Enhanced Seismic Risk Assessment of the Diablo Canyon Power Plant

Dennis C. Bley, Harold F. Perla, Donald J. Wakefield
Pickard, Lowe and Garrick, Inc., Newport Beach, CA USA
Bruce D. Smith
Pacific Gas and Electric Company, San Francisco, CA USA

INTRODUCTION

Pacific Gas and Electric Company (PG&E) performed a seismic probabilistic risk assessment (PRA) of the Diablo Canyon Nuclear Power Plant. The PRA is part of a reevaluation of the seismic design bases for the plant that is required by a license condition specified by the U.S. Nuclear Regulatory Commission. The overall effort, entitled "The Long-Term Seismic Program" (PG&E, 1988), generated extensive new geologic and seismologic data as well as new models and evaluations that are reported in a number of papers at this conference.

The objective of the PRA is to "assess the significance of the conclusions drawn from the seismic reevaluation studies...utilizing a probabilistic risk analysis..." as stated in the license condition. In addition to the license requirement, the risk assessment provides a quantitative estimate of the seismic risk in operating the plant, and permits a comparison with other more common risks that we are subjected to in our daily lives. The quantitative risk assessment provides a basis for managing risk, allowing the evaluation of the impact changes in design and procedures.

Various unique factors in the PRA required enhancement of existing methods for integrating the hazard analysis and fragility curves into the detailed plant models for sequence quantification. Key features of this seismic risk assessment include the integration of each of the 59 seismic fragilities into the full system models along with all of the nonseismic system failure modes; the construction of seismic-specific event trees and support system state groupings; the subdividing of the seismic hazard curves into discrete ranges for treatment as separate initiating events; the use of human error rates, which are seismic-level dependent; and, finally, the thorough structural failures involving electrical panels or other key equipment.

THE PHASED APPROACH

Three phases of sequence modeling and quantification were performed. For each phase, the key seismic-initiated sequences were identified, and the efforts of the next phase in hazard analysis and fragility analysis, as well as in plant modeling enhancements, were then focused on the issues related to these sequences.

Phase A

The first phase was a limited-scope PRA with fragilities based on existing methodology and hazard analysis based on new models, but on incomplete research. The PRA included a thorough model for plant response to transients, coverage of the initiating events judged to be most significant, and preliminary judgments about system success criteria. Allowance was made for uncertainty in key assumptions.

Both seismic and nonseismic risks were strongly affected by reactor coolant pump (RCP) seal leak scenarios originating with loss of component cooling water (CCW) or AC power. These scenarios involved phenomena that were not completely understood. Other scenarios were of low impact based on judgments that were not supported by convincing documentation. These major uncertainties defined several factors requiring resolution in later phases:

- Sensitivity of RCP seals to loss of CCW and time of recovery of CCW.
- Realistic evaluation of the low-end fragility for piping and DC electric power components.
- Realistic fragility curves for relay chatter and a detailed understanding of its impact.
- Detailed understanding of room heatup and of the likelihood of equipment failure following loss of room cooling, including methods of recovery and time available.
- Detailed understanding of the likelihood of many operator actions, including recovery.
- Detailed understanding of the impact of events not analyzed in Phase A.

The sources of uncertainty listed above led to possible variation in results of about a factor of 10. In addition, analysis of the Phase A results identified unique sensitivity to both the seismic hazard and the fragility analyses. The high frequency, low probability members of the hazard curve family were most significant--especially the top 20% in the range of 1.75 to 2.75g spectral. In future phases, it would be important to focus on better understanding of the potential physical phenomena contributing to those curves and their likelihood. Also, by adding fine structure to those curves, the contributions of important phenomena could be better identified.

The seismic results were dominated by one structural failure (the turbine building) and many equipment failures all in the low ends of the fragility curves; i.e., many conditionally independent seismic failures, each with less than a 10% chance of failure (most were 1 to 2%), were involved in the seismic damage sequences. This condition was new to PRA. In the past, failure fractions in the 30% to 50% region of the curves were most important, and the fragility analysis had therefore concentrated on accuracy in the central regions, not the low-end tails. Thus, in later phases, fragility analysts must change their focus.

Phase A had served its purpose. It gave a preliminary indication of the risk under wide uncertainty bounds, and identified key issues for emphasis in later work.

Phase B

The second phase expanded the PRA to include all initiators as well as improvements in several of the key areas identified in Phase A. It involved:

- Much more thorough low-end fragility curve evaluation, especially for potentially high contributors such as piping, DC electric power components, and turbine building structure.
- Thorough fragility treatment of structural failures involving electric panels.
- Complete relay chatter analysis with broad generic fragilities.
- Incorporation of detailed room heatup analyses.
- Development of a seismic frontline event tree--a modification of the transient event tree to account for earthquake-induced dependent failures and specially required human actions.
- Complete integration of seismically-induced failures into the full systems model with all nonseismic failures; construction of seismic support system state groupings.
- Detailed human actions analysis for more than 70 scenarios; development of seismic-level dependent human error rates.
- Increased fine structure in the highest seismic hazard curves.
- Discretization of the seismic hazard curves into six seismic initiator groups based on acceleration ranges of special interest and significance.

The results of Phase B yielded one surprise: one failure mode not analyzed in detail in Phase A was found to be significant; i.e., failure of the diesel generator fuel oil transfer system. That mode significantly increased the chance of loss of all AC power given seismic or nonseismic loss of offsite power.

Six issues were identified (most were anticipated) that required resolution in Phase C to reduce uncertainty or to reduce the already low level of risk. These issues are shown in Table 1 along with the resolution that came out of Phase C.

Phase C

During the final phase, various approaches for dealing with the six issues raised in Phase B were considered: improved analyses (thermal-hydraulic, reliability, nonlinear structural, etc.), hardware modifications, and procedural modifications. Generally, the most cost-effective approach was chosen (Table 1). Several minor modifications were implemented:

- **Diesel Generator Fuel Oil Transfer System.** Constant recirculation paths have been designed to eliminate multiple pump starts. Connections for a backup portable fuel oil pump will be added.
- **Charging Pump Backup Cooling.** Hose connections will be added to allow use of the fire water system for emergency cooling in the event of a total loss of CCW.
- **Substation Spare Parts.** Dedicated spare parts will be stored at the 230-kV substation to allow rapid recovery of offsite power in the event of a substation failure.

RESULTS

The plant event sequence model was quantified for all initiating event groups accounting for all identified sources of uncertainty in the model and the data. The results summarized on Figure 1 show the probability distributions for core damage frequency.

Several important conclusions are evident. The risk of core damage is driven by the internal initiating events. Seismic events contribute contribute about 18% on a mean basis. The uncertainty in seismic risk is quite broad (95th percentile/5th percentile = 100) compared with the overall frequency of the core damage (95th percentile/5th percentile = 5).

The best estimate core damage frequency is the median value of 1.5×10^{-4} event per year; that is, approximately one damaged core every 7,000 years. The mean core damage frequency due to seismic initiators, including nonseismic equipment failures, operator failures, and maintenance unavailability as well as seismic failures, was found to be 3.7×10^{-5} per year. This seismic component is a small contributor to the total mean core damage frequency of 2.0×10^{-4} per year.

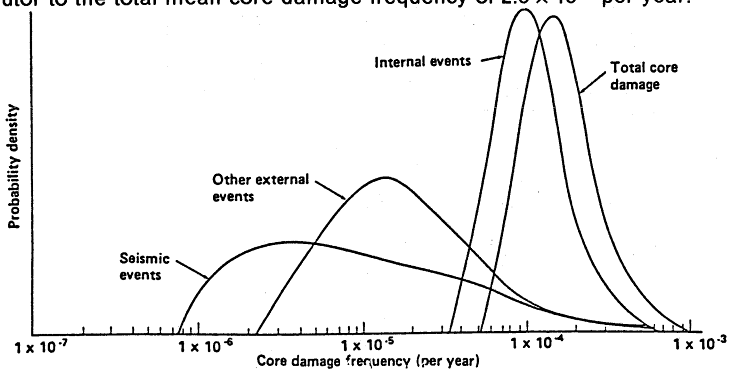

Figure 1. Results of the Diablo Canyon Probabilistic Risk Assessment

We can approach the contributors to seismic core damage frequency from three directions. The first is to identify the contribution of each earthquake (spectral acceleration category). This viewpoint is of primary interest to geologists and structural engineers. The second develops a scenario-by-scenario ranking. From this direction, the focus is on functional failures, an operational approach, and perhaps the best viewpoint for understanding risk and how to control it. The third approach, more traditional to systems and structural analysts, focuses on contributions from specific component failures due to the earthquake.

The complete PRA model was quantified for six discrete ranges of spectral acceleration between 0.25g and 4.00g. The most significant contribution, 55% of the core damage frequency, comes from accelerations spanning 2.0 to 3.0 g spectral. Only 14% comes from the highest range because there is little chance of earthquakes this large. There is a contribution of 31% coming from earthquakes of less than 2.0 g spectral. It is important to realize that these earthquake levels are substantially below the high confidence low probability of failure (see Budwitz, 1985) values for most of the affected equipment, and this contribution to core damage might be eliminated if we had better knowledge of the chance of equipment failure at very low accelerations.

Table 1. Key Issues Affecting Risk at Diablo Canyon — Phase B Results

Issue	Significance	Discussion	Phase C Action
1. RCP Seal LOCA	Most significant core damage scenarios involve seal LOCAs.	A thorough analysis of seal LOCA progression on loss of seal cooling could determine leak rates over time for various scenarios.	The analysis was performed for the important scenarios. The resulting time windows were used in the recovery analyses.
2. Charging Pump Dependence on CCW	Many seal LOCA scenarios originate with failure of CCW followed by charging pump failure due to loss of CCW. Loss of both CCW cooling and seal injection leads to seal failure.	If charging pumps could operate without CCW, many seal LOCA scenarios would be eliminated.	Design calculations indicated charging pump failure would follow loss of CCW--probably within 15 to 30 minutes. However, the addition of hose connections to allow the use of fire water to cool the charging pumps on loss of CCW was feasible. A human actions analysis of this process was incorporated.
3. Fuel Oil Transfer System	The existing design incurs many starts of the fuel oil transfer pumps when the diesel generators are loaded. The resulting high unavailability leads to loss of all AC and therefore to RCP seal LOCA and core damage.	If the unavailability of the fuel oil transfer system could be improved, the frequency of loss of all AC would decrease. Note that resolution of Issue 1 could reduce the impact of this issue.	Analysis improvements were considered, including a data search for failure rates of similar pumps in multistart environments. However, a plant modification to reduce pump starts by providing continuous recirculation and the addition of connections for use of backup pump appeared to be more cost effective. System unavailability was reanalyzed under the new configuration.
4. Relay Chatter	Relay chatter scenarios lead to core damage primarily by causing loss of all AC that requires recovery outside the control room and by changing MOV position, possibly causing failure of the associated pumps.	If human recovery of relay chatter could be improved, if more realistic relay-specific chatter fragilities could be developed, or if circuit modifications could reduce chatter impact, a substantial improvement in uncertainty of core damage would result.	The control circuits of several relays affecting MOVs will be modified to seal-in the normal valve position under chatter. Data were uncovered to permit development of specific fragility curves for several key plant relays.
5. AC Power Recovery Following Earthquake	Many earthquake scenarios lead to a loss of all AC power through loss of offsite power (switchyard failures) and loss of diesel generators. Such scenarios lead to seal LOCA and core damage.	Recovery of AC power eliminates many scenarios leading to core damage. Note that many of these scenarios are common to issues 1 and 3. Resolving one issue reduces the impact of solving the others.	Improvements in the fragility calculations for loss of offsite power were investigated. Development of different fragilities for 230-kV and 500-kV was significant. Provision of dedicated spare parts at the 230-kV substation will improve recovery time. A detailed evaluation of the required human actions to implement recovery was performed.
6. Revised Seismic Analysis	Incorporation of LTSP research into the hazard and fragility analyses will change the seismic PRA results.	The LTSP results will make the PRA more plant-specific and improve confidence in the results. Because the thrust of the LTSP was set, no complete uncertainty analysis of the seismic PRA had been pursued before Phase C.	Among other effects, all fragilities changed due to incorporation of LTSP geotechnical and soil structure interaction results. Nonlinear time history analysis established the turbine building fragility. A more careful uncertainty analysis of the low end fragility curve fails and more careful accounting for dependencies was incorporated.

From the viewpoint of scenarios, seismically-induced loss of station electrical power scenarios are in the forefront of the seismic contributors. Furthermore, many of these scenarios involve failure of the turbine building. Note that, although the seismic capacity of offsite power is less than that of the turbine hall or other components, for many of these scenarios (occurring at accelerations as high as 2.25 g), offsite power has not failed. In other words, the uncertainty in the fragility has a strong impact on the results. Finally, although further recovery is possible for some of the scenarios, the only recourse is to recover offsite power. Substantial time will be required for this activity, enough so that the chance of timely recovery is not especially high; that is, very little conservatism is introduced by our failure to model that recovery.

The final look at the seismic risk contributors is in terms of the significance of individual components. First, in Table 2, we present the fragilities of key components in rank order, with the weakest first. However, this ordering is not directly correlated to risk, the impact of some failures is more direct than others. As a closer approximation of importance, Table 3 looks at key groups of equipment that have direct impact on core damage. For each group, the table gives the mean frequency of failure found by convolving the seismic hazard curve with the equipment fragility curves. Consistent with the scenario results, the most likely failures of key equipment groups involve vital electric power.

Table 2. Mean Frequency of Component Seismic Failures

Component	Frequency (per year)	Comment on Failure Impact
500-kV Offsite Power Grid	3.34×10^{-3}	Plant automatically switches to 230-kV grid.
230-kV Offsite Power Grid	5.87×10^{-4}	Challenges onsite emergency power.
Chatter of 4-kV Switchgear	5.86×10^{-5}	Interrupts 4.16-kV vital AC, recoverable.
Turbine Building (TB) Shear Wall	1.10×10^{-5}	Assumed failure of all AC, unrecoverable.
4.16-kV Safeguard Relay Panel if TB Strut Fails	1.01×10^{-5}	Strut has greater capacity; impact is failure of vital AC transfer to 230-kV grid.
Potential Transformer for Bus HF if TB Strut Fails	9.24×10^{-6}	Strut has greater capacity; impact is failure of vital 4.16-kV bus HF.
Diesel Generator Control Panel	5.22×10^{-6}	If offsite power fails, all five onsite diesel generators assumed failed.
Pressurizer PORV	3.20×10^{-6}	Assumed that valves stick open; isolable by closing block valves.
125V DC SWGR Panels	2.58×10^{-6}	Fails all three trains of 125V DC.
HHVAC Ducting and Supports	2.55×10^{-6}	Fails 480V switchgear and control room ventilation open doors to recover.
4-kV/480V Transformers	2.19×10^{-6}	Conservatively modeled as unrecoverable failure of all 4-kV vital AC.
DG Excitation Cubicle	1.50×10^{-6}	If offsite power fails, all five onsite diesel generators assumed failed.
CCW Heat Exchangers	1.43×10^{-6}	Failure leads to draining CCW system; fire water system provides backup cooling for RCP seal injection.
Steam Generator	1.35×10^{-6}	Failure assumed to result in excessive LOCA.
Turbine Building Strut	1.26×10^{-6}	Lowers seismic capacity of safeguard panel, potential transformer, and 4-kV SWGR.
Impulse Lines	1.21×10^{-6}	Unisolable small LOCA.
Auxiliary Building	1.00×10^{-6}	Assumed to fail all building contents; modeled as failure of all 125V DC.

Table 3. Groups of Seismic Failures Contributing to Core Damage	
Sequences Evaluated	**Failure Frequency (per year)**
Total Seismic Core Damage	3.7×10^{-5}
All 4.16-kV Vital AC Switchgear Fail	1.7×10^{-5}
Loss of Offsite Power	1.2×10^{-5}
Excessive LOCAs	7.8×10^{-6}
All Vital 125V DC Fails	5.6×10^{-6}
All 120V Vital Instrumentation Fails	1.4×10^{-6}
Relay Chatter with Failure To Recover	1.2×10^{-6}
Control Room Boards and Hot Shutdown Panel Fail	9.7×10^{-7}

The majority of seismic risk is due to a very small group of components. Of these, the turbine building is the largest contributor; however, even this building contributes very little to the total risk. Except for offsite power, the equipment has minor impact on seismic risk. Offsite power is potentially a large contributor, but only when coupled with other component failures. Furthermore, the loss of offsite power is mitigated by the ability to take timely recovery actions.

Overall, the seismic risk assessment shows that the Diablo Canyon design is well-balanced, with no outstanding weak links. The components and structures are strong, and the seismic risk is low.

CONCLUSIONS

The nature of the seismic conditions at Diablo Canyon has led to substantial improvements in modeling fragility of structures and components. While many of these results will be applicable in regions of lower seismic hazard, some results (refinements in modeling for low-end fragility curves of components) may not be significant for plants in those regions.

Improvements in methods for integrating hazard analysis and fragility curves into the full plant models are generally applicable and will lead to a more consistent treatment of seismic and nonseismic events.

Most significantly, the phased approach to seismic PRA permitted us to focus the fragility, hazard, and plant analyses on the most risk-significant scenarios: scenarios where the frequency of hazard was highest or potentially highest because our state of knowledge was weak; i.e., it had broad uncertainty. We believe that the overall quality of the study, confidence in its results, and cost control were significantly improved by following the phased analysis approach.

REFERENCES

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