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Probability of Pipe Failure in the Reactor Coolant Loops of Westinghouse PWR Plants

Volume 4: Pipe Failure Induced by Crack Growth in West Coast Plants

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Prepared for
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The NUREG/CR-3660 report series, "Probability of Pipe Failure in the Reactor Coolant Loops of Westinghouse PWR plants," contains four volumes:

Volume 1: Summary Report
Volume 2: Pipe Failure Induced by Crack Growth
Volume 3: Guillotine Break Indirectly Induced by Earthquakes
Volume 4: Pipe Failure Induced by Crack Growth, West Coast Plants

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ABSTRACT

The U.S. Nuclear Regulatory Commission contracted with the Lawrence Livermore National Laboratory to conduct a study to determine if the probability of occurrence of a double-ended guillotine break in primary coolant piping warrants the current design requirements that safeguard against the effects of such a break. This report assesses the reactor-coolant-loop piping system of west coast Westinghouse plants. The results indicate that directly induced DEGB is an unlikely event in the west coast Westinghouse plants. For the Trojan plant, leak is far more likely than a direct DEGB. Further, earthquakes have very little effect on the probabilities of leak and direct DEGB. At the Diablo Canyon plant, the increase in postulated seismic levels due to reevaluation of the site to account for the Hosgri Fault has caused directly induced DEGB failure probability to be dependent on earthquake occurrences. The resulting direct DEGB failure probability is still much lower than the indirect DEGB failure probability for Diablo Canyon.

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EXECUTIVE SUMMARY

The Nuclear Regulatory Commission (NRC) contracted with the Lawrence Livermore National Laboratory (LLNL), Livermore, California, to conduct a probabilistic assessment of the primary coolant piping of all existing nuclear power plants in the U.S. The goal was to determine if the probability of occurrence of direct and indirect double-ended guillotine breaks (DEGB) is small enough to safely eliminate the postulation of DEGB in the design requirement. Direct DEGB is defined as pipe failure caused by crack growth and instability at welded joints; indirect DEGB is defined as pipe failure due to causes other than crack growth, such as the seismically-induced failure of component supports.

Postulation of DEGB in the primary coolant loop piping has resulted in severe design loading conditions and has therefore caused difficulties and excessive costs in areas of plant design, construction, and maintenance. Furthermore, the older operating plants, which were not designed for such loading conditions, would require extensive plant retrofitting to meet the current requirements that may be unnecessary. This report documents the work related to the direct DEGB assessment done on the reactor coolant loop piping of Westinghouse plants on the west coast.

There are three Westinghouse plant sites on the **west coast**: Trojan, Diablo Canyon 1 and 2, and San Onofre 1. These plants are considered separately from the eastern Westinghouse plants since they are situated in a more seismically active region. Trojan and Diablo Canyon are evaluated here. San Onofre 1 was not covered in this report for two reasons: (1) San Onofre 1 is a Westinghouse pressurized water reactor (PWR) plant. The results of the direct DEGB assessment of Trojan and Diablo Canyon provide insight for San Onofre 1. Conclusions made about Trojan or Diablo Canyon are assumed to apply also to San Onofre; (2) Vol. 3 assessed the indirect DEGB failure probability of San Onofre 1. Based on the experience with other Westinghouse RCL piping, the direct DEGB failure probability of San Onofre 1 is expected to be considerably less than the indirect DEGB failure probability. San Onofre 2 and 3 are PWR units manufactured by Combustion Engineering and are analyzed along with other Combustion Engineering plants in Reference 2.

The procedures used to analyze Trojan and Diablo Canyon were the same as those used on the Westinghouse plants east of the Rocky Mountains as described in Vol. 2 of this report. A best-estimate analysis was performed on both plants yielding a point estimate for the failure probability. An uncertainty analysis was performed on Trojan while a seismic sensitivity study was performed on Diablo Canyon.

The results from these analyses indicate that:

(1) directly induced DEGB is an unlikely event in the west coast Westinghouse plants.

(2) The Trojan plant is similar to the eastern plants in two respects. First, earthquakes have very little effect on the probabilities of leak and direct DEGB and second, leak is far more likely than a direct DEGB.

(3) The increase in postulated seismic levels due to reevaluation of the Diablo Canyon site to account for the Hosgri Fault has caused the directly induced DEGB failure probability to be dependent on postulated earthquakes which have larger than 2.25g PGA. The resulting lifetime best-estimate DEGB failure probability of 10^{-9} is still much lower than the indirect DEGB failure probability found for Diablo Canyon in Vol. 3.

1. BACKGROUND

1.1 Purpose

The postulation of double-ended guillotine breaks (DEGB) in the reactor coolant loop (RCL) piping of nuclear power plants has resulted in severe design loading conditions that include asymmetric blowdown, pipe whip, and safe shutdown earthquake (SSE) and DEGB load combinations. These conditions increase the complexity and cost of plant design, construction, and maintenance, and can also increase the radiation exposure of maintenance personnel. Many experts believe that a DEGB is extremely unlikely and that it may do more harm than good to consider DEGB in plant design. Further, older operating plants, which were not designed for such loading conditions, would have to be retrofitted extensively to meet current requirements that may be unnecessary.

To determine if the probability of DEGB is small enough to safely eliminate its postulation in the design requirements, the Nuclear Regulatory Commission (NRC) contracted with the Lawrence Livermore National Laboratory (LLNL) to conduct a probabilistic assessment of the primary coolant-loop piping of all U.S. nuclear power plants, both pressurized water reactors (PWR) and boiling water reactors (BWR). Two causes of pipe break are considered: direct DEGB, caused by crack growth and instability at welded joints, and indirect DEGB, induced by causes other than crack growth, such as the seismically-induced failure of component supports.

This four volume report focuses exclusively on the LLNL assessment of Westinghouse PWR plants and estimates failure probability in the form of a point estimate and within uncertainty bounds. Volume 1 summarizes the study. Volume 2 addresses the probability of direct DEGB in the reactor coolant loop piping of Westinghouse plants east of the Rocky Mountains. The analysis of indirectly induced DEGB in all Westinghouse plants is reported in Volume 3. This volume, Volume 4, concludes the direct DEGB failure assessment of Westinghouse plants by covering plants located on the **west coast** .

1.2 Scope and Objectives

The objectives in this volume are (1) to present the failure probability of directly induced DEGB in Westinghouse west coast plants and (2) to compare the results with the results and conclusions of the eastern plants, found in Volume 2. Two of the three Westinghouse plant sites on the west coast, Diablo Canyon 1 and 2 (Avila Beach, California) and Trojan (Prescott, Oregon) were selected for analysis. San Onofre 1 (San Onofre, California) was not analyzed for two reasons: (1) San Onofre 1 has plant and site characteristics which are bounded by the Diablo Canyon and Trojan plants. The results of the direct DEGB assessment of Trojan and Diablo Canyon provide insight for San Onofre 1. Conclusions made about Trojan or Diablo Canyon are assumed to apply also to San Onofre 1.; (2) Vol. 3 of this report includes the indirect DEGB assessment for San Onofre 1. Based on the experience with other Westinghouse RCL piping, the direct DEGB failure probability of San Onofre 1 is expected to be considerably less than the indirect DEGB failure. Hence the direct DEGB assessment of San Onofre 1 is bounded by the Trojan and Diablo Canyon analyses as well as by the indirect DEGB assessment of San Onofre 1. San Onofre 2 and 3 were included in the evaluation of Combustion Engineering plants.[2]

2. PLANT DESCRIPTION

Diablo Canyon and Trojan are typical of the four-loop Westinghouse PWR design exhibited in Fig. 1. The piping for each of the four RCL is almost identical in layout. Figure 2 shows the location of the 16 circumferential weld joints under consideration. Table 1 lists the material and the primary dimensions of the RCL piping. Both plants use stainless steel in the RCL piping. Appendix A tabulates pipe geometry and design loadings at the 16 welds. These loadings consist of pipe internal pressure, dead weight, thermal resistant loads, and seismic loads. All information in Appendix A is shown as it was transmitted by the Westinghouse data package.[1] Because Diablo Canyon 1 and 2 have identical RCL piping and stresses, only one analysis was performed for the plant site.

Table 1. Properties of RCL piping material for west coast Westinghouse plants.

Plant	Diablo Canyon 1 & 2	Trojan
Pipe material	ASTM-A376-316	SA-351-CF8A
Pipe wall thickness type	A(1)	A(1)

(1) Pipe wall thickness type A:

	Thickness	Inside Diameter
Hot leg	2.43-2.50 in.	29 in.
Crossover leg	2.58-2.66 in.	31 in.
Cold leg	2.31-2.375 in.	27.5 in

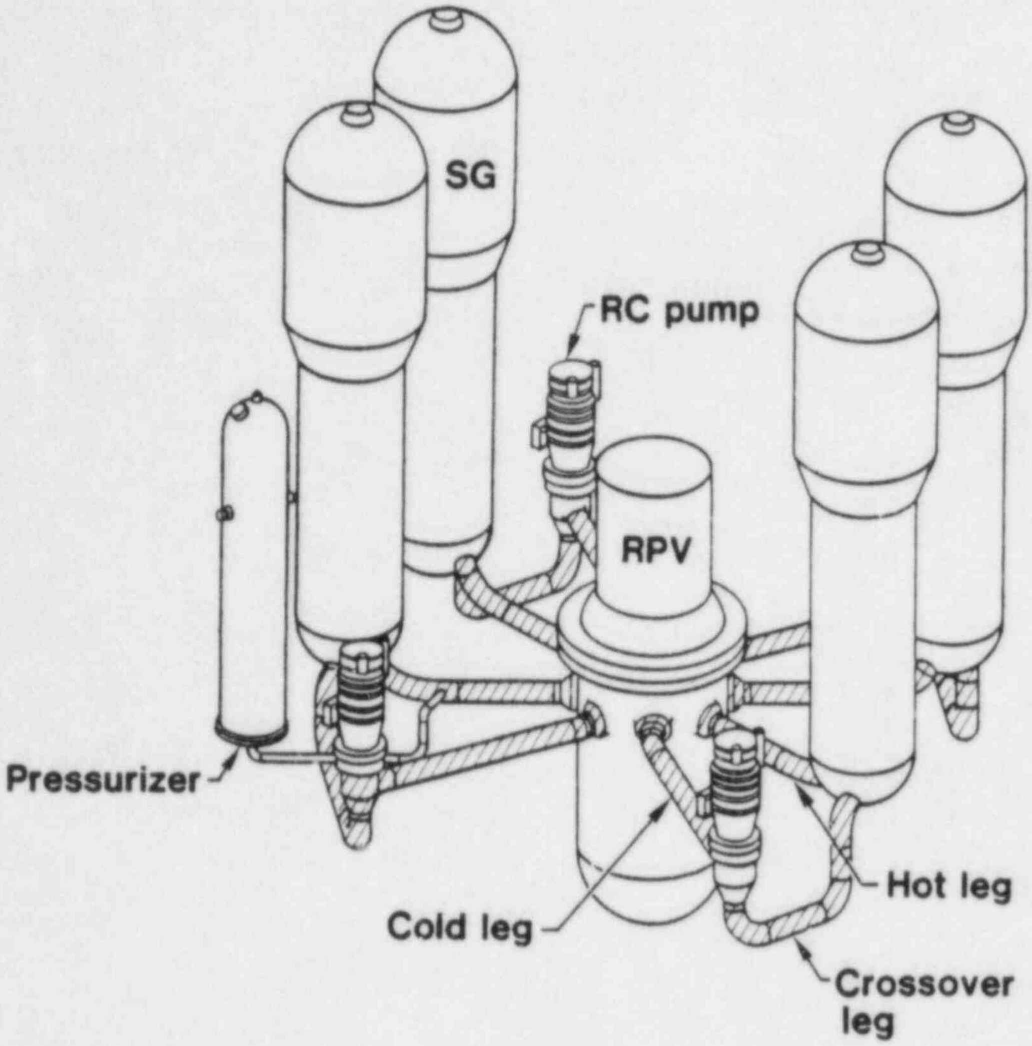

Figure 1. Typical Westinghouse four-loop nuclear steam supply system (NSSS)

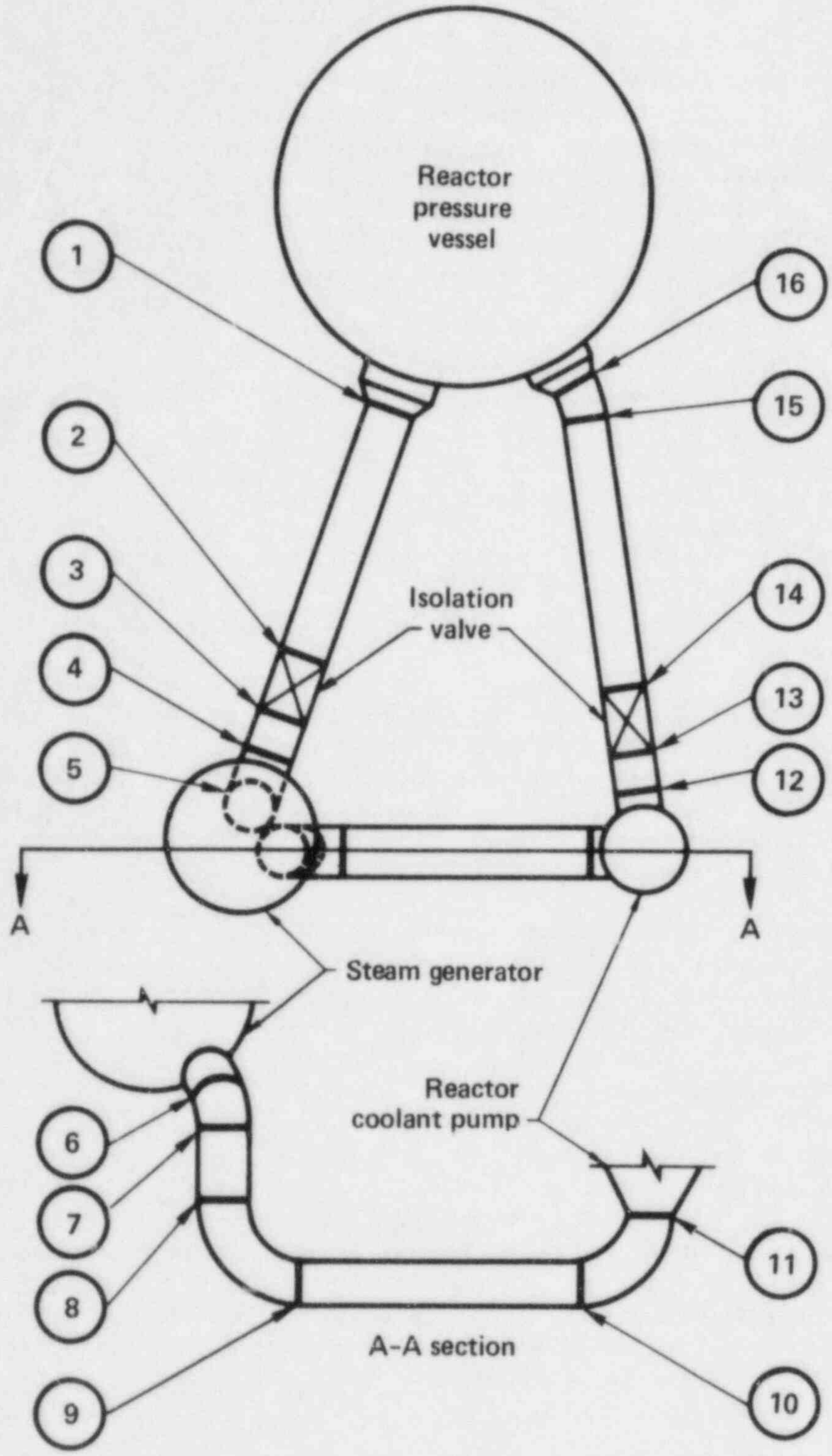

Figure 2. Locations of 16 circumferential weld joints in the reactor coolant loop (RCL) piping.

3. TROJAN

The probability of direct DEGB in the RCL piping of the Trojan plant was estimated using the same two-stage technique employed for the eastern Westinghouse plants: a best-estimate analysis and an uncertainty analysis. In the best-estimate analysis, no modeling uncertainty is considered. In the uncertainty analysis, modeling uncertainty was estimated for five parameters for which the effects of uncertainty were considered to be significant. These five parameters are crack depth, crack aspect ratio, thermal expansion stresses, seismic stresses and seismic hazard curve.

3.1 Best-Estimate Analysis

The best-estimate analysis yields a point-estimate of the failure probability for the RCL piping.

3.1.1 Methodology and Input Parameters

The methodology used in this analysis was the same as that used to analyze the eastern Westinghouse plants. A probabilistic fracture mechanics model was employed to simulate fatigue crack growth in the welds. Details of the methodology may be found in Volume 2 and will not be repeated here.

Modeling uncertainty addresses differences due to inherent random physical variation of various parameters in this analysis. For those parameters whose modeling uncertainties were considered, the best-estimate value corresponds to the median, or 50th-percentile values from their uncertainty distributions. These parameters were given the same uncertainty distribution as in the eastern Westinghouse analysis with the exception of the seismic parameters.

The necessity for studying the western Westinghouse plants separately from the eastern plants is due to the fact that they are located in a more seismically active geographical region. Thus, special attention must be paid to local plant-site conditions needed for modeling seismic parameters.

3.1.2 Seismic Parameters

Seismic loads for Trojan, supplied to LLNL in the Westinghouse data package and listed in Appendix A, are based on a safe shutdown earthquake (SSE) of 0.25g peak ground acceleration. The operating basis earthquake (OBE) level is one-half of the SSE level, in other words, 0.125g. A median response factor was derived for scaling down the seismic design stresses from the design values. Table 2 shows the estimated factors considered appropriate for Trojan RCL piping. The resulting response factor of 2.0 reflects the conservatism inherent in the original seismic design calculations. The median response factor was calculated on the basis of the approach used to estimate structural fragilities as described in Volume 3.

The Trojan plant is located very close to the Combustion Engineering (CE) WPPSS 3 plant. In light of this proximity, the seismic hazard curve developed for the WPPSS 3 site was also used for Trojan.[2] The curve, shown in Fig. 3, was based on three return periods found in Refs. 3 and 4, with an extrapolation made past a 2500-year return period.

3.1.3 Best-Estimate Results and Discussion

Failure probabilities are reported in conjunction with an earthquake occurrence. The three scenarios for pipe failure are: (1) pipe failure(1) occurs simultaneously with the first earthquake, i.e., the earthquake causes failure; (2) pipe failure occurs prior to the first earthquake; and (3) pipe failure occurs with no earthquake. The sum of these three probabilities is the total failure probability for the plant. Table 3 shows the failure probabilities for leak and DEGB in the RCL piping of the Trojan plant. The annual failure probability (per year) is listed for each of the three scenarios, as well as the annual total failure probability. Each of the scenarios are labeled Event 1, 2 or 3. The last column shows the cumulative failure probability over the entire 40-year plant life from which the annual failure probabilities are derived by simply averaging the cumulative probability over 40 years. Each value represents a point estimate of failure probability of RCL piping for the plant. The per year failure probabilities are applicable if failure occurs (at random) over the 40-year lifetime of the plant. However, this is not completely accurate since cracks grow over time, thus a failure is more likely to occur during the later years of the plant lifetime.

The contribution of Event 1 (earthquake and failure occur simultaneously) to the total failure probability is 0.01% for leak and 0.2% for DEGB. Thus, both leak and DEGB failure probabilities for the Trojan plant are dominated by Events 2 and 3. These two events represent the probability of failure of the RCL piping under normal operating loads. The large contribution of these two events to the total failure probability indicates that the loads experienced during normal operation of the Trojan plant are much more likely to induce failure than those loads experienced during earthquakes. This result is consistent with our findings for plants east of the Rocky Mountains.

The best-estimate lifetime failure probability found in the last column of Table 3 shows that leak has approximately a 10^{-6} lifetime probability of occurrence while DEGB has approximately 10^{-11} lifetime probability of occurrence. These values for Trojan are on the same order of magnitude as the Westinghouse plants located east of the Rocky Mountains.

3.2 Uncertainty Analysis

The uncertainty analysis yields a range of values or a distribution for leak and DEGB probabilities which considers the whole range of modeling uncertainty. This analysis determines uncertainty bounds on the leak and DEGB probabilities.

3.2.1 Uncertainty Analysis Input Parameters

Five parameters were considered in the uncertainty analysis: initial crack depth, initial crack length, thermal expansion stresses, seismic response factor, and seismic hazard. The parameter distributions for initial crack depth, initial crack aspect ratio, and thermal expansion stresses were identical to those used in the uncertainty analysis described in Volume 2. The seismic load factor described in Section 3.1.2 of this volume had a median value of 2.0 and a coefficient of variation of 0.40. The seismic hazard

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(1) The word failure is a generic term used to denote either "leak or DEGB".

curve, developed previously for WPPSS 3, had curves describing the 10th and 90th percentile bounds in addition to the median curve, thus providing a distribution for this parameter. As before, we took 20 samples of these modeling uncertainty parameters. The Latin hypercube sampling technique was used to generate values for the parameters in each sample.

3.2.2 Uncertainty Analysis Results and Discussion

Table 4 presents the annual and lifetime cumulative leak probabilities for each of the 20 uncertainty samples taken for the Trojan plant. Figure 4 plots the empirical cumulative distribution derived from the Trojan leak uncertainty analysis. The lifetime probabilities of cumulative leak range from 10^{-5} to 10^{-7}, the same as the range found in the uncertainty analysis of the worst-case eastern plant. This range is fairly small and demonstrates the insensitivity of leak probability to modeling uncertainties. A lognormal curve fit of the data is also presented in Figure 4.

Table 5 lists the annual and lifetime cumulative DEGB probabilities for each of the 20 samples. Figure 5 shows the empirical cumulative DEGB probability distribution for the samples. The range of the cumulative DEGB probability, 10^{-9} to 10^{-21}, is very large and is consistent with the findings of Volume 2, namely that the modeling parameters significantly affect the estimated probability of direct DEGB, especially in the lower end of the distribution. In this case, a lognormal curve does not fit the data well.

Table 6 tabulates the 10th-, 50th-, and 90th-percentile values for the leak and DEGB empirical cumulative distributions. From these findings, we conclude that:

(1) We are 90% confident that the RCL piping in the Trojan plant has a leak probability less than 1.5×10^{-7} events per plant-year.

(2) We are 90% confident that the RCL piping in the Trojan plant has a probability of direct DEGB less than 1.0×10^{-9} events per plant-year.

(3) The median probability of leak is about four orders of magnitude morethan that of DEGB, implying that "leak before break" is a valid concept for RCL piping.

(4) The probability of earthquake-induced failure is typically two orders of magnitude less than the total failure probability, implying that earthquakes contribute negligibly to pipe failure.

Table 2. Estimated factors used to calculate Trojan seismic median response factors.[1]

		Trojan	
		Factor	β_u
Structure:	F_{SA}	1.0	0.15
	F_D	1.0	0.1
	F_M	1.0	0.1
	F_{SSI}	1.0	0.1
	F_{RS}	1.0	0.23
Equipment:	F_{SA}	1.0	0.15
	F_D	2.0	0.2
	F_M	1.0	0.1
	F_{MC}	1.0	0.0
	F_{EC}	1.0	0.15
	F_{RE}	2.0	0.31

$F_T = 2.0 \times 1.0 = 2.0$

$\beta_{T,u} = (0.23^2 + 0.31^2)^{1/2} = 0.39$

where:

$$F_{RS} = F_{SA} \cdot F_D \cdot F_M \cdot F_{SSI}$$

$$F_{RE} = F_D \cdot F_M \cdot F_{MC} \cdot F_{EC}$$

F_{RS} = structural response factor

F_{SA} = spectral shape factor

F_D = damping factor

F_M = modeling uncertainty factor

F_{SSI} = soil-structure interaction factor

F_{RE} = equipment response factor

F_{MC} = mode combination factor

F_{EC} = earthquake component combination factor

β_u = variation due to uncertainty

(1) See Vol. 3 for calculational methodology

Table 3. Best-estimate values of leak and DEGB probability for RCL piping in Trojan plant, annual and cumulative.

	P(PF)[a], annual				(PF), 40 yrs
Failure type	Simultaneous with earthquake	Prior to 1st earthquake (Event 1)	No earthquake (Event 2)	Total annual (Event 3)	Total cumulative
Leak	7.6×10^{-12}	4.5×10^{-9}	4.8×10^{-8}	5.2×10^{-8}	2.1×10^{-6}
DEGB	3.2×10^{-15}	1.6×10^{-13}	1.3×10^{-12}	1.5×10^{-12}	6.0×10^{-11}

[a] Probability of failure due to event

Table 4. Annual and cumulative probability of leak in RCL piping of Trojan plant, uncertainty analysis.

	P(leak), annual				P(leak), 40 yrs
Sample	Simultaneous with earthquake	Prior to 1st earthquake	No earthquake	Total annual	Total cumulative
1	1.5×10^{-10}	3.5×10^{-8}	3.5×10^{-8}	7.0×10^{-8}	2.8×10^{-6}
2	5.6×10^{-11}	3.2×10^{-9}	3.3×10^{-8}	3.6×10^{-8}	1.4×10^{-6}
3	6.5×10^{-11}	6.3×10^{-9}	1.1×10^{-7}	1.1×10^{-7}	4.5×10^{-6}
4	8.7×10^{-11}	5.5×10^{-9}	3.0×10^{-7}	3.0×10^{-7}	1.2×10^{-5}
5	3.1×10^{-11}	3.4×10^{-9}	2.0×10^{-8}	2.3×10^{-8}	9.3×10^{-7}
6	6.0×10^{-10}	1.1×10^{-8}	5.6×10^{-8}	6.8×10^{-8}	2.7×10^{-6}
7	8.2×10^{-10}	7.3×10^{-8}	2.7×10^{-9}	7.6×10^{-8}	3.0×10^{-6}
8	6.1×10^{-12}	7.3×10^{-10}	1.8×10^{-8}	1.9×10^{-8}	7.4×10^{-7}
9	1.7×10^{-10}	1.8×10^{-8}	7.5×10^{-8}	9.4×10^{-8}	3.8×10^{-6}
10	6.4×10^{-11}	1.2×10^{-8}	4.6×10^{-8}	5.8×10^{-8}	2.3×10^{-6}
11	2.9×10^{-11}	3.5×10^{-9}	3.8×10^{-8}	4.2×10^{-8}	1.7×10^{-6}
12	5.3×10^{-10}	6.2×10^{-8}	1.9×10^{-7}	2.5×10^{-7}	1.0×10^{-5}
13	1.5×10^{-11}	2.6×10^{-9}	6.9×10^{-8}	7.1×10^{-8}	2.8×10^{-6}
14	7.7×10^{-12}	1.1×10^{-9}	3.1×10^{-8}	3.2×10^{-8}	1.3×10^{-6}
15	1.8×10^{-12}	2.6×10^{-10}	2.1×10^{-8}	2.2×10^{-8}	8.7×10^{-7}
16	3.2×10^{-11}	3.7×10^{-9}	2.7×10^{-8}	3.1×10^{-8}	1.2×10^{-6}
17	3.6×10^{-11}	7.7×10^{-9}	7.6×10^{-8}	8.4×10^{-8}	3.3×10^{-6}
18	1.3×10^{-10}	8.0×10^{-9}	4.3×10^{-8}	5.1×10^{-8}	2.0×10^{-6}
19	1.1×10^{-10}	7.7×10^{-9}	1.5×10^{-7}	1.6×10^{-7}	6.3×10^{-6}
20	4.3×10^{-12}	5.4×10^{-10}	2.4×10^{-8}	2.5×10^{-8}	9.9×10^{-7}

Table 5. Annual and cumulative probability of DEGB in RCL piping of Trojan plant, uncertainty analysis.

	P(DEGB), annual				P(DEGB), 40 yrs
Sample	Simultaneous with earthquake	Prior to 1st earthquake	No earthquake	Total annual	Total cumulative
1	1.1×10^{-19}	0	0	1.1×10^{-19}	4.4×10^{-18}
2	3.6×10^{-23}	0	0	3.6×10^{-23}	1.4×10^{-21}
3	1.1×10^{-16}	6.3×10^{-16}	8.6×10^{-15}	9.3×10^{-15}	3.7×10^{-13}
4	3.7×10^{-13}	1.4×10^{-12}	6.5×10^{-11}	6.6×10^{-11}	2.6×10^{-9}
5	7.6×10^{-15}	5.9×10^{-14}	2.7×10^{-13}	3.4×10^{-13}	1.4×10^{-11}
6	1.6×10^{-12}	1.2×10^{-12}	4.5×10^{-12}	7.3×10^{-12}	2.9×10^{-10}
7	6.3×10^{-12}	6.1×10^{-11}	1.5×10^{-12}	6.9×10^{-11}	2.8×10^{-9}
8	1.7×10^{-14}	1.2×10^{-13}	2.5×10^{-12}	2.6×10^{-12}	1.0×10^{-10}
9	1.2×10^{-13}	1.4×10^{-12}	4.6×10^{-12}	6.1×10^{-12}	2.4×10^{-10}
10	6.0×10^{-13}	7.6×10^{-12}	2.3×10^{-11}	3.1×10^{-11}	1.3×10^{-9}
11	2.0×10^{-17}	1.6×10^{-16}	1.6×10^{-15}	1.8×10^{-15}	7.0×10^{-14}
12	2.8×10^{-14}	1.8×10^{-13}	4.8×10^{-13}	6.9×10^{-13}	2.8×10^{-11}
13	2.2×10^{-13}	2.1×10^{-12}	5.4×10^{-11}	5.6×10^{-11}	2.3×10^{-9}
14	4.3×10^{-14}	3.2×10^{-13}	7.6×10^{-12}	7.9×10^{-12}	3.2×10^{-10}
15	3.1×10^{-16}	4.7×10^{-15}	3.0×10^{-13}	3.1×10^{-13}	1.2×10^{-11}
16	8.2×10^{-15}	6.3×10^{-14}	3.6×10^{-13}	4.3×10^{-13}	1.7×10^{-11}
17	1.6×10^{-12}	2.0×10^{-11}	1.6×10^{-10}	1.8×10^{-10}	7.4×10^{-9}
18	6.4×10^{-15}	1.4×10^{-14}	6.4×10^{-14}	8.5×10^{-14}	3.4×10^{-12}
19	5.1×10^{-14}	2.8×10^{-13}	4.6×10^{-12}	4.9×10^{-12}	2.0×10^{-10}
20	6.2×10^{-16}	4.4×10^{-15}	1.8×10^{-13}	1.8×10^{-13}	7.4×10^{-12}

Table 6. 10th, 50th, and 90th percentiles of empirical failure probabilities for Trojan uncertainty analysis, per plant year.

Failure type	Percentile 10th	50th	90th
P(leak)	2.0×10^{-8}	5.9×10^{-8}	1.5×10^{-7}
P(DEGB)	2.6×10^{-17}	2.2×10^{-13}	1.0×10^{-9}

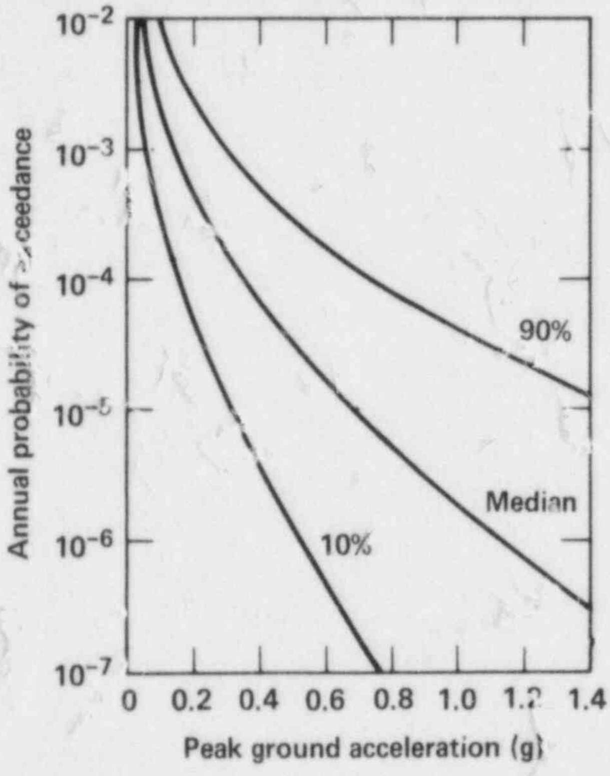

Figure 3. Site-specific seismic hazard curves for WPPSS3, used in the Trojan assessment.

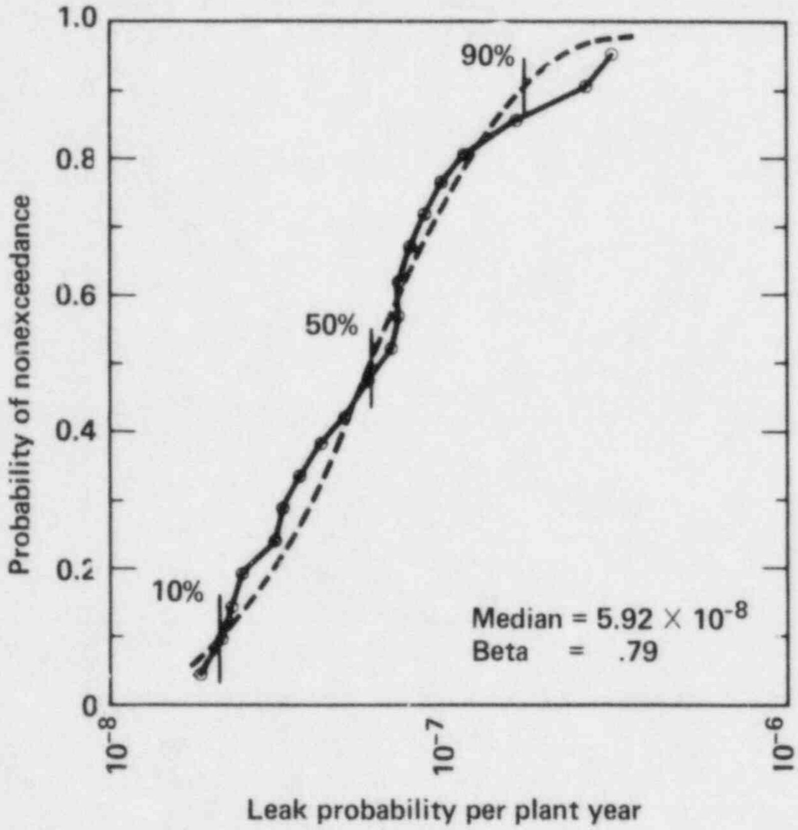

Figure 4. Empirical cumulative leak probability distribution for Trojan.

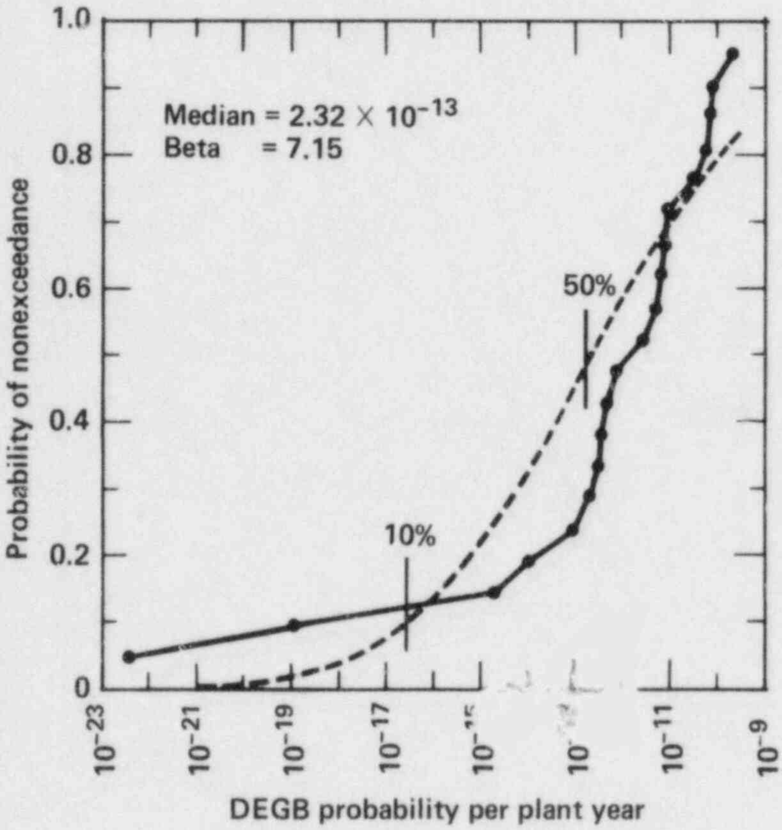

Figure 5. Empirical cumulative DEGB probability distribution for Trojan.

4. DIABLO CANYON

The close proximity of the Diablo Canyon plant to the potentially active Hosgri fault necessitated an analysis which considered large effects of seismic parameters. As we had done for other Westinghouse plants, a two-stage evaluation was performed beginning with the best-estimate analysis. Instead of an uncertainty analysis, however, an extensive sensitivity study was performed to determine the effects that varying the seismic parameters had on the probabilities of leak and DEGB.

4.1 Best-Estimate Analysis

4.1.1 Input Parameters

The best-estimate analysis was performed using the median of the uncertainty distributions for those parameters with modeling uncertainty. As for Trojan, the three parameters unrelated to seismic events were assigned the same values that were used in the eastern plants. These parameters are initial crack depth, initial crack aspect ratio and thermal expansion stress design ratio.

The seismic design loads for Diablo Canyon originally supplied by Westinghouse were based on the original SSE level of 0.4g. To account for the Hosgri Fault the plant has since been reevaluated on the basis of a site-specific response spectra of 0.75g peak ground acceleration (PGA) developed by Blume and Newmark, corresponding to the SSE.[5] The median response factor for the analysis had to not only consider the conservatism in the original design calculation, but account for the increase in SSE level and the difference in spectral shapes as well. The portion of the seismic response factor that accounts for the conservatism in the original seismic design was calculated in the same manner as that for Trojan and is described in Table 7. The seismic stresses at the welds were scaled in two steps: (1) the original design spectra was increased linearly to correspond to a PGA of 0.75g, and (2) the difference in the shapes of the scaled original response spectra and the Blume and Newmark response spectra was found in the range of frequencies seen by the RCL. The scaling factor for the seismic stresses based on this procedure was conservatively estimated to be 1.55.

We modeled earthquake occurrence by statistically combining seismic hazard curves presented by Cornell[6] which reflected the results of independent seismic hazard evaluations performed for the site by Blume,[7] Trifunac and Anderson,[8] and Ang and Newmark[9] (Fig. 6). Because none of the curves presented considered peak ground accelerations above 1.2g (about 1.5 times the 0.75g safe shutdown earthquake), we extrapolated our curve to five times the SSE assuming a quadratic relationship in log-log space between occurrence rate and PGA (Fig 7). This type of relationship has been observed in other seismic hazard curves which extend out to PGA levels significantly greater than the SSE.

4.1.2 Best-Estimate Results

Our evaluation of the Diablo Canyon nuclear power plant was unique in that earthquakes contributed significantly to the probability of direct DEGB. Table 8 shows the probabilities of leak and DEGB in the reactor coolant loop piping. The leak probability has virtually no dependence on earthquake occurrence and is of the same

magnitude as that for Trojan and the Westinghouse plants east of the Rocky Mountains, approximately 10^{-6} over plant lifetime.

Table 9 lists conditional failure probabilities for Diablo Canyon ; the failure probabilities given in Table 9 are estimated over a 40-year plant lifetime, and are conditioned upon (i.e., assume) the occurrence of an earthquake with the level indicated, the effect of earthquake occurrence rate (seismic hazard) is not included. A close examination of Table 9 shows that contrary to our past experience, a point is reached at which the simultaneous occurrence of DEGB and earthquake dominates the overall probability of DEGB. Our calculations show that this occurs when peak ground acceleration reaches a level between 0.75g and 2.25g, or between one and three times the SSE level for the Diablo Canyon site. This is indicated in Table 9 by the transition from Event 3 (no earthquake occurs) to Event 1 (DEGB and earthquake occur simultaneously) as the dominant failure event. A plot of the data in Table 9 (Fig. 8) shows that this transition occurs at about two-and-a-half times the SSE ground acceleration.

Table 9 shows that as earthquake level increases, the conditional probability of leak approaches that of DEGB. The physical implication here is that for very large earthquakes the resultant stresses in the pipe become so large that fatigue crack growth is of less importance. Instead, as the ultimate strength of the unflawed pipe is approached, pipe break occurs. The DEGB probability therefore becomes more strongly dependent on earthquakes than was the case in our other evaluations. Note, however, that even at five times the SSE, the conditional DEGB probability is still only 0.33×10^{-5} events during plant life, or less than 10^{-7} events per plant-year, assuming that an earthquake of this intensity occurs.

When interpreting these results and those of the sensitivity evaluations that follow, it is important to keep in mind that five times the SSE at Diablo Canyon is 3.75g, or 25 times the minimum SSE assumed for plants east of the Rocky Mountains. Furthermore, recall that in our evaluations stresses for earthquakes larger than the SSE are estimated by linearly extrapolating the SSE stresses. The high conditional DEGB probability given above is hardly surprising in light of the very high stresses implied by this overconservative assumption coupled with a seismic response factor one-and-a-half standard deviations off of the median value.

Table 9 also shows that the conditional probability of leak follows the same general trend, but less dramatically. An interesting result in Table 9 is that the leak and DEGB probabilities are very nearly equal for very large earthquakes. This result contrasts with earlier findings that leak probability was several orders of magnitude less than DEGB probability, and implies that "leak before break" would not apply for earthquakes significantly larger than one SSE. Such behavior would be consistent with pipe rupture, not pipe fracture, being the dominant failure mode.

4.2 Sensitivity Studies

It was recognized that the results for the best-estimate analysis of Diablo Canyon were dominated by the probability values of the seismic hazard curve at large peak ground accelerations. Since the hazard curves available for this study were not defined and highly debatable at these high levels, it did not seem appropriate to perform an

uncertainty analysis based on all five parameters for Diablo Canyon. Besides, the seismic hazard curve dominates the other four parameters, and therefore the lack of a viable description, i.e. the hazard curve, of the hazard at higher accelerations would likely render any uncertainty analysis unuseable. One possible alternative analysis would be to vary the other four parameters while maintaining one hazard curve to examine the effects of the other modeling uncertainties. The uncertainty analysis performed for Trojan and the eastern Westinghouse plants showed a range of results for leak and DEGB and, at the same time, indicated that earthquake occurrences had little effect on failure. If an uncertainty analysis were performed on four parameters for Diablo Canyon with a fixed hazard curve, the bandwidth of results would be similar since the effects due to uncertainty in the seismic hazard would be held constant and, in effect, eliminated. The range would be similar to that of previous Westinghouse analyses, where the range for the probability of leak is two orders of magnitude while the range of probability of DEGB covers approximately six to eight orders of magnitude. Since this information has already been established, the costs of running even a partial uncertainty analysis would outweigh the benefits.

An extensive series of sensitivity analyses was performed to determine the effects of the uncertainty associated with seismic parameters. The effects of both the seismic hazard curve and the seismic response factor were studied. Best-estimate values were used for the other input parameters on each of the weld joints.

4.2.1 Effect of Seismic Response Factor

The seismic response factor calculated in Table 7 represents the conservatism inherent in the plant's initial design. Since there is a modeling uncertainty associated with this parameter, the effect of varying its value at different extremes within its distribution was studied. The median value of 2.39 was used in the best-estimate analysis. For the log-normal distribution described by the estimated β_u, values of the 10th and 90th percentiles were determined. These upper and lower bounds represent values at approximately 1.3 standard deviations away from the median.

The results for this study are presented in Table 10. The conditional probabilities are shown without the effects of a seismic hazard curve. Again, conditional probability values represent the probability of failure assuming that an earthquake of the indicated level occurs. Leak probability is plotted versus earthquake level in Fig. 9. DEGB probability is plotted in Fig. 10. Varying the seismic response factor between the 10th and 90th percentile results in a difference of seven orders of magnitude for DEGB failure probability at five times the SSE. Thus, DEGB failure probability is clearly very sensitive to the value of the seismic response factor at high earthquake levels.

The highest failure probability in Table 10, $.20 \times 10^{-1}$, occurs at five times the SSE and at a 90% confidence limit. This conditional failure probability does not reach 1.0 because of the inclusion of pre-service inspection and hydrostatic proof tests. These two events eliminate potentially failing cracks from the original weld.

4.2.2 Seismic Hazard Curve Sensitivity Study

A precise description of seismic hazard for the Diablo Canyon site has been, and continues to be, a subject of great controversy, particularly for large peak ground

accelerations. The shape of the curve used in our best-estimate analysis was extrapolated to high earthquake levels based on our previous experience. For the sensitivity study, several configurations of hazard curves were employed to determine the effects of varying the curve in different ways. The median seismic response factor of 2.39 was used in each study.

4.2.2.1 Effect of Maximum Peak Ground Acceleration

Our first sensitivity study investigated the effect that maximum peak ground acceleration had on the probability of DEGB. We modified our original seismic hazard curve and estimated DEGB probability assuming that the maximum peak ground acceleration asymptotically approached one, two, three, and four times the SSE level. The curve set is shown in Fig. 11, and the corresponding DEGB probabilities are presented in Table 11 and Fig. 12. These results indicate the probability of direct DEGB decreases by about two orders of magnitude -- from 2.5×10^{-11} to 2.0×10^{-13} events per plant-year -- when the maximum ground acceleration level is reduced from five to one SSE. The leak probabilities are essentially unaffected by the maximum earthquake level.

4.2.2.2 Results for Individual Seismic Hazard Curves

Our original calculations were based on a seismic hazard curve derived from three independent -- and substantially different -- site-specific seismic hazard evaluations. Because our previous experience had shown that the simultaneous occurrence of earthquake and DEGB contributed only negligibly to the overall probability of direct DEGB, we considered this a reasonable representation of seismic hazard despite the differences. However, when the results of our best-estimate evaluation indicated the increased importance of earthquake effects, we performed another series of sensitivity calculations in which we estimated the probability of leak and direct DEGB for each of the three consultant curves individually as well as the LLNL curve. We applied each curve in two different ways as follows:

- as originally presented, that is, with peak ground acceleration limited to 1.2g (about 1.5 times the SSE). All four curves are shown in this manner in Fig. 13.

- as extrapolated by Structural Mechanics Associates (SMA) for estimating the probability of indirect DEGB. In these evaluations, each curve was extrapolated log-linearly to five times the SSE peak ground acceleration. These curves are shown in Fig. 14 along with the LLNL extrapolated curve used in the best-estimate analysis.

The median leak and DEGB probabilities estimated using these curves are given in Tables 12 and 13, respectively, and compared against those estimated using the LLNL curve. The DEGB probabilities estimated using the original (i.e., unextrapolated) curves range from 2.0×10^{-13} to 3.8×10^{-13} events per plant-year -- less than a factor of two variation -- and bound the value obtained by truncating the LLNL curve at 1.2g. The DEGB probabilities for the extrapolated curves range from 2.5×10^{-12} to 1.5×10^{-11} events per plant-year, all of which are exceeded by that obtained using the original LLNL curve (2.5×10^{-11} events per plant-year). This bounding effect reflects the higher probabilities of occurrence for large earthquakes yielded by the LLNL extrapolation scheme. In any case, the variation is no more than one order of magnitude.

4.2.3 Sensitivity Study Discussion

The best estimate analysis determined that leak probability has little dependence on the occurrence of earthquakes. The sensitivity studies performed dealt with uncertainty in two seismic modeling parameters. As such, leak probabilities were not affected in the sensitivity study.

Determining the effect of the occurrence of earthquakes on DEGB probabilities was the purpose of the sensitivity study. It was found that varying the seismic hazard curve over several possible configurations gave a range of results between 9.4×10^{-12} and 9.8×10^{-10}, covering two orders of magnitude. The best estimate total lifetime DEGB probability of 9.8×10^{-10} falls at the high end of this range. Thus, altering the seismic hazard curve to a configuration close to those curves examined in the sensitivity study could only decrease the initial best-estimate DEGB probability.

Varying the seismic response factor between the 10th and 90th percentile of its distribution results in a range of conditional DEGB probabilities covering seven orders of magnitude at an earthquake level of **5 SSE.** Conditional probabilities do not include the effects of seismic hazard. The inclusion of a seismic hazard curve would decrease the range of 10th to 90th percentile probabilities by several orders of magnitude. The resulting range of probabilities would still be large however. One reason for the large range of probabilities is the distribution of the seismic response factor. For the assumed lognormal distribution of the seismic response factor, the seismic stress at the 90th percentile on the distribution is 12.93 (or $e^{2 \times 1.28}$) times higher than that at the 10th percentile. Another reason for the seismic response factors magnified effects on DEGB probabilities is that the stresses to which the factors have been applied are conservative at higher earthquake levels. Seismic stresses for three and five times the SSE were determined by making a linear extrapolation from the SSE design stresses. The assumption of linearly increasing stresses is accurate for earthquakes of lower levels. For earthquakes of higher magnitudes, energy dissipation in the structure and the material due to inelastic behavior results in nonlinearly increasing stresses. The degree of conservatism in a linear extrapolation of stresses at higher seismic levels depends on the earthquake level. At five times the SSE (i.e., 3.75g), linearly extrapolated stresses are more conservative than at three times the SSE. The seven order-of-magnitude range at five times the SSE versus the five order-of-magnitude range at three times the SSE exemplify this conservatism.

Table 10 shows that as earthquake level increases, the conditional probability of DEGB approaches and ultimately equals leak. This is in contrast to previous findings which reinforced the "leak-before-break" behavior of RCL piping The implication here is that the ultimate strain capacity of the pipe is reached before severe cracking can occur. Thus, for very high seismic stress levels, pipe break occurs before cracking through the wall creates a leak.

The results of the maximum earthquake level sensitivity study discussed in Section 4.2.2.1 indicate a transition point at which the total DEGB failure probability becomes dependent on earthquakes instead of on normal operating transients. Figure 12 indicates that at large earthquake limits, the total DEGB failure probability is determined largely by Event 1, pipe failure simultaneous with an earthquake. At limits between one and three times the SSE, Event 1 has a decreasing effect on the total while Event 3, pipe

failure and no earthquake, begins to dominate. At or below one SSE, Event 3, resulting from operating transients, determines the total probability of failure. Inspection of Fig. 12 indicates that the transition point, where the occurrence of earthquakes begin to dominate total failure probability, occurs between two and three times the SSE. For the Diablo Canyon plant this corresponds to earthquakes with peak ground accelerations between 1.5g and 2.25g. Thus, for any PGA above 2.25g, earthquakes affect the total DEGB failure probability. For a PGA below 1.5g, the total DEGB failure probability at Diablo Canyon is similar to the other Westinghouse plants in that earthquakes have very little effect.

Is is recognized that the seismic hazard information upon which the Diablo Canyon evaluation was based is now some eight years old, and furthermore that information for earthquakes significantly larger than the SSE is as good as non-existent. In the intervening period new, relevant strong ground motion prediction information has been generated, and new information about the Hosgri fault itself has come to light. These issues will be revisited in the near future by a new study of the Diablo Canyon seismic basis performed for NRC by PG&E.

It is outside our scope to pass judgement on what constitutes the "best" description of seismic hazard for any particular site. Instead, we rely on information generated by recognized seismic experts and then assess the effect that variations in this information have on our probabilistic results. Our prior results had been negligibly affected by earthquakes. In the case of Diablo Canyon, however, seismic events were clearly a significant (and, for earthquakes much larger than the SSE, a dominant) contributor to pipe break. For this reason, we chose to perform extensive seismic sensitivity analyses rather than the usual multi-parameter uncertainty analysis. The results of these analyses indicated that the median probability of failure is relatively insensitive to the particular seismic hazard curve selected from among those used in our evaluation, despite the relatively wide variation among the individual curves and our lack of a firm basis for extrapolating these curves for very large earthquakes. We are therefore confident that our evaluation provides a reasonable representation of the relationship between direct DEGB and seismic events for the Diablo Canyon plant.

Table 7. Estimated factors used to calculqte Diablo Canyon seismic response factors.[1]

		Diablo Canyon Factor	β_u
Structure:	F_{SA}	1.0	0.15
	F_D	1.1	0.11
	F_M	1.0	0.15
	F_{SSI}	1.0	0.10
	F_{RS}	1.0	0.26
Equipment:	F_{SA}	1.30	0.10
	F_D	1.45	0.18
	F_M	1.0	0.20
	F_{MC}	1.0	0.15
	F_{EC}	1.15	0.15
	F_{RE}	2.17	0.32

Total: $F_T = 2.17 \times 1.10 = 2.39$

$\beta_{T,u} = (0.26^2 + 0.32^2)^{1/2} = 0.42$

where:

$$F_{RS} = F_{SA} \cdot F_D \cdot F_M \cdot F_{SSI}$$

$$F_{RE} = F_D \cdot F_M \cdot F_{MC} \cdot F_{EC}$$

F_{RS} = structural response factor

F_{SA} = spectral shape factor

F_D = damping factor

F_M = modeling uncertainty factor

F_{SSI} = soil-structure interaction factor

F_{RE} = equipment response factor

F_{MC} = mode combination factor

F_{EC} = earthquake component combination factor

β_u = variation due to uncertainty

(1) See Vol. 3 for calculational methodology

Table 8. Best-estimate values of leak and DEGB probability for RCL piping in Diablo Canyon plant, annual and cumulative.

	P(F), annual				P(F), 40 yrs
Failure Type	Simultaneous with earthquake (Event 1)	Prior to 1st earthquake (Event 2)	No earthquake (Event 3)	Total annual	Total cumulative
Leak	1.5×10^{-10}	1.6×10^{-9}	3.5×10^{-8}	3.8×10^{-8}	1.5×10^{-6}
DEGB	2.4×10^{-11}	1.0×10^{-14}	1.0×10^{-14}	2.4×10^{-11}	9.8×10^{-10}

Table 9. Effect of seismic PGA level on median probability of failure[1] in reactor coolant loop piping at Diablo Canyon.

Seismic PGA Level	Event[2] Event 1	Event 2	Event 3	P(PF)[3]
		DEGB		
1 x OBE (0.375g)	0.25×10^{-12}	0.59×10^{-12}	0.10×10^{-10}	0.11×10^{-10}
1 x SSE (0.75g)	0.23×10^{-11}	0.59×10^{-12}	0.10×10^{-10}	0.12×10^{-10}
3 x SSE (2.25g)	0.21×10^{-8}	0.59×10^{-12}	0.10×10^{-10}	0.21×10^{-8}
5 x SSE (3.75g)	0.33×10^{-5}	0.59×10^{-12}	0.10×10^{-10}	0.33×10^{-5}
		Leak		
1 x OBE (0.375g)	0.35×10^{-8}	0.91×10^{-7}	0.20×10^{-5}	0.20×10^{-5}
1 x SSE (0.75g)	0.84×10^{-8}	0.91×10^{-7}	0.20×10^{-5}	0.21×10^{-5}
3 x SSE (2.25g)	0.78×10^{-7}	0.91×10^{-7}	0.20×10^{-5}	0.22×10^{-5}
5 x SSE (3.75g)	0.35×10^{-5}	0.91×10^{-7}	0.20×10^{-5}	0.56×10^{-5}

(1) Conditional probability of failure (DEGB or leak) during 40-year plant life, assuming occurrence of an earthquake with the indicated peak ground acceleration. Seismic hazard is not included.

(2) Event 1: Probability of failure simultaneous with first earthquake
Event 2: Probability of failure prior to first earthquake
Event 3: Probability of failure with no earthquake

(3) P(PF): Total probability of pipe failure

Table 10. Event I lifetime failure probability of 10th, 50th and 90th percentile values of seismic response factor for Diablo Canyon.

	Confidence Limit (1)		
	10%	50%	90%
P(EQ + DEGB)			
1 x OBE	0.24×10^{-13}	0.25×10^{-12}	0.30×10^{-11}
1 x SSE	0.16×10^{-12}	0.23×10^{-11}	0.30×10^{-10}
3 x SSE	0.34×10^{-10}	0.21×10^{-8}	0.84×10^{-5}
5 x SSE	0.15×10^{-8}	0.33×10^{-5}	0.20×10^{-1}
P(EQ + Leak)			
1 x OBE	0.12×10^{-8}	0.35×10^{-8}	0.22×10^{-7}
1 x SSE	0.30×10^{-8}	0.84×10^{-8}	0.24×10^{-7}
3 x SSE	0.26×10^{-7}	0.78×10^{-7}	0.85×10^{-5}
5 x SSE	0.72×10^{-7}	0.35×10^{-5}	0.20×10^{-1}

(1) Probability that earthquake and failure occur simultaneously during 40-year plant life, assuming occurrence of an earthquake with the indicated peak ground acceleration. A confidence limit of 90% implies that there is a 90% subjective probability (confidence) that the probability of failure is less than the value indicated.

Table 11. Lifetime probability of failure using hazard curves subject to maximum earthquake level.

PGA Upper Limit	Probability of Direct DEGB(1)			
	Event(2)			
	Event 1	Event 2	Event 3	P(FP)(3)
1 x SSE (0.75g)	0.42×10^{-12}	0.41×10^{-12}	0.73×10^{-11}	0.81×10^{-11}
				(2.0×10^{-13})
2 x SSE (1.50g)	0.25×10^{-11}	0.41×10^{-12}	0.73×10^{-11}	0.11×10^{-10}
				(2.8×10^{-13})
3 x SSE (2.25g)	0.13×10^{-10}	0.41×10^{-12}	0.73×10^{-11}	0.20×10^{-10}
				(5.0×10^{-13})
4 x SSE (3.00g)	0.90×10^{-10}	0.41×10^{-12}	0.73×10^{-11}	0.98×10^{-10}
				(2.5×10^{-12})
5 x SSE (3.75g)	0.97×10^{-9}	0.41×10^{-12}	0.73×10^{-10}	0.98×10^{-9}
				(2.5×10^{-11})

(1) Probability of DEGB during 40-year plant life using modified LLNL seismic hazard curves shown in Fig. 11. Values in parentheses are annual probabilities of DEGB.

(2) Event 1: Probability of failure coincident with first earthquake
Event 2: Probability of failure prior to first earthquake
Event 3: Probability of failure with no earthquake

(3) P(PF): Total probability of pipe failure

Table 12. Median probabilities of leak in Diablo Canyon for various seismic hazard curves.[1]

Seismic Hazard Curve	PGA Limit of Seismic Hazard Curve	
	Cut-off	Extrapolated
LLNL (2)	0.15×10^{-5}	0.15×10^{-5}
	(3.8×10^{-8})	(3.8×10^{-8})
Trifunac and Anderson (3)	0.14×10^{-5}	0.14×10^{-5}
	(3.5×10^{-8})	(3.5×10^{-8})
Newmark and Ang (3)	0.15×10^{-5}	0.15×10^{-5}
	(3.5×10^{-8})	(3.5×10^{-8})
Blume (4)	0.15×10^{-5}	0.15×10^{-5}
	(3.5×10^{-8})	(3.5×10^{-8})

(1) Probability of leak during 40-year plant life using indicated seismic hazard curve. Annual leak probability in parentheses.

(2) LLNL curve developed from consultant curves presented by Cornell.[6] Extrapolation by LLNL to 3.75g (five times SSE) assumes quadratic behavior in log-log space.

(3) Original curves as presented by Cornell.[6] Extrapolation by SMA from 1.2g to 3.75g assumes linear behavior in log-normal space.

(4) Original curve presented by Cornell limited to 1.1g. Extrapolation by SMA to 1.2g and 3.75g by SMA assumes linear behavior in log-normal space.

Table 13. Median probabilities of direct DEGB in Diablo Canyon for various seismic hazard curves.(1)

Seismic Hazard Curve	PGA Limit of Seismic Hazard Curve	
	Cut-off	Extrapolated
LLNL (2)	0.94×10^{-11}	0.98×10^{-9}
	(2.4×10^{-13})	(2.5×10^{-11})
Trifunac and Anderson (3)	0.15×10^{-10}	0.60×10^{-9}
	(3.8×10^{-13})	(1.5×10^{-11})
Newmark and Ang (3)	0.86×10^{-11}	0.32×10^{-10}
	(2.2×10^{-13})	(8.0×10^{-13})
Blume (4)	0.81×10^{-11}	0.10×10^{-9}
	(2.0×10^{-13})	(2.5×10^{-12})

(1) Probability of DEGB during 40-year plant life using indicated seismic hazard curve from Figs. 13 and 14. Annual DEGB probability in parentheses.

(2) LLNL curve developed from consultant curves presented by Cornell.[6] Extrapolation by LLNL to 3.75g (five times SSE) assumes quadratic behavior in log-log space.

(3) Original curves as presented by Cornell.[6] Extrapolation by SMA from 1.2g to 3.75g assumes linear behavior in log-normal space.

(4) Original curve presented by Cornell limited to 1.0g. Extrapolation by SMA to 1.2g and 3.75g by SMA assumes linear behavior in log-normal space.

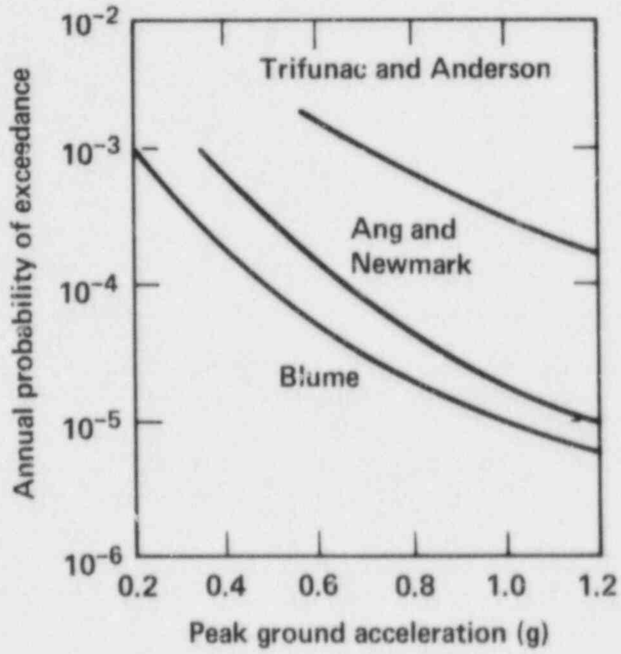

Figure 6. Seismic hazard curves for Diablo Canyon as presented by Cornell.[6]

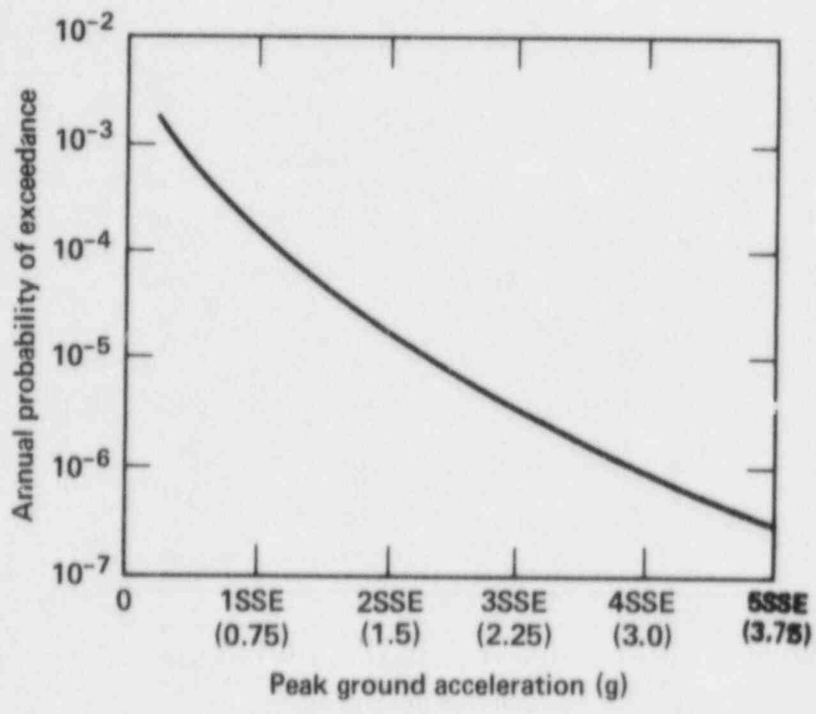

Figure 7. Seismic hazard curve used for Diablo Canyon best-estimate analysis.

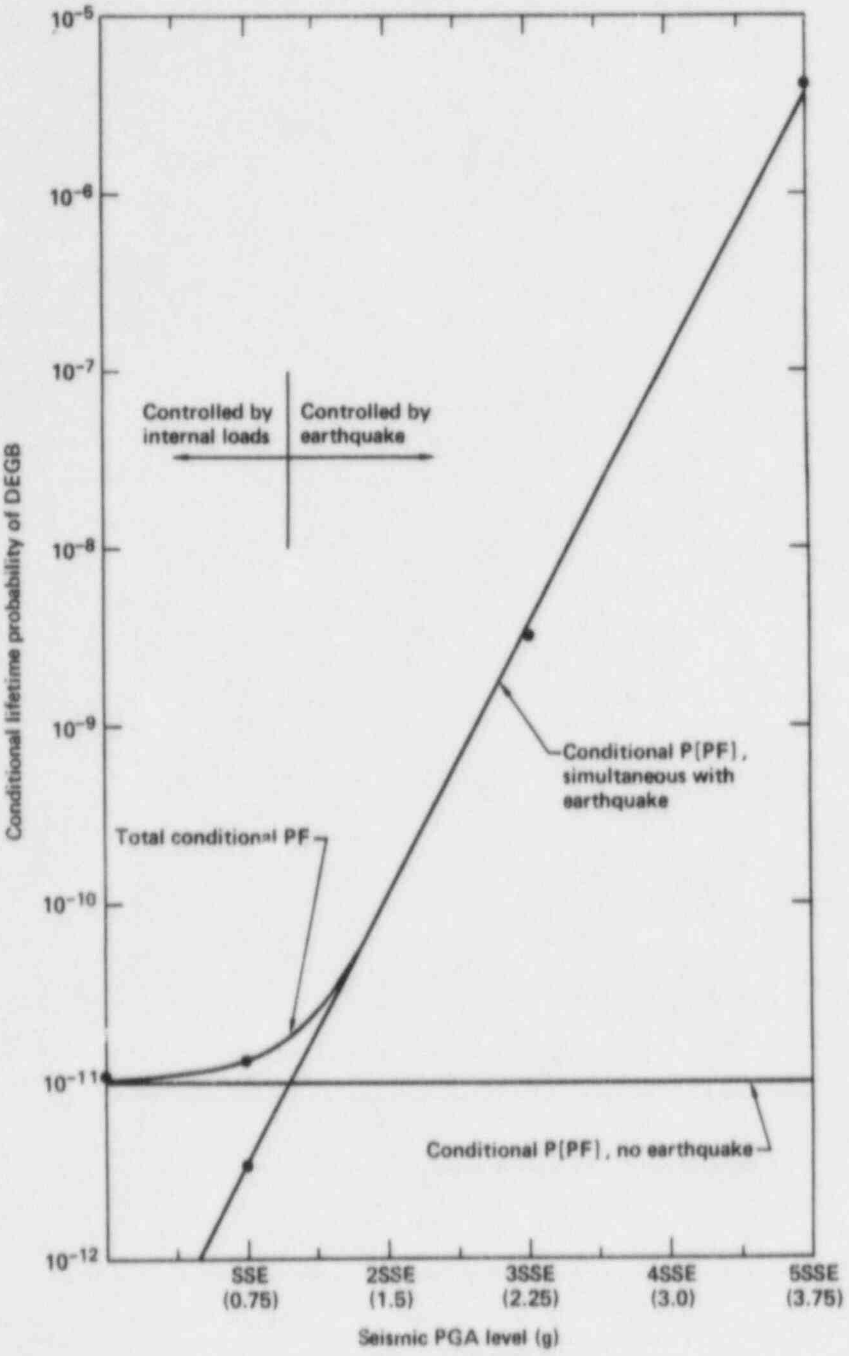

Figure 8. Comparison of conditional DEGB probabilities with and without occurrence of earthquake for Diablo Canyon reactor coolant loop piping.

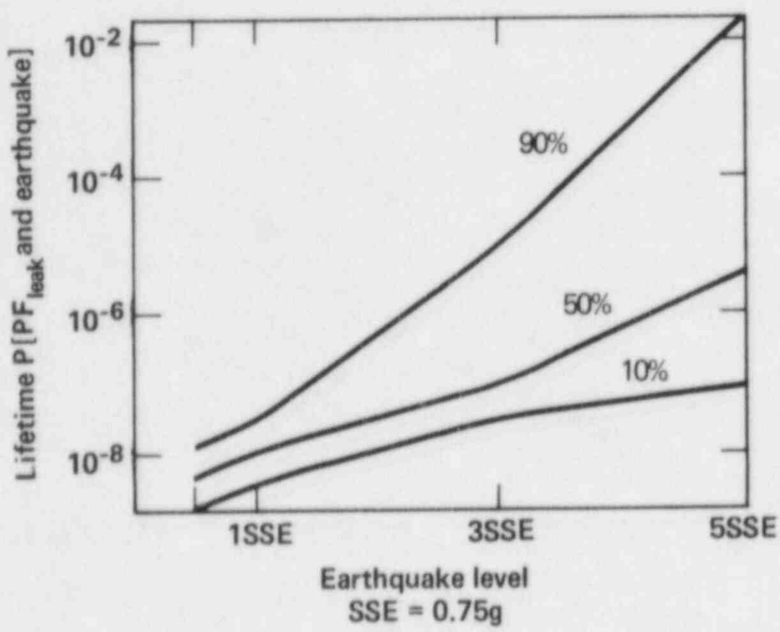

Figure 9. Conditional probability of leak in Diablo Canyon RCL piping for 10th, 50th and 90th percentile levels of seismic response factor.

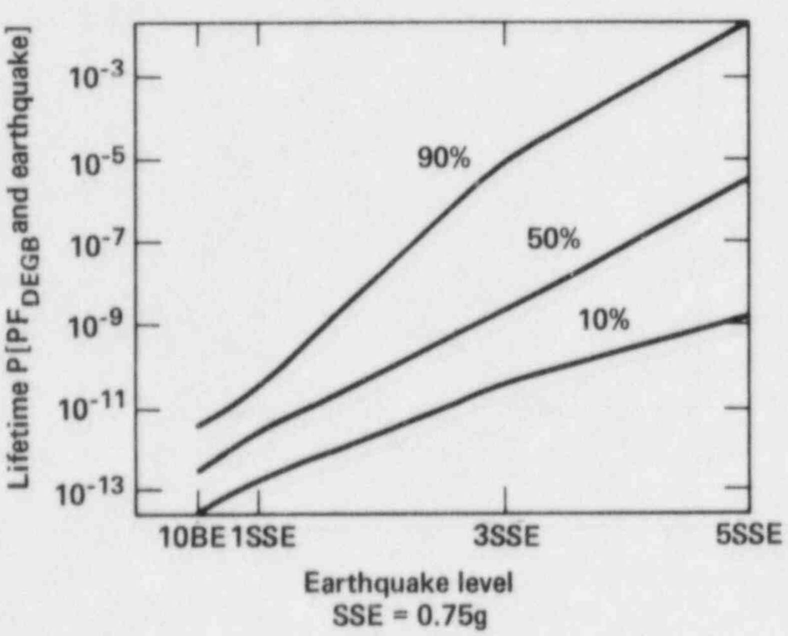

Figure 10. Conditional probability of direct DEGB in Diablo Canyon RCL piping for 10th, 50th and 90th percentile levels of seismic response factor.

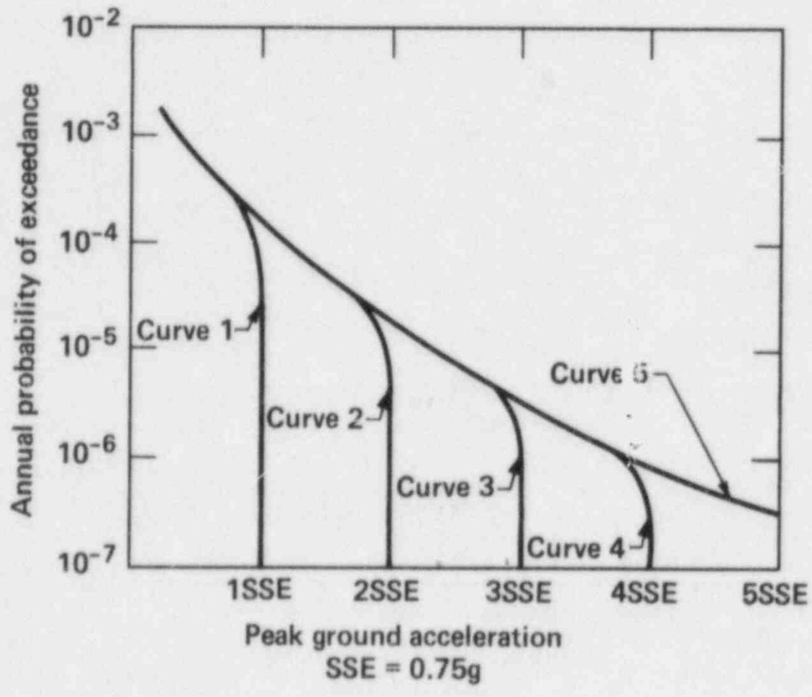

Figure 11. Modified seismic hazard curve for Diablo Canyon for investigating sensitivity of DEGB probability to maximum peak ground acceleration.

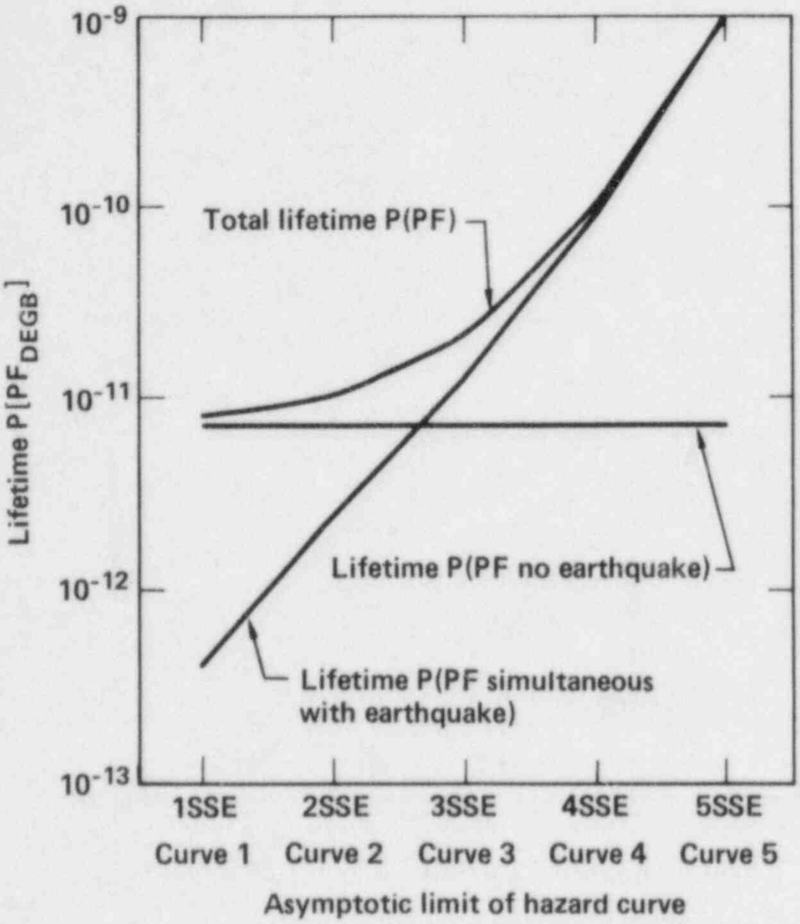

Figure 12. Lifetime failure probability as a function of maximum peak ground acceleration level of the seismic hazard curve.

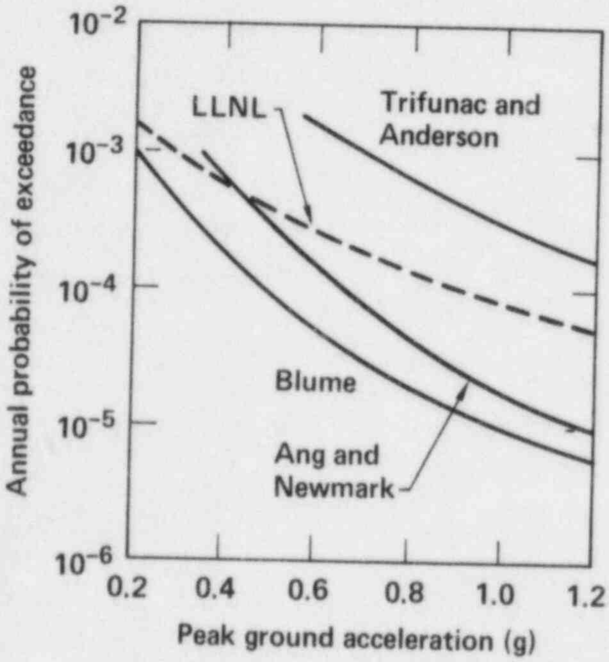

Figure 13. Original seismic hazard curves for Diablo Canyon site.

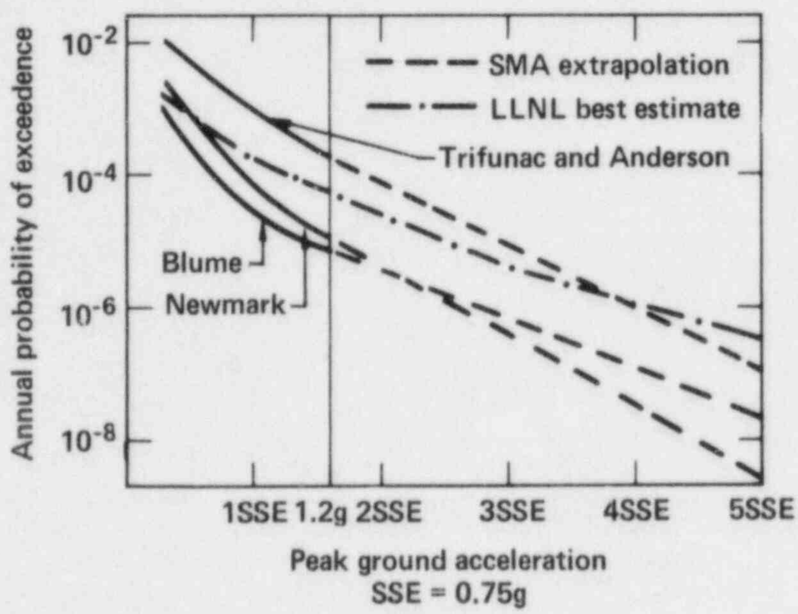

Figure 14. Extrapolated seismic hazard curves for Diablo Canyon site.

5. CONCLUSIONS

The failure probabilities for two of the **west coast** Westinghouse plants have been examined. The best-estimates for both plants fall within the same probabilistic range as the **east coast** plants. Leak probabilities were no larger than 10^{-8} per plant year, and DEGB probabilities did not exceed 10^{-11} per plant year. In both plants studied, best-estimate leak probability was not affected by earthquakes.

The results for Trojan are consistent with those for the eastern Westinghouse plants. Therefore, the conclusions drawn in Volume 2 are valid for Trojan: (1) a direct DEGB is a highly unlikely event for RCL piping, (2) earthquakes contribute negligibly to failure, and (3) the four-order-of-magnitude difference between leak and DEGB probabilities suggests that leak is far more likely to occur than break.

For Diablo Canyon, the simultaneous occurrence of earthquakes and pipe break made a non-negligible contribution to the overall probability of direct DEGB. Using seismic hazard curves that we derived from three independent seismic hazard evaluations of the plant site, we estimated the probability of direct DEGB to be 2.5×10^{-11} events per plant-year, about one order of magnitude higher than the median value for plants east of the Rocky Mountains. We found that earthquakes less than or equal to the SSE had a negligible effect on conditional failure probabilities (i.e., assuming that a specified level of earthquake occurs), but that for earthquakes above this level, the simultaneous occurrence of earthquake and DEGB dominated the conditional probability of failure. However, the extremely low probability that such large earthquakes actually occur offsets the high conditional DEGB probabilities, keeping the overall DEGB probability low.

When comparing probabilities of direct DEGB for west coast plants with those for plants east of the Rocky Mountains, it is important to keep in mind that the west coast evaluations were made using site-specific seismic hazard information while the eastern plants were evaluated using generic seismic hazard curves. The wide spread of uncertainty in the generic seismic hazard curves, combined with the assumption of a 0.15g minimum SSE, is expected to cover all sites in the eastern and midwestern United States; using the generic curves in lieu of site-specific seismic hazard information may be overly conservative for certain sites having particularly low seismicity. Therefore, the probabilities of direct DEGB for these eastern sites may actually be lower -- and the difference compared to west coast values accordingly greater -- than the median value estimated using the generic hazard curves.

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APPENDIX A. GEOMETRY AND LOADING INFORMATION FOR CIRCUMFERENTIAL WELD JOINTS IN THE RCL PIPING FOR WEST COAST WESTINGHOUSE PLANTS

The information provided here includes pipe wall thickness and inside radius, pipe internal pressure and deadweight, thermal expansion, and seismic loads at each of the weld joints for Trojan and Diablo Canyon, two of the **west coast** Westinghouse PWR plants. This information is presented in Tables A-1 through A-10.

Table A-1. Pipe wall thickness and inside radius for thickness type A.

Weld location	Wall thickness	Inside radius
1	2.45	14.5
2	2.45	14.5
3	2.45	14.5
4	2.45	14.5
5	3.375	15.5
6	3.3125	15.5
7	2.60	15.5
8	2.60	15.5
9	2.60	15.5
10	2.60	15.5
11	3.3125	15.5
12	2.32	13.75
13	2.32	13.75
14	2.32	13.75
15	2.32	13.75
16	3.03	13.75

Table A-2. Pipe internal pressure.

Weld	Pressure (psia)
1	2235
2	2235
3	2235
4	2235
5	2235
6	2198
7	2198
8	2198
9	2198
10	2198
11	2198
12	2281
13	2281
14	2281
15	2281
16	2281

Table A-3. Deadweight axial loads and bending moments at weld locations for the Trojan plant.

Weld location	Axial load (kips)	Bending moment (in.-kips)
1	9	94
2	--	--
3	--	--
4	4	94
5	8	158
6	19	126
7	15	97
8	10	64
9	2	198
10	10	169
11	12	103
12	9	240
13	--	--
14	--	--
15	9	232
16	10	399

Table A-4. Thermal expansion axial loads and bending moments at weld locations for the Trojan plant.

Weld location	Axial load (kips)	Bending moment (in.-kips)
1	-2	24150
2	--	--
3	--	--
4	-2	11295
5	-200	20540
6	-60	3655
7	-80	3349
8	-80	4563
9	-6	1433
10	-6	2240
11	80	7596
12	5	7273
13	--	--
14	--	--
15	5	6794
16	5	7878

Table A-5. OBE (operating basis earthquake) axial loads and bending moments at weld locations for the Trojan plant.

Weld location	Axial load (kips)	Bending moment (in.-kips)
1	261	2131
2	--	--
3	--	--
4	260	2057
5	259	5032
6	53	3220
7	52	2349
8	50	1145
9	84	2108
10	83	3878
11	80	3450
12	83	2563
13	--	--
14	--	--
15	86	3156
16	85	3495

Table A-6. SSE (safe shutdown earthquake) axial loads and bending moments at weld locations for the Trojan plant.

Weld location	Axial load (kips)	Bending moment (in.-kips)
1	436	3559
2	--	--
3	--	--
4	434	3435
5	433	8403
6	89	5377
7	87	3923
8	84	1912
9	140	3520
10	139	6476
11	134	5762
12	139	4280
13	--	--
14	--	--
15	144	5271
16	142	5837

Table A-7. Deadweight axial loads and bending moments at weld locations for the Diablo Canyon plant.

Weld location	Axial load (kips)	Bending moment (in.-kips)
1	--	--
2	--	--
3	--	--
4	--	--
5	10	150
6	23	200
7	18	100
8	12	80
9	2	280
10	3	250
11	15	150
12	8	90
13	--	--
14	--	--
15	10	325
16	12	515

Table A-8. Thermal expansion axial loads and bending moments at weld locations for the Diablo Canyon plant.

Weld location	Axial load (kips)	Bending moment (in.-kips)
1	-9	32725
2	--	--
3	--	--
4	-9	10270
5	-200	21400
6	-100	8521
7	-120	7413
8	-120	7814
9	-9	2214
10	-9	3644
11	100	10334
12	12	3729
13	--	--
14	--	--
15	12	3895
16	10	4241

Table A-9. OBE axial loads and bending moments at weld locations for the Diablo Canyon plant.

Weld location	Axial load (kips)	Bending moment (in.-kips)
1	378	8706
2	--	--
3	--	--
4	378	4637
5	378	10432
6	135	7401
7	135	3567
8	135	3734
9	135	3325
10	135	10034
11	135	13385
12	262	3729
13	--	--
14	--	--
15	262	4582
16	262	6122

Table A-10. SSE axial loads and bending moments at weld locations for the Diablo Canyon plant.

Weld location	Axial load (kips)	Bending moment (in.-kips)
1	528	12070
2	--	--
3	--	--
4	528	6383
5	528	12698
6	212	15488
7	212	10715
8	212	5290
9	212	5442
10	212	4786
11	212	16617
12	430	22026
13	--	--
14	--	--
15	430	7514
16	430	10046

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The U.S. Nuclear Regulatory Commission contracted with the Lawrence Livermore National Laboratory to conduct a study to determine if the probability of occurrence of a double-ended guillotine break in primary coolant piping warrants the current design requirements that safeguard against the effects of such a break. This report assesses the reactor-coolant-loop piping system of west coast Westinghouse plants. The results indicate that directly induced DEGB is an unlikely event in the west coast Westinghouse plants. For the Trojan plant, leak is far more likely than a direct DEGB. Further, earthquakes have very little effect on the probabilities of leak and direct DEGB. At the Diablo Canyon plant, the increase in postulated seismic levels due to reevaluation of the site to account for the Hosgri Fault has caused directly induced DEGB failure probability to be dependent on earthquake occurrences. The resulting direct DEGB failure probability is still much lower than the indirect DEGB failure probability for Diablo Canyon.

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