built condition of the support feet.

NRC-requested 3-D studies show that the corresponding stress ratio is significantly reduced (0.743). This decrease is due to the introduction of realistic spring constants. The revised stress ratio provides a factor of safety greater than 2.5 over the allowable (2.0).

For a friction coefficient of 0.2, the maximum stress ratio (0.551) is higher than the corresponding stress ratio (0.298) for the design basis analysis. However, it is less than the stress ratio (0.743) reported for the friction coefficient of 0.8 and provides a factor of safety of 3.6 over the allowable.

d. The rack-to-rack impact force on the girdle bar (85 kips) is higher than the force (76 kips) reported for the design basis analysis (ACORN 10). However, the resulting stress ratios are significantly lower than those reported for the design basis analysis. In addition, the 85 kip load is enveloped by other design basis analyses documented in the Seismic Report, and the revised girdle bar impact force results in a factor of safety greater than 2.0 against local deformation.

e. Although the NRC-requested 3-D studies indicated rack-to-wall impacts, the impact force (48 kips) is less than the corresponding force (85 kips) resulting from rack-to-rack impact. Accordingly, rack qualification is not affected. Additionally, the load is substantially lower than the maximum impact load the wall is capable of resisting as reported in PGandE's submittal dated April 7, 1987.

4.2 COMPARISON WITH 2-D PARAMETRIC STUDIES

There are some similarities between the 2-D single-rack parametric studies reported earlier (Reference 3) and the NRC-requested 3-D studies discussed herein. These similarities are:

- The fuel-to-rack impact load in the 2-D parametric studies decreased significantly when the 2-D model was revised to incorporate realistic assumptions. Consistent with this trend, the NRC-requested 3-D studies show a similar reduction in impact loads.

- For the governing cases ($\mu = 0.8$), both the 2-D parametric and NRC-requested 3-D studies show a reduction of floor impact loads when realistic assumptions are used. In the 2-D parametric studies, the floor impact load (not previously reported) for the support foot of a 10x10 rack decreased from 339 kips (Case 1 of Reference 2) to 166 kips (Case 2), and in the NRC-requested 3-D studies the load (for a 10x11 rack) decreased from 296 kips to 202 kips (Table 4-1).

- For the friction coefficient 0.2, the 2-D parametric study showed an increase of the support foot load (not previously reported) from 103 kips (Case 1) to 155 kips (Case 2); however, the increased load was enveloped by the load obtained from the conservative 2-D model with a coefficient of friction of 0.8. A similar trend was observed in the NRC-requested 3-D analysis in that the maximum support foot

load increased from 126 kips (ACORN 12) to 261 kips. This load is still enveloped by the load predicted by the conservative design basis analysis (ACORN 10).

- The maximum rack-to-rack and rack-to-wall impact forces obtained for 2-D and 3-D single-rack models using realistic assumptions are comparable after accounting for differences in rack size (10 x 10 vs. 10 x 11). These loads are further enveloped by the maximum design basis analysis loads used for qualification of the racks.

4.3 SUMMARY

A key decision in predicting the seismic response of the high density racks involves selecting a conservative model and input data sets which will produce conservative design loads in lieu of developing a very complex model with more realistic input data sets. The modeling of the groups of racks to simulate nonlinear behavior is an extremely complex and time-consuming task. As a practical solution, a 3-D single rack model was selected for the design basis analysis. Such a model, however, required that the motion of the adjacent racks be predefined. Accordingly, conservative (out-of-phase) motions of the adjacent rack were assumed, and this assumption was utilized in conjunction with several conservatisms in other aspects of the model. In particular, increasing the stiffness of the impact springs and underestimating the value of the fluid coupling effects contributed to obtaining conservative results.

In addition, a number of cases were evaluated to study the effects of the differing rack sizes, variations of friction coefficients, variations in fuel loading, and location of the racks in the pool. The maximum values of loads obtained from these sets of analyses were used for design and qualification of racks.

The recent 2-D parametric studies confirm the validity of the above methodology in the context of planar motions. PGandE initially conducted planar motion studies of racks where a single rack was simulated by two degrees-of-freedom (DOF) containing one rattling mass. It was found that a single-rack, 2 DOF model produced conservative results when compared with those obtained by a multi-rack model with a more realistic set of parameters (Reference 6).

The same conclusion was reached when the dynamic analysis was extended to a 4 DOF model (per rack) incorporating variations in friction coefficients, fabrication and installation tolerances, and layout and loading of the racks (Reference 2).

The NRC-requested 3-D study reported herein shows that the design basis loads used for qualification of the racks envelop the loads from the revised analyses. Furthermore, it has also been demonstrated that PGandE's design of the rack hardware is conservative in that large design margins exist for both gross section and local stresses.

Finally, it should be noted that several aspects of conservatism in the design basis model (such as ignoring nonlinear coupling) were retained in all of the studies performed. Considering these aspects would show that design margins are even higher.

5. CONCLUSIONS

The NRC-requested 3-D studies further demonstrate that the design basis analysis predicted conservative rack qualification loads. In responding to NRC Staff requests for additional information on rack behavior, PGandE has performed numerous parametric studies, including 2-D multi-rack analyses, using a spectrum of modeling assumptions. The results of these studies confirm in all cases that rack impact loads and stresses due to the Hosgri earthquake are significantly below allowable values. Therefore, PGandE concludes, with a high degree of confidence, that the design basis evaluation was conservative and the high density spent fuel racks will maintain their integrity for the postulated Hosgri event.

6. REFERENCES

1. "Reracking of Spent Fuel Pools, Diablo Canyon Units 1 and 2," Enclosure to PGandE Letter No. DCL-85-306, dated September 19, 1985.

2. "Additional Information on Rack-to-Rack Interactions," Enclosure 1 to PGandE Letter No. DCL-87-070, dated April 7, 1987.

3. NRC Staff letter to PGandE, dated April 1, 1987, Re: Spent Fuel Rack Analysis - Request for Additional Information.

4. Seismic Analysis Report, "Seismic Analysis of High Density Fuel Racks for Pacific Gas and Electric for Diablo Canyon Nuclear Power Station," Rev. 3, September 3, 1986, A. Soler, TM #779.

5. Technical Evaluation Report, "Evaluation of Spent Fuel Racks Structural Analysis; Pacific Gas and Electric Company, Diablo Canyon Units 1 and 2," April 30, 1986, R. C. Herrick, Franklin Research Center, TER-C5506-625.

6. "Rack Interaction Studies," Enclosure to PGandE Letter No. DCL-87-022, dated February 6, 1987.