Investigation of Techniques for the Development of Seismic Design Basis Using the Probabilistic Seismic Hazard Analysis

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ABSTRACT

The Nuclear Regulatory Commission asked Lawrence Livermore National Laboratory to form a group of experts to assist them in revising the seismic and geologic siting criteria for nuclear power plants, Appendix A to 10 CFR Part 100. This document describes a deterministic approach for determining a Safe Shutdown Earthquake (SSE) Ground Motion for a nuclear power plant site. One disadvantage of this approach is the difficulty of integrating differences of opinions and differing interpretations into seismic hazard characterization. In answer to this, probabilistic seismic hazard assessment methodologies incorporate differences of opinion and interpretations among earth science experts. For this reason, probabilistic hazard methods were selected for determining SSEs for the revised regulation, 10 CFR Part 100.23. However, because these methodologies provide a composite analysis of all possible earthquakes that may occur, they do not provide the familiar link between seismic design loading requirements and engineering design practice. Therefore, approaches used to characterize seismic events (magnitude and distance) which best represent the ground motion level determined with the probabilistic hazard analysis were investigated.

This report summarizes investigations conducted at 69 nuclear reactor sites in the central and eastern U.S. for determining SSEs using probabilistic analyses. Alternative techniques are presented along with justification for key choices.

CONTENTS

ABSTRACT.....	iii
ACKNOWLEDGMENTS	xiii
ABBREVIATIONS	xv
1. INTRODUCTION	1
1.1 Background.....	1
1.2 Seismic Hazard Characterization	3
1.3 Issues.....	3
1.4 Purpose and Scope	4
1.5 Report Organization	5
2. DETERMINATION OF CONTROLLING EARTHQUAKES.....	7
2.1 Concept of Controlling Earthquakes.....	7
2.2 Reference Probability.....	7
2.3 Methodology for Estimating Controlling Earthquakes Adopted in RG1.165	11
2.3.1 Introduction.....	11
2.3.2 Methodology for Estimating Controlling Earthquakes.....	11
2.4 Example	16
2.5 Summary of Results of the Controlling Earthquakes	24
2.6 Comparison with Seismic Criteria of Existing Sites.....	32
2.7 Return Periods of Controlling Earthquakes	32
3. ISSUES IN DETERMINING CONTROLLING EARTHQUAKES.....	39
3.1 Ground Motion Parameter	39
3.2 Sensitivity of M_c and D_c to the Reference Probability.....	39
3.3 Alternative Techniques to Determine Controlling Earthquakes.....	40
3.3.1 Mean Hazard Results	40
3.3.2 Hazard Surface.....	41
3.4 Selection of Parameters in the Deaggregation Process.....	41
3.4.1 Magnitude and Distance Intervals	41
3.4.2 Geometric Versus Arithmetic Mean Calculation for D_c	41
3.5 Selection of Site Condition	42
3.6 Stability of the Results Using LLNL and EPRI Seismic Hazard Methodology	42
4. INTERPRETATION OF CONTROLLING EARTHQUAKES.....	57
4.1 Introduction.....	57
4.2 Range of Rates and Upper Bound Magnitude of LLNL Seismicity Experts.....	57
4.3 Effect of μ , b -value, and Rate on M_c and D_c	57
4.4 Effect of Lower Bound Magnitude	60
4.5 Effect of Site Conditions.....	61
4.6 Effect of the Uncertainty in the Ground Motion Model	61
4.7 Effect of Changing Ground Motion Models.....	62
4.8 Examination of the Differences Between SSEs and CEs	62

5. GUIDELINES TO DETERMINE WHEN UPDATING IS NEEDED.....	85
5.1 Background.....	85
5.2 Approach.....	85
5.3 Effect of the New Zone on Hazard.....	86
5.3.1 Effect of Distance from a New Zone's Boundary.....	87
5.3.2 Effect of Source Characteristics.....	88
5.4 Effect of New Zone on Mc and Dc.....	88
5.5 Examples at Actual Sites.....	89
5.6 Conclusions on When Updating is Needed.....	90
6. DETERMINATION OF THE SSE GROUND MOTION.....	117
6.1 Design Spectra.....	117
6.2 Issues in Determining the SSE Ground Motion.....	117
6.3 Discussion of Issues.....	118
REFERENCES.....	131
APPENDIX A. SEISMIC HAZARD CHARACTERIZATION OF A SITE IN THE WESTERN U.S.....	133
Summary.....	133
Parameters of the Seismic Hazard Analysis.....	133
Location.....	133
Input Parameters.....	133
Site Conditions.....	134
Lower Magnitude of Integration.....	134
Variability Estimates on Ground Motion Modeling.....	134
Determination of the Controlling Earthquakes.....	134
Sensitivity.....	135
First Test.....	135
Second Test.....	135
Third Test.....	135
Fourth Test.....	136

TABLES

Table 1.1. Members of the Expert Group (EG) for revision of Appendix A, 10 CFR Part 100.....	1
Table 1.2. List of sites used in the analysis.....	2
Table 2.1. List of plants/sites used in determining the reference probability.....	8
Table 2.2. Recommended magnitude and distance bins.....	14
Table 2.3. Ground motion levels at the Clinton site at a hypothetical rock outcrop.....	16
Table 2.4. Ground motion levels at the Clinton site at the top of the soil column.....	16
Table 2.5. Average ground motion values.....	16
Table 2.6. Median hazard values for spectral accelerations at 1 Hz (79 cm/s/s).....	21
Table 2.7. Hazard values for spectral accelerations at 2.5 Hz (169 cm/s/s).....	21
Table 2.8. Hazard values for spectral accelerations at 5 Hz (225 cm/s/s).....	22
Table 2.9. Hazard values for spectral accelerations at 10 Hz (316 cm/s/s).....	22
Table 2.10. $P(m,d)_1$ for average spectral accelerations 1 and 2.5 Hz corresponding to the reference probability.....	23
Table 2.11. $P(m,d)_2$ for average spectral accelerations 5–10 Hz corresponding to the reference probability.....	23

Table 2.12. $P_{>100}(m,d)_1$ for average spectral accelerations 1-2.5 Hz corresponding to the reference probability	24
Table 2.13. Magnitudes and distances of controlling earthquakes from the LLNL probabilistic analysis.....	24
Table 2.14. Controlling earthquakes for central and eastern United States sites	26
Table 2.15. Sites for which contributions of distances greater than 100 km are more than 5%	29
Table 2.16. Comparison of controlling earthquakes to SSEs established at existing sites at operating license review period by NRC Staff.....	33
Table 3.1. Effect of RP level on $\underline{M}_c$ and $\underline{D}_c$ based on the average of 5- and 10-Hz hazard curves	43
Table 3.2. Percent contribution to the hazard for distance and magnitude bins for three RP cases— Seabrook and Browns Ferry sites.....	43
Table 3.3. Seabrook: median rate of EQ occurrence.....	45
Table 3.4. Matrix of distances and magnitude bins suggested in RG1.165: 16 bins total	45
Table 3.5. Matrix of distances and magnitude bins currently recommended: 35 bins total	46
Table 3.6. Estimates of controlling earthquakes	46
Table 3.7. Sites selected to study impact of soil type on the controlling earthquake	47
Table 3.8. Controlling earthquakes calculated for the sites listed in Table 3.7. For both soil and rock conditions for the average of 5-10-Hz and 1-2.5-Hz cases.....	47
Table 3.9. Comparison of $\underline{M}_c$ s and $\underline{D}_c$ s based on the average of the 5-10Hz hazard curves at RP=1.-05 using the LLNL and EPRI results	48
Table 4.1. 18th Percentile, median, and 82 percentile for most likely value for maximum magnitude, M_u , within 35 km of each site and rate of recurrence of $M \geq 5$ within 35 km of each site for all 69 NPP sites in the central and eastern United States	65
Table 4.2. Summary of values for all sites	67
Table 4.3. Effect of M_u and RP on $\underline{M}_c$ and $\underline{D}_c$ for the 1-Zone model	67
Table 4.4. Normalized median rate of activity in each distance and magnitude bin Normalized by area and rate of the $M=5.25$, $D=10$ km bin (a) 1-Zone model.....	68
Table 4.5. Normalized median rate of activity in each distance and magnitude bin for the North Anna site	69
Table 4.6. Normalized median rate of activity in each distance and magnitude bin for the Vogtle site.....	69
Table 4.7. Normalized median rate of activity in each distance and magnitude bin for the Turkey Point site	70
Table 4.8. $\underline{M}_c$ and $\underline{D}_c$ for average of 5-10 Hz as a function of rate and M_u	70
Table 4.9. Effect of b-value on $\underline{M}_c$ and $\underline{D}_c$ for the 1-Zone model for two values of M_u . The rates of $M \geq 5$ are the same for all b-values.....	71
Table 4.10. Comparison of $\underline{M}_c$ and $\underline{D}_c$ between lower bound of integration of 3.75 and 5 for six cases using the 1-Zone model at RP level of 1.E-05 for average of 5-10Hz.....	71
Table 4.11. Effect of site soil condition on the controlling earthquake based on the average of 5-10-Hz hazard curves as a function of M_u	72
Table 4.12. Effect of the sigma of the Ground Motion Model on $\underline{M}_c$ and $\underline{D}_c$ for the simple 1-Zone Model.....	72
Table 4.13. Median S_a values at RP = 1.E-05 for 1-Zone Model for two different ground motion models for selected M_u values	73
Table 4.14. $\underline{M}_c$ and $\underline{D}_c$ for 1-Zone Model for various M_u for the case of the composite ground motion model for two cases discussed in text. $\underline{M}_c$ and $\underline{D}_c$ are based on the average of 5-10-Hz median hazard curves.	73
Table 5.1. Change in the number of earthquakes in Zone S as compared to Zone L as a function of the b-value in Zone S	92
Table 5.2. $\underline{M}_c$ and $\underline{D}_c$ for average of 5-10-Hz hazard curve for selected sites for 2-Zone models shown in 5-1 at RP level of 1E-05	92
Table 5.3. 1-Zone results from Table 4.8	93
Table 5.4. Three Cases for the Value of M_u in the Wabash Valley zone.....	93
Table 5.5. Effect of Possible Modification of M_u on the CE for the hypothetical Wabash Valley site for the three cases given in Table 5.4	93
Table 5.6. Three Cases for M_u in the Zone Containing the Vogtle Site.....	94

Table 5.7. Effect of Possible Modification of M_H on the CE for the Vogtle site.....	94
Table A.1 Contribution of Magnitude-Distance Intervals to Total Seismic Hazard-Median Hazard; 5-10 Hz RG2 case; PE = 1.0×10^{-5} Sv (5Hz) = 29.18 cm/s; SV (10 Hz) = 13.20 cm/s	136
Table A.2 Contribution of Magnitude-Distance Intervals to Total Seismic Hazard-Mean Hazard; 5-10 Hz RG2 case; PE = 7.5×10^{-5} Sv (5Hz) = 23.70 cm/s; SV (10 Hz) = 9.95 cm/s	137
Table A.3 Contribution of Magnitude-Distance Intervals to Total Seismic Hazard-Median Hazard; 1-2.5 Hz RG2 case; PE = 1.0×10^{-5} Sv (1Hz) = 41.88 cm/s; SV (2.5 Hz) = 40.29 cm/s	137
Table A.4 Contribution of Magnitude-Distance Intervals to Total Seismic Hazard-Mean Hazard; 1-2.5 Hz RG2 case; PE = 7.5×10^{-5} Sv (1Hz) = 30.59 cm/s; SV (2.5 Hz) = 33.21 cm/s	138
Table A.5 Contribution of Magnitude-Distance Intervals to Total Seismic Hazard-Median Hazard; 5-10 Hz Test case; PE = 1.0×10^{-7} ; First Test Sv (5Hz) = 84.31 cm/s; SV (10 Hz) = 40.87 cm/s.....	138
Table A.6 Contribution of Magnitude-Distance Intervals to Total Seismic Hazard-Mean Hazard; 5-10 Hz Test case; PE = 7.5×10^{-7} ; First Test Sv (5Hz) = 120.16 cm/s; SV (10 Hz) = 49.04 cm/s.....	139
Table A.7 Contribution of Magnitude-Distance Intervals to Total Seismic Hazard-Median Hazard; 1-2.5 Hz Test case; PE = 1.0×10^{-7} ; First Test Sv (1Hz) = 108.39 cm/s; SV (2.5 Hz) = 129.93 cm/s.....	139
Table A.8 Contribution of Magnitude-Distance Intervals to Total Seismic Hazard-Mean Hazard; 1-2.5 Hz Test case; PE = 7.5×10^{-7} ; First Test Sv (1Hz) = 151.49 cm/s; SV (2.5 Hz) = 179.32 cm/s.....	140
Table A.9 Contribution of Magnitude-Distance Intervals to Total Seismic Hazard-Median Hazard; 5-10 Hz RG2 case; PE = 1.0×10^{-5} ; Second Test Sv (1Hz) = 19.08 cm/s; SV (10 Hz) = 9.82 cm/s	140
Table A.10 Contribution of Magnitude-Distance Intervals to Total Seismic Hazard- Median Hazard; 1-2.5 Hz RG2 case; PE = 1.0×10^{-5}	141
Table A.11 Contribution of Magnitude-Distance Intervals to Total Seismic Hazard- Median Hazard; 5-10 Hz RG2 case; PE = 1.0×10^{-5}	141
Table A.12 Contribution of Magnitude-Distance Intervals to Total Seismic Hazard- Median Hazard; 1-2.5 Hz RG2 case; PE = 1.0×10^{-5}	142

FIGURES

Figure 2-1. Procedure to compute probability of exceeding design basis	9
Figure 2-2. Probability of exceeding SSE using median hazard estimates.....	10
Figure 2-3a and 2-3b. Total median seismic hazard curves for a site.....	12
Figure 2-4a and 2-4b. De-aggregated median seismic hazard curves for a site.....	13
Figure 2-5. Distribution of the percent contribution to the hazard as a function of magnitude and distance bins for the average of 5-10 Hz hazard curves at the ground motion level corresponding to the RP level of Section 2.2 for the Clinton site	14
Figure 2-6. Total median hazard at Clinton at a hypothetical rock outcrop	18
Figure 2-7. Median hazard curves for 1-Hz magnitude-bin 5.5-6.0 and distance-bins 1-1, 0-15; 2-2, 15-25; and 3-3, 25-50.....	19
Figure 2-8. Distribution of the percent contribution to the hazard as a function of magnitude and distance bins for the average of 1-2.5 Hz hazard curves at the ground motion level corresponding to the RP level of Section 2.2 for the Clinton site	20
Figure 2-9. Plot of $\bar{M}_C$ and $\bar{D}_C$ given in Table 2.14 for the 69 NPPs in the central and eastern United States based on the average of the 5- and 10-Hz hazard curve.....	25
Figure 2-10. Most likely yearly recurrence model for earthquakes for a typical site for each of the eleven LLNL seismicity experts based on the zones within 35 km of a site.....	34
Figure 2-11. Composite recurrence model for the rate of activity based on the most likely models of the eleven LLNL experts shown in Figure 2-10	35
Figure 2-12. Plot of $\bar{M}_C$ based on the average of 5-10Hz versus return period for the sites given in Table 2.14. Return period is based on the most likely composite recurrence model for all zones within 35 km of each site.....	36

Figure 2-13. Plot of $\underline{M}_c$ versus rate of $M \geq 5.25$ earthquakes for the sites given in Table 2.14. Rate of $M \geq 5.25$ is based on the most likely composite recurrence model for all zones within 35 km of each site.	37
Figure 3-1. Typical distribution of percent contribution to the total hazard as a function of magnitude and distance bins for the average of the 5-10-Hz hazard curves at the ground motion level corresponding to the RP selected in Section 2.2.	49
Figure 3-2. Distribution of the percent contribution to the hazard as a function of the magnitude and distance bins for the average of 1-2.5-Hz hazard curves at the ground motion level corresponding to RP level of Section 2.2 for the Seabrook site.	50
Figure 3-3. Distribution of the percent contribution to the hazard as a function of magnitude and distance bins for the average of 1-2.5-Hz hazard curves at the ground motion level corresponding to the RP level of Section 2.2 for the 1-2.5-Hz Clinton site. For this site, the figure shows the need for an $\underline{M}_c$ and $\underline{D}_c$ for the 1-2.5-Hz case.	51
Figure 3-4. Change in $\underline{M}_c$ and $\underline{D}_c$ between case RG and case CP1.	52
Figure 3-5. Change in $\underline{M}_c$ and $\underline{D}_c$ between case RG and case CP0.	53
Figure 3-6. Mean hazard surface for the average of 5-10-Hz hazard curves for the Seabrook site at the ground motion level corresponding to the RP level RG.	54
Figure 3-7. Comparison of $\underline{M}_c$ and $\underline{D}_c$ for RP level RG average of 5-10-Hz median and mean hazard curves.	55
Figure 3-8. Comparison of $\underline{M}_c$ and $\underline{D}_c$ based on the average of 5-10 Hz hazard curves for RP case RG between $\underline{D}_c$ computed as a geometric average and an arithmetic average.	56
Figure 4-1. Plot of $\underline{M}_c$ versus M_u for all 69 NPPs in the central and eastern United States based on average of 5-10-Hz hazard curves at RP level RG. Also shown are the results for the simple case given in Table 4.1.	74
Figure 4-2. Comparison of the median composite normalized recurrence models for the North Anna and Calvert Cliffs sites based on the zones within 35 km of each site.	75
Figure 4-3. Comparison of the median composite normalized recurrence models for the Palisades, Comanche Peak and Turkey Point sites based on the zones within 35 km of each site.	76
Figure 4-4. Plot of $\underline{M}_c$ versus rate of $M \geq 5.25$ earthquakes. Several sites have been identified for reference.	77
Figure 4-5. Comparison of the normalized recurrence models for the Seabrook and North Anna sites. Also shown is the normalized recurrence models for the 1-Zone model with b-values = -1 and -1.2.	78
Figure 4-6. Comparison of a simple truncated exponential model with $M_u = 6.5$ to the Richter $\log N = a - bM$ model.	79
Figure 4-7. Median recurrence model for each LLNL seismicity expert for the Braidwood site based on the region within 35 km of the site.	80
Figure 4-8. Comparison of the median composite recurrence models based on the region within 35 km of the sites for the 1—1 Braidwood, 2—2 Watts Bar, 3—3 Seabrook, 4—4 Sequoyah, and 5—5 Bellefonte sites.	81
Figure 4-9. Comparison of the median composite recurrence models based on the region out to 35 km of the 1—1 Braidwood, 2—2 Clinton, and 3—3 Callaway sites.	82
Figure 4-10. Comparison of the median composite recurrence models based on the region out to 100 km of the 1—1 Braidwood, 2—2 Clinton, and 3—3 Callaway sites.	83
Figure 5-1. Geometry of the 2-Zone model used and location of the sites relative to the boundary between Zone L and Zone S.	95

Figure 5-2. Illustration of how the PEs are determined.	96
Figure 5-3. Illustration of how the S_a s are determined.	97
Figure 5-4. 10-Hz effect of distance and rate $M_U = 6.25$ in Zone S with a moderate GM level and a ratio of <div style="text-align: center;">(PE)</div> <div style="text-align: center;">(PE base case)</div>	98
Figure 5-5. 10-Hz effect of distance and rate $M_U = 6.25$ in Zone S with PE of $1E-05$ and a ratio of <div style="text-align: center;">(S_a)</div> <div style="text-align: center;">(S_a base case)</div>	98
Figure 5-6. 1-Hz effect of distance and rate $M_U = 6.25$ in Zone S with a moderate GM level and a ratio of <div style="text-align: center;">(PE)</div> <div style="text-align: center;">(PE base case)</div>	99
Figure 5-7. 1-Hz effect of distance and rate $M_U = 6.25$ in Zone S with PE of $1E-05$ and a ratio of <div style="text-align: center;">(S_a)</div> <div style="text-align: center;">(S_a base case)</div>	99
Figure 5-8. 10-Hz effect of distance and M_U for the same rate in both Zone L and S with a moderate GM <div style="text-align: center;">(PE)</div> <div style="text-align: center;">level and a ratio of (PE base case)</div>	100
Figure 5-9. 10-Hz effect of distance and M_U for the same rate in both Zone L and S with a PE of $1E-05$ and <div style="text-align: center;">(S_a)</div> <div style="text-align: center;">a ratio of (S_a base case)</div>	100
Figure 5-10. 1-Hz effect of distance and M_U for the same rate in both Zone L and S with a moderate GM <div style="text-align: center;">(PE)</div> <div style="text-align: center;">level and a ratio of (PE base case)</div>	101
Figure 5-11. 1-Hz effect of distance and M_U for the same rate in both Zone L and S with a PE of $1E-05$ and <div style="text-align: center;">(S_a)</div> <div style="text-align: center;">a ratio of (S_a base case)</div>	101
Figure 5-12. 10-Hz base rate in both zones with a PE of $1E-05$ and a ratio of <div style="text-align: center;">(S_a)</div> <div style="text-align: center;">(S_a base case)</div>	102
Figure 5-13. 10-Hz 8x base rate in Zone S with a PE of $1E-05$ and a ratio of <div style="text-align: center;">(S_a)</div> <div style="text-align: center;">(S_a base case)</div>	102
Figure 5-14. 1-Hz base rate in both zones with a PE of $1E-05$ and a ratio of <div style="text-align: center;">(S_a)</div> <div style="text-align: center;">(S_a base case)</div>	103
Figure 5-15. 1-Hz 8x base rate in Zone S with a PE of $1E-05$ and a ratio of <div style="text-align: center;">(S_a)</div> <div style="text-align: center;">(S_a base case)</div>	103
Figure 5-16. 5-Hz base rate in Zone S with a PE of $1E-05$ and a ratio of <div style="text-align: center;">(S_a)</div> <div style="text-align: center;">(S_a base case)</div>	104
Figure 5-17. 2.5-Hz 8x base rate in Zone S with a PE of $1E-05$ and a ratio of <div style="text-align: center;">(S_a)</div> <div style="text-align: center;">(S_a base case)</div>	104
Figure 5-18. 10-Hz effect of distance and b-value with the same M_U (6.25) in both zones with a moderate <div style="text-align: center;">(PE)</div> <div style="text-align: center;">GM level and a ratio of (PE base case)</div>	105
Figure 5-19. 10-Hz effect of distance and b-value with the same M_U (6.25) in both zones with a PE of <div style="text-align: center;">(S_a)</div> <div style="text-align: center;">1E-05 and a ratio of (S_a base case)</div>	105

Figure 5-20. 1-Hz effect of distance and b-value with the same M_U (6.25) in both zones with a moderate (PE) GM level and a ratio of (PE base case)	106
Figure 5-21. 1-Hz effect of distance and b-value with the same M_U (6.25) in both zones with a PE of 1E-05 (S_a) and a ratio of (S_a base case)	106
Figure 5-22. Site 2L 10-Hz effect of M_U and rate changes in S with a high GM level and a ratio of (PE) (PE base case)	107
Figure 5-23. Site 2L 10-Hz effect of M_U and rate changes in S with a moderate GM level and a ratio of (PE) (PE base case)	107
Figure 5-24. Site 2L 10-Hz effect of M_U and rate changes in S with a PE of 1E-07 and a ratio of (S_a) (S_a base case)	108
Figure 5-25. Site 2L 10-Hz effect of M_U and rate changes in S with a PE of 1E-05 and a ratio of (S_a) (S_a base case)	108
Figure 5-26. Site B 10-Hz effect of M_U and rate changes in S with a high GM level and a ratio of (PE) (PE base case)	109
Figure 5-27. Site B 10-Hz effect of M_U and rate changes in S with a moderate GM level and a ratio of (PE) (PE base case)	109
Figure 5-28. Site B 10-Hz effect of M_U and rate changes in S with a PE of 1E-07 and a ratio of (S_a) (S_a base case)	110
Figure 5-29. Site B 10-Hz effect of M_U and rate changes in S with a PE of 1E-05 and a ratio of (S_a) (S_a base case)	110
Figure 5-30. Site 2S 10-Hz effect of M_U and rate changes in S with a high GM level and a ratio of (PE) (PE base case)	111
Figure 5-31. Site 2S 10-Hz effect of M_U and rate changes in S with a moderate GM level and a ratio of (PE) (PE base case)	111
Figure 5-32. Site 2S 10-Hz effect of M_U and rate changes in S with a PE of 1E-07 and a ratio of (S_a) (S_a base case)	112
Figure 5-33. Site 2S 10-Hz effect of M_U and rate changes in S with a PE of 1E-05 and a ratio of (S_a) (S_a base case)	112
Figure 5-34. Most likely yearly recurrence model for each of the seismicity experts based on the zones within 50 km of the hypothetical Wabash Valley site (base case).	113
Figure 5-35. Most likely yearly recurrence model for each of the seismicity experts for Case M based on the zone within 50 km of the hypothetical Wabash Valley site.	113

Figure 5-36. Most likely yearly recurrence model for each of the seismicity experts for Case L based on the zone within 50 km of the hypothetical Wabash Valley site.	114
Figure 5-37. Comparison of the UHS_a at a PE level of $1E-05$ for the hypothetical Wabash Valley site for the three cases of modified M_u given in Table 5.4.	114
Figure 5-38. Most likely yearly recurrence model for each of the seismicity experts based on the zones within 35 km of the Vogtle site.	115
Figure 5-39. Most likely yearly recurrence model for each of the seismicity experts for Case M based on the zones within 35 km of the Vogtle site.	115
Figure 5-40. Most likely yearly recurrence model for each of the seismicity experts for Case L based on the zones within 35 km of the Vogtle site.	116
Figure 5-41. Comparison of the UHS_a at a PE level of $1E-05$ for the Vogtle site for the three cases of modified M_u given in Table 5.6 and CEs on Table 5.7. For this plot, the soil category was used as rock.	116
Figure 6-1. Plot of the average of 5–10 Hz S_a values at RP level RG versus rate of $M \geq 5.25$ earthquakes within 35 km of each site. Only S_a values for rock sites plotted.	122
Figure 6-2. $\underline{M}_c$ versus S_a (average of 5–10–Hz at RP level RG) for all rock NPP sites in the central and eastern U.S.	123
Figure 6-3a. Comparison between the Uniform Hazard Acceleration Spectra (UHS_a) at RP RG obtained from the PSHA and a 1-Sigma estimate of the UHS_a using the Boore-Atkinson model evaluated at $\underline{M}_c$ and $\underline{D}_c$ for a higher-seismicity site.	124
Figure 6-3b. Comparison between the UHS_a at RP RG obtained from the PSHA and a 1-Sigma estimate of the UHS_a using the Boore-Atkinson model evaluated at $\underline{M}_c$ and $\underline{D}_c$ for a low-seismicity site.	125
Figure 6-4a. Comparison between the UHS_a (P—P), an estimate of S_a using the EPRI GMM at the 1-Sigma level evaluated at $\underline{M}_c$ and $\underline{D}_c$ based on the average of the 5–10–Hz hazard curves (C—C), and the estimate of S_a using the EPRI GMM at the 1-Sigma level evaluated at $\underline{M}_c$ and $\underline{D}_c$ based on the average of 1–2.5–Hz hazard curves for distances greater than 100 km (C3—C3) for RP level RG for the Browns Ferry site.	126
Figure 6-4b. Same curves plotted as in Figure 6-4a except for the Shearon Harris site.	127
Figure 6-5a. Comparison between the UHS_a (P—P) and the SSS scaled to the UHS_a at 7.5 Hz (X—X) and 1-Sigma estimate of the S_a based on the EPRI GMM evaluated at the $\underline{M}_c$ and $\underline{D}_c$ based on the average of 1–2.5–Hz hazard curves for distances greater than 100 km for the Browns Ferry site. The SSS shape is for the $M=5.25$ set given in Bernreuter et al. 1987.	128
Figure 6-5b. Same curves plotted as in Figure 6-5a except for the Wolf Creek site. The SSS shape is for the $M=5.25$ set given in Bernreuter et al. (1987).	129
Figure A-1 Seismotectonic Setting of the ESRP.	143
Figure A-2 Map showing the locations of earthquakes ($M > 5.5$) within 200 miles of INEEL.	144
Figure A-3 Map showing locations of the faults closest to INEEL.	145
Figure A-4 Map showing the locations of the basaltic rift zones at INEEL.	146
Figure A-5 INEEL Spectra Hazard Estimates, $M_g > 5$, 9-sx, 6-gx, sigma = .037, 0.48, 0.65.	147
Figure A-6 INEEL Spectra Hazard Estimates, 2/12/92, 9-Sx, 6-Gx, sigma = 0.37, 0.48, 0.65.	148
Figure A-7 Seismotectonic Setting of the ESRP.	149
Figure A-8 INEEL Spectra Hazard Estimates, for Site 2, 9-Sx, 6-Gx, sigma = 0.37, 0.48, 0.65.	150
Figure A-9 INEEL Spectra Hazard Estimates, for Site 3, 9-Sx, 6-Gx, sigma = 0.37, 0.48, 0.65.	151

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ABBREVIATIONS

BR	Base Rate (See Sections 4.3 and 5.2)
CE	Controlling Earthquake (See Section 2.3)
CEUS	Central and Eastern United States
CP0	Reference probability case of $RP = 1 \times 10^{-4}$
CP1	Reference probability case of $RP = 1 \times 10^{-6}$
CTB	Centennial Tectonic Belt
D	Distance
D _{bar}	Used on a few figures in place of <u>D_c</u>
<u>D_c</u>	Distance from site of controlling earthquake
EG	Expert Group (See Table 1.1)
EPRI	Electric Power Research Institute
ESRP	Eastern Snake River Plain
GM	Ground Motion
GMM	Ground Motion Model and in a few cases Ground Motion Measure
INEEL	Idaho National Engineering and Environmental Laboratory
ISB	Intermountain Seismic Belt
LLNL	Lawrence Livermore National Laboratory
LS	Large Sigma Case (See Section 4.6)
M	Magnitude
Mag	Magnitude
M _{bar}	Used on a few figures in place of <u>M_c</u>
<u>M_c</u>	Magnitude of the controlling earthquake
MMI	Modified Mercalli Intensity
MS	Moderate Sigma Case (See Section 4.6)
M _u	Maximum magnitude in a zone—technically the truncation magnitude of the truncated exponential distribution used for the recurrence model.
NPP	Nuclear Power Plants
PE	Probability of Exceedance
NRC	U.S. Nuclear Regulatory Commission
NUMARC	Nuclear Management and Resource Council
PGA	Peak Ground Acceleration
PSHA	Probabilistic Seismic Hazard Analysis
RG	Reference Probability case of $RP = 1 \times 10^{-5}$
RP	Reference Probability (See Section 2.2)
S _a	Spectral Acceleration
SS	Small Sigma Case (See Section 4.6)
SSE	Safe Shutdown Earthquake
SSS	Site Specific Spectra
UHS _a	Uniform Hazard Acceleration Spectrum

INVESTIGATION OF TECHNIQUES FOR THE DEVELOPMENT OF SEISMIC DESIGN BASIS USING THE PROBABILISTIC SEISMIC HAZARD ANALYSIS

1. INTRODUCTION

1.1 Background

The existing approach for determining Safe Shutdown Earthquake Ground Motions (SSE) for currently operating nuclear power plant sites is described in Appendix A to 10 CFR Part 100. This determination is primarily based on a deterministic approach. Using this deterministic approach, a single set of earthquake sources is selected. For each source, a maximum earthquake is used as the source of ground motion that can affect the site.

Because of the uncertainty about earthquake phenomena—especially in the central and eastern United States (CEUS)—differences of opinion and differing interpretations among experts (i.e., regarding the characteristics of the seismic sources, the largest earthquakes to be considered, and the ground motion models to be used), have made the licensing process relatively cumbersome. Therefore, the United States Nuclear Regulatory Commission (NRC) identified the need to formulate procedures that quantitatively incorporate uncertainty in the evaluation of seismic hazard.

Probabilistic procedures developed specifically for nuclear power plant seismic hazard assessments in the CEUS during the past 15 years provide a structured approach, when performed together with site-specific investigations, for making decisions regarding the determination of the SSE.

For these reasons, in September of 1990, the NRC began the formal rulemaking process to revise the seismic and geologic siting criteria for nuclear power plants (NPP). NRC requested that Lawrence Livermore National Laboratory (LLNL) form a group of experts to assist them in the revision of these criteria. The members of this group of experts are listed in Table 1.1.

Table 1.1. Members of the Expert Group (EG) for revision of Appendix A, 10 CFR Part 100

Dr. R. Budnitz
Dr. K. Coppersmith
Dr. C. Cornell
Mr. J. Devine
Dr. W. Hays
Dr. P. Pomeroy
Dr. R. Kennedy

At the start of the project, one issue that received considerable discussion was how best to use the probabilistic seismic hazard analysis instead of, or in addition to, a deterministic seismic hazard analysis.

Probabilistic seismic hazard methodologies are powerful tools for incorporating uncertainties associated with identifying and characterizing seismic sources and defining ground shaking levels consistent with given safety criteria (for example, a 1×10^{-5} annual probability of exceeding the seismic design loading). However, because these methods provide a composite analysis of all possible earthquakes that may occur, they do not provide the familiar link between seismic design loading requirements and engineering design practice. Seismic design generally requires the type of events (expressed in terms of magnitude and distance) and the type of seismic source within which the event occurs. From this earthquake, parameters such as ground motion time history and duration can be derived for engineering purposes.

1. Introduction

Therefore, the goal of this project was to develop a procedure which could use probabilistic evaluations of earthquake ground motions which are reasonably consistent with deterministic results.

An acceptable procedure, in addition to the purely probabilistic approach, was to use the probabilistic seismic hazard analysis to determine one or several hazard-consistent scenario earthquakes or controlling earthquakes (CE). These earthquake events could then be used to develop design ground motion. LLNL explored this concept with the support of the Expert Group (EG) and applied it to 69 existing nuclear reactor sites in the central and eastern United States. These sites are listed in Table 1.2.

Table 1.2. List of sites used in the analysis

No.	Plant Name
55	Arkansas
40	Beaver Valley
56	Bellefonte
41	Big Rock Point
3	Braidwood
26	Browns Ferry
27	Brunswick
42	Byron
57	Callaway
28	Calvert Cliffs
29	Catawba
43	Clinton
58	Comanche Peak
44	Cook
59	Cooper
60	Crystal River
45	Davis Besse

No.	Plant Name
46	Dresden
61	Duane Arnold
30	Farley
47	Fermi
11	Fitzpatrick
62	Ft. Calhoun
12	Ginna
63	Grand Gulf
13	Haddam Neck
31	Hatch
32	Hope Creek
14	Indian Point
48	Kewaunee
4	Lacrosse
49	Lasalle
1	Limerick
10	Mame Yankee
33	McGuire
9	Millstone
64	Monticello
15	Nine Mile Pt.
34	North Anna
35	Oconee
16	Oyster Creek
50	Palisades
17	Peach Bottom
51	Perry
18	Pilgrim
52	Point Beach

No.	Plant Name
53	Prairie Island
65	Quad Cities
5	River Bend
36	Robinson
19	Salem
20	Seabrook
37	Sequoyah
2	Shearon Harris
21	Shoreham
66	South Texas
67	St. Lucie
38	Summer
39	Surry
22	Susquehanna
23	Three Mile Is.
68	Turkey Point
24	Vermont Yankee
8	Vogtle
69	Waterford
7	Watts Bar
6	Wolf Creek
25	Yankee Rowe
54	Zion

The approach developed during the course of this project is incorporated in Regulatory Guide RG1.165, "Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motions," a guidance document to 10 CFR Part 100.23, "Geologic and Seismic Siting Factors," published in December 1996.

1.2 Seismic Hazard Characterization

There are three basic inputs to Probabilistic Seismic Hazard Analyses (PSHA). First, the seismic sources in the study region are identified and earthquake recurrence rates are estimated for each source. Second, ground motion attenuation relations, which are generally expressed as ground motion level as a function of magnitude and distance, are then used to model the seismic energy propagation from the source to give the ground motion. Third, an uncertainty analysis is then carried out to incorporate the range of interpretations for each parameter involved in determining earthquake recurrence, maximum magnitude, and ground motion attenuation.

In 1982, the eastern U.S. Seismic Hazard Characterization project, sponsored by the NRC (Bernreuter et al. 1985, 1989) was started, and in 1983 its equivalent, sponsored by Electric Power Research Institute (EPRI) (EPRI 1989), was started. These two major projects were undertaken to incorporate all of the aspects of PSHA, with major emphasis on quantifying the uncertainty. The LLNL and EPRI methodologies were used to characterize the seismic hazard at 69 sites (Bernreuter et al. 1989) and 49 sites (EPRI 1989), respectively, east of the Rocky Mountains. The LLNL methodology was subsequently reviewed and improved for the 69 sites (Savy et al. 1993). The details and guidelines on how to perform a PSHA are given in the report of the Senior Seismic Hazard Analysis Committee (SSHAC) (SSHAC 1995).

The primary advantage of these PSHA methodologies over the deterministic approach is that they calculate seismic hazard by integration over all possible earthquake occurrences and intensity and ground motion levels. These methodologies also integrate over multiple seismic source interpretations and alternative ground motion attenuation models to represent different scientific interpretations.

1.3 Issues

Both deterministic approaches, such as those outlined in Appendix A to 10 CFR Part 100, and

1. Introduction

PSHA rely on the same field data, historical records, etc. The main differences are in how:

- (1) they incorporate the data into the analysis
- (2) in what form the "answer" is given.

Relative to (1) above, it is easy to incorporate all of the data and uncertainties into the probabilistic approach and formally include it in the final results. This is not the case for the approach given in Appendix A. No formal process is given to include rate or the use of the recurrence model. Alternative models must be handled judgmentally and so on. Section 4.8 discusses the implication of treating the data differently.

Relative to (2) above, both approaches give very different forms for the results. For example, in the probabilistic approach, the "final answer" is a probability distribution giving the probability that the ground motion at any level will be exceeded. The "final answer" from the deterministic approach is simply a ground motion level.

The output of the deterministic analysis can be directly input into the usual design process.

If seismic designs were generally performed in a probabilistic manner, then the output of the PSHA could be directly input into the analysis; however, most seismic designs are performed deterministically. This is a problem for the PSHA because one needs to select a single value from the full distribution to use in the design analysis. The difficulty is having a basis on which to choose this value.

Finding a basis on which to select a single number from the resultant distribution of hazard can be overcome by a calibration process. Section 2.2 of this report outlines one approach (the approach chosen) to arrive at this value. The calibration process considers the fact that at 69 nuclear power plant sites east of the Rocky Mountains, the SSE has been determined by application of Appendix A. In Section 3 we explore the impact of other possible choices.

The methodology given in RG1.165 is linked to the deterministic results in two ways. First, the calibration process is used to select the

appropriate reference probability (RP) to use in developing the input needed for design. Second, this methodology determines the CE (or at some sites two CEs are defined). This concept is outlined in Section 2 of this report.

The concept of the CE was introduced for two main reasons:

- (1) To provide a "deterministic-like" representation for the SSE rather than just a probability of exceeding a specific Uniform Hazard Spectrum for the site. Having a "concrete" value for the SSE in terms of magnitude and distance makes it easier to judge if the SSE is reasonable.
- (2) More importantly, the CE provides a more appropriate spectral shape to use for design than the Uniform Hazard Spectrum given by the PSHA.

The NRC Staff and members of the EG concluded that the new approach used to define the SSE given in RG1.165 (and in this report) had considerable advantage over the older deterministic approach of Appendix A. Both require the same detailed field investigations and data. The new approach allows, in a formal way, a means to incorporate all the alternative models and data into the analysis, thus eliminating the difficult and somewhat arbitrary judgmental process needed when using the Appendix A approach.

1.4 Purpose and Scope

This report presents the approach developed during this project for determining seismic ground motion using results from LLNL or EPRI PSHAs. In this report, justification for the choices incorporated into Regulatory Guide RG1.165 are provided.

An objective of this study is to understand the consequences of the choices made. For this reason, results of the 1989 and 1993 LLNL and 1989 EPRI PSHAs are used in the investigation.

1.5 Report Organization

In Section 2.0, the concept of controlling earthquakes is presented. A description of the methodology is given with examples and results for 69 sites east of the Rocky Mountains.

Section 3.0 describes the key choices and the justifications that have to be made in assessing controlling earthquakes.

Section 4.0 examines how the sensitivities of seismic characterization parameters affect the determination of controlling earthquakes.

Section 5.0 presents the results of the sensitivity analyses performed to define when a probabilistic seismic hazard study needs to be updated.

Section 6.0 presents issues in determining Safe Shutdown Earthquake Ground Motions.

Appendix A of this report presents an application of the methodology to a western U.S. site.

 

2. DETERMINATION OF CONTROLLING EARTHQUAKES

2.1 Concept of Controlling Earthquakes

Given a reference probability (RP) (expressed as an annual probability of exceeding a ground motion level), the total seismic hazard can be deaggregated to obtain contributions from different magnitude and distance events. The earthquakes obtained from this process which most contribute to this hazard are then called controlling earthquakes (CE).

Although approaches for characterizing these earthquakes were introduced in the literature (Ishikawa and Kameda 1992; McGuire and Sheldock 1981) for single and multiple sources, they did not address the case of how PSHA treats uncertainties resulting from the consideration of multiple seismic source interpretations and alternative ground motion attenuation models. This is the case with the present methodologies used to assess seismic hazards in the central and eastern U.S. (Sobel 1993; EPRI 1989).

The procedure used to determine the RP, an annual probability of exceeding the safe shutdown earthquake ground motion, is described in Section 2.2. Section 2.3 gives the mathematical details of the adopted method for determining the controlling earthquake.

2.2 Reference Probability

Determining the RP of exceeding the seismic design basis is based on considering the experience data base of the 69 reactor sites in the central and eastern U.S. The RP is defined so that the SSE at future reactor sites compares favorably to the hazard level of currently operating plants.

The RP is defined as "the annual probability level such that 50% of a subset of the currently operating plants has an annual median probability of exceeding the SSE ground motion level (average of 5 and 10 Hz)." The following steps define the procedure.

Step 1

Using the LLNL seismic hazard methodology (Savy et al. 1993), the seismic hazard is calculated for the sites listed in Table 2.1 for spectral responses at 5 and 10 Hz. The selection of the sites listed in Table 2.1 is based on a consensus among the EG and NRC Staff. For these sites, Newmark type spectra were used to determine the design ground motion. The ground motion measures at 5 and 10 Hz are judged to be the most representative ground motion parameters for determining the controlling earthquake. This selection is based on judgment derived from the comparative analysis of typical nuclear power plant structures and systems for earthquake ground motions.

Step 2

The median composite annual probability of exceeding the SSE for spectral velocities at 5 and 10 Hz using median hazard estimates is calculated for each site listed in Table 2.1. The composite annual probability is determined by using the formula:

$$\text{composite probability} = 1/2(a_1) + 1/2(a_2)$$

where a_1 and a_2 represent median annual probabilities of exceeding SSE spectral ordinates at 5 and 10 Hz, respectively. The procedure is illustrated in Figure 2-1.

Step 3

Figure 2-2 illustrates the distribution of median probabilities of exceeding the SSEs for plants listed in Table 2.1 operating in the eastern U.S. These figures indicate a limit; approximately 50% of the plants have a probability of exceeding the SSE ground motion below this limit. This limit defines the RP. The RP is about $1E-05/\text{yr}$.

Although the RP is dependent on probabilistic seismic hazard studies, this value is similar for both the 1993 LLNL and EPRI seismic hazard studies (Nuclear Energy Institute 1994).

2. Determination of Controlling Earthquakes

Table 2.1. List of plants/sites used in determining the reference probability

Plant		Primary Soil Conditions
No.	Name	
1	Limerick	Rock
2	Shearon Harris	Sand - S1
3	Braidwood	Rock
5	River Bend	Deep soil
6	Wolf Creek	Rock
7	Watts Bar	Rock
8	Vogtle	Deep soil
20	Seabrook	Rock
23	Three Mile Is.	Rock
29	Catawba	Rock
32	Hope Creek	Deep soil
33	McGuire	Rock
34	North Anna	Rock
38	Summer	Rock
40	Beaver Valley	Sand - S1
42	Byron	Rock
43	Clinton	Till - T3
45	Davis Besse	Rock
49	Lasalle	Till - T2

Plant		Primary Soil Conditions
No.	Name	
51	Perry	Rock
56	Bellefonte	Rock
57	Callaway	Rock
58	Comanche Peak	Rock
63	Grand Gulf	Deep soil
66	South Texas	Deep soil
69	Waterford	Deep soil
9/83	Millstone	Rock
15/85	Nine Mile Point	Rock
27/88	Brunswick	Sand - S1
70	Nine Mile Point	Sand - S1
73	North Anna	Sand - S1
75	Summer	Sand - S1
77	Callaway	Sand - S1
81	Three Mile Is.	Sand - S1
72	Catawba	Sand - S1

Figure 2-1. Procedure to compute probability of exceeding design basis

2. Determination of Controlling Earthquakes

Figure 2-2. Probability of exceeding SSE using median hazard estimates

2.3 Methodology for Estimating Controlling Earthquakes Adopted in RG1.165

2.3.1 Introduction

This section gives the mathematical details for determining the controlling earthquake. The concept behind the methodology to estimate controlling earthquakes is illustrated by the following example. Figures 2-3a and b show total median seismic hazard curves in terms of 5- and 10-Hz spectral velocities. Figures 2-4a and b show deaggregated seismic hazard curves for a set of magnitude and distance intervals. Figure 2-5 shows the contributions of magnitude and distance intervals to the total hazard for the average of 5 and 10 Hz. In this example, the major contributing earthquakes are nearby and of moderate sizes. Thus, in concept, this defines the notion of a controlling earthquake. Mathematically, the controlling earthquakes can be determined using the following equations:

$$\underline{Mc} = \frac{\sum_m \sum_d m H_{md}}{\sum_m \sum_d H_{md}} \quad \text{Ln}(\underline{Dc}) = \frac{\sum_m \sum_d \text{Log}(d) H_{md}}{\sum_m \sum_d H_{md}}$$

where $\underline{Mc}$ and $\underline{Dc}$ are the distance and magnitude values of the controlling event. H_{md} is the average of the seismic hazard values of 5 and 10 Hz for each magnitude and distance interval estimated at ground motion levels for the RP established in Section 2.2.

A software package (Short 1995) implementing the procedure described in this section has been developed for estimating the controlling earthquakes in the central and eastern U.S.

2.3.2 Methodology for Estimating Controlling Earthquakes

This section describes the methodology adopted to determine the controlling earthquakes using probabilistic seismic hazard analysis.

Step 1

A site-specific probabilistic seismic hazard assessment is performed for actual or assumed rock conditions. The median (50th percentile) hazard assessment is performed for spectral accelerations at 1, 2.5, 5, and 10 Hz. A lower-bound magnitude of 5.0 is recommended.

Step 2

Using the RP of 1E-05/yr established in Section 2.2, the ground motion levels for the spectral accelerations at 1, 2.5, 5, and 10 Hz are determined from the total median hazard obtained in Step 1.

The average ground motion level for the 1- and 2.5-Hz and the 5- and 10-Hz spectral acceleration pairs are calculated at the RP level.

Step 3

A complete probabilistic seismic hazard analysis is performed for each magnitude-distance bin described in Table 2.2. These bins were selected for sites in the central and eastern U.S.

2. Determination of Controlling Earthquakes

Figure 2-3a and 2-3b. Total median seismic hazard curves for a site

Figure 2-4a and 2-4b. De-aggregated median seismic hazard curves for a site

2. Determination of Controlling Earthquakes

Clinton 5-10 Hz Rock Outcrop

Figure 2-5. Distribution of the percent contribution to the hazard as a function of magnitude and distance bins for the average of 5-10 Hz hazard curves at the ground motion level corresponding to the RP level of Section 2.2 for the Clinton site

Table 2.2. Recommended magnitude and distance bins

Distance Range of Bin (km)	Magnitude Range of Bin				
	5-5.5	5.5-6	6-6.5	6.5-7	>7
0-15					
15-25					
25-50					
50-100					
100-200					
200-300					
>300					

Step 4

Using the deaggregated median hazard results from Step 3, at the ground motion levels obtained from Step 2, the fractional contributions to the total median hazard of earthquakes in the selected set of magnitude and distance bins for the average of 1 and 2.5 Hz and 5 and 10 Hz are calculated. The median annual probability of exceeding the ground motion levels calculated in Step 2 for each magnitude and distance bin and ground motion measure is denoted by H_{mdf} .

The fractional contribution of each magnitude and distance bin to the total hazard for the average of 1 and 2.5 Hz, $P(m,d)_1$, is computed according to:

$$P(m,d)_1 = \frac{\frac{(\sum_{f=1,2} H_{mdf})}{2}}{\sum_m \sum_d \frac{(\sum_{f=1,2} H_{mdf})}{2}}$$

where $f = 1$ and $f = 2$ represent the ground motion measure at 1 and 2.5 Hz, respectively.

The fractional contribution of each magnitude and distance bin to the total hazard for the average of 5 and 10 Hz, $P(m,d)_2$, is computed according to:

$$P(m,d)_2 = \frac{\frac{(\sum_{f=1,2} H_{mdf})}{2}}{\sum_m \sum_d \frac{(\sum_{f=1,2} H_{mdf})}{2}}$$

where $f = 1$ and $f = 2$ represent the ground motion measure at 5 and 10 Hz, respectively.

Step 5

The magnitude-distance distribution for the average of 1 and 2.5 Hz is reviewed to determine whether the contribution to the hazard for distances of 100 km or greater is substantial. If the contribution of events at distances greater than 100 km exceeds 5%, additional calculations are needed, using the magnitude-distance distribution for distances greater than 100 km, that is,

$P_{>100}(m,d)_1$, to determine the controlling earthquake. This distribution is defined by:

$$P_{>100}(m,d)_1 = \frac{P(m,d)_1}{\sum_m \sum_{d>100} P(m,d)_1}$$

The purpose of this calculation is to identify a distant but larger event which may control low-frequency content of a response spectrum. The distance of 100 km is chosen for sites in the central and eastern U.S. because the controlling earthquakes identified for these distances compare well with past design events (see Section 2.6).

Step 6

The following relation calculates the mean magnitude and distance of the controlling earthquake associated with the ground motion determined in Step 2 for the average of 5 and 10 Hz.

$$M_c(5-10\text{Hz}) = \sum_m m \sum_d P(m,d)_2$$

where m is the central magnitude value for each magnitude bin.

The mean distance of the controlling earthquake is determined as:

$$\text{Ln}\{D_c(5-10\text{Hz})\} = \sum_d \text{Ln}(d) \sum_m P(m,d)_2$$

where d is the centroid distance value for each distance bin.

Step 7

If the contribution to the hazard calculated in Step 5 for distances of 100 km or greater exceeds 5% for the average of 1 and 2.5 Hz, then the mean magnitude and distance of the controlling earthquakes associated with the ground motions determined in Step 2 for the average of 1 and 2.5 Hz are calculated. The following relation is used to calculate the mean magnitude using calculations based on magnitude-distance bins greater than distances of 100 km as discussed in Step 5:

2. Determination of Controlling Earthquakes

$$\underline{Mc}(1 - 2.5\text{Hz}) = \sum_m \sum_{d>100} P > 100(m, d)_1$$

where m is the central magnitude value for each magnitude bin.

The mean distance of the controlling earthquake is based on magnitude-distance bins greater than distances of 100 km as discussed in Step 4 and is determined by:

$$\text{Ln}\{\underline{Dc}(1 - 2.5\text{Hz})\} = \sum_{d>100} \text{Ln}(d) \sum_m P > 100(m, d)_2$$

where d is the centroid distance value for each distance bin.

2.4 Example

To illustrate the procedure in Section 2.3, calculations are shown for an eastern U.S. site using the 1993 LLNL hazard results (Savy et al. 1993). It must be emphasized that the magnitude and distance bins and procedure to establish two controlling earthquakes recommended and used in this example were specifically developed for application in the eastern and central U.S., where the nearby earthquakes generally control the response in the 5- to 10-Hz frequency range; larger, but distant, events controlled the lower-frequency range. For other situations, an alternate binning scheme and a study of contributions from controlling earthquakes are identified consistent with the distribution of the seismicity.

Step 1

The 1993 LLNL seismic hazard methodology is used to determine the hazard at the site. A lower bound magnitude of 5.0 is used in this analysis. The analysis was performed for spectral acceleration at 1, 2.5, 5, and 10 Hz. For this example, we use the Clinton site which is a soil site. As required in Step 1 of Section 2.3.2, we reran the hazard analysis for the Clinton site as a rock site. Figure 2-6 shows the hazard curves for 1, 2.5, 5, and 10 Hz.

Step 2

The hazard curves at 1, 2.5, 5, and 10 Hz obtained in Step 1 are entered with the RP value of $1\text{E-}05/\text{yr}$, as defined in Section 2.2. The corresponding ground motion level values are

given in Table 2.3. In Table 2.4, we give the ground motion levels at the Clinton site at the top of the soil column. We see from the two tables that the soil additions at a site have a significant impact on the estimated ground motion at a site. In Section 3.5, we examine the impact of the choice of requiring that the determination of the controlling earthquake be based on using rock as the base case.

Table 2.3. Ground motion levels at the Clinton site at a hypothetical rock outcrop

Frequency (Hz)	1	2.5	5	10
Spectral Acc. (cm/s/s)	77	169	225	316

Table 2.4. Ground motion levels at the Clinton site at the top of the soil column

Frequency (Hz)	1	2.5	5	10
Spectral Acc. (cm/s/s)	139	373	396	374

The average of the ground motion levels in Table 2.3 at the 1 and 2.5 Hz, $S_{a1-2.5}$, and 5 and 10 Hz, S_{a5-10} , are given in Table 2.5.

Table 2.5. Average ground motion values

$S_{a1-2.5}$ (cm/s/s)	123
S_{a5-10} (cm/s/s)	270

It is useful to note here that the values for spectral acceleration (S_a) given in Tables 2.3 and 2.4 define a uniform hazard acceleration spectra (UHS_a) at an RP of $1\text{E-}05$.

Step 3

A complete probabilistic hazard analysis is performed for each of the magnitude-distance ranges given in Table 2.2 to determine the contribution to the hazard for all earthquakes within each bin. Figure 2-7 shows the median

hazard curves for 1 Hz for magnitude-bin 5.5–6.0 and distance-bins 0–15, 15–25, and 25–50 km. The hazard values corresponding to the ground motion levels found in Table 2.3 of Step 2 are then determined.

For example, for the 1-Hz hazard curves, the value for S_a from Table 2.3 is 77 cm/s/s. This is the vertical line in Figure 2-7. We see from Figure 2-7 that for the magnitude 5.5–6 and distance 0–15 km bin that the contribution to the hazard $H_{mdf} = 1.25 \times 10^{-8}$ and for the 5.5–6 and 15–25 bin $H_{mdf} = 5.2 \times 10^{-9}$.

The hazard values corresponding to the ground motion levels given in Table 2.3 are listed in Tables 2.6–2.9 for 1, 2.5, 5, and 10 Hz, respectively.

It is important to note that because the value in each bin in Tables 2.6–2.9 is the median value of the hazard in each bin, the sum over all bins will not equal the total median hazard plotted in Figure 2-6. However, the mean hazard in each bin does sum to the mean hazard.

Step 4

Using the deaggregated median hazard results, the fraction contribution of each magnitude–distance pair to the total hazard is determined.

Tables 2.10 and 2.11 show $P(m,d)_1$ and $P(m,d)_2$ for the average of 1–2.5 Hz and 5–10 Hz, respectively. Figure 2-5 shows the data given in Table 2.11 and Figure 2-8 shows the data given in Table 2.10. In both figures, the data is plotted percentage of contribution to the hazard.

Step 5

Because the contribution of the distance bins greater than 100 km in Table 2.12 accounts for more than 5% of the total hazard for the average of 1 and 2.5 Hz, the controlling earthquake for the spectral average of 1 and 2.5 Hz will be calculated using magnitude-distance bins for distance greater than 100 km. Table 2.12 shows $P_{>100}(m,d)_1$ for the average of 1 and 2.5 Hz.

2. Determination of Controlling Earthquakes

Total Median Hazard Curves at a Hypothetical Rock Outcrop
1--1 1Hz 2--2 2.5Hz 3--3 5Hz 4--4 10Hz

Figure 2-6. Total median hazard at Clinton at a hypothetical rock outcrop

Median Hazard Curves for 1Hz Mbin 5.5-6.0
 Dbins 1---1 0-15 2---2 15-25 3---3 25-50

Figure 2-7. Median hazard curves for 1-Hz magnitude-bin 5.5-6.0 and distance-bins 1—1, 0-15; 2—2, 15-25; and 3—3, 25-50

Figure 2-8. Distribution of the percent contribution to the hazard as a function of magnitude and distance bins for the average of 1-2.5 Hz hazard curves at the ground motion level corresponding to the RP level of Section 2.2 for the Clinton site

Table 2.6. Median hazard values for spectral accelerations at 1 Hz (79 cm/s/s)

Distance Range of Bin (km)	Magnitude Range of Bin				
	5-5.5	5.5-6	6-6.5	6.5-7	>7
0-15	6.24-9	1.25-8	0	0	0
15-25	1.14-9	5.20-9	0	0	0
25-50	3.72-10	2.17-9	0	0	0
50-100	2.27-11	6.99-10	4.89-10	0	0
100-200	8.19-12	2.46-9	4.02-8	0	0
200-300	0	6.76-11	2.75-9	2.76-10	0
> 300	0	0	2.91-10	1.54-8	1.11-6

Table 2.7. Hazard values for spectral accelerations at 2.5 Hz (169 cm/s/s)

Distance Range of Bin (km)	Magnitude Range of Bin				
	5-5.5	5.5-6	6-6.5	6.5-7	>7
0-15	1.95-7	1.07-7	0	0	0
15-25	6.34-8	7.25-8	0	0	0
25-50	3.15-8	4.86-8	0	0	0
50-100	2.80-9	1.93-8	1.07-8	0	0
100-200	6.72-10	3.01-8	1.96-7	0	0
200-300	2.01-11	5.04-10	6.89-9	2.54-10	0
> 300	0	7.87-13	1.76-10	3.83-9	1.55-7

2. Determination of Controlling Earthquakes

Table 2.8. Hazard values for spectral accelerations at 5 Hz (225 cm/s/s)

Distance Range of Bin (km)	Magnitude Range of Bin				
	5-5.5	5.5-6	6-6.5	6.5-7	>7
0-15	7.01-7	2.42-7	0	0	0
15-25	2.16-7	1.86-7	0	0	0
25-50	8.12-8	1.24-7	0	0	0
50-100	3.30-9	2.89-8	1.20-8	0	0
100-200	1.17-10	1.04-8	9.53-8	0	0
200-300	0	2.77-11	8.54-10	2.28-11	0
> 300	0	0	0	1.35-10	1.56-8

Table 2.9. Hazard values for spectral accelerations at 10 Hz (316 cm/s/s)

Distance Range of Bin (km)	Magnitude Range of Bin				
	5-5.5	5.5-6	6-6.5	6.5-7	>7
0-15	1.39-6	3.94-7	0	0	0
15-25	4.87-7	3.16-7	0	0	0
25-50	1.75-7	2.22-7	0	0	0
50-100	3.48-9	3.15-8	1.39-8	0	0
100-200	3.10-11	3.42-9	3.63-8	0	0
200-300	0	1.33-11	6.44-11	1.57-12	0
> 300	0	0	3.86-14	6.68-12	1.33-9

Table 2.10. $P(m,d)_1$ for average spectral accelerations 1 and 2.5 Hz corresponding to the reference probability

Distance Range of Bin (km)	Magnitude Range of Bin				
	5-5.5	5.5-6	6-6.5	6.5-7	>7
0-15	0.94	0.056	0.000	0.000	0.000
15-25	0.030	0.036	0.000	0.000	0.000
25-50	0.015	0.024	0.000	0.000	0.000
50-100	0.001	0.009	0.005	0.000	0.000
100-200	0.000	0.015	0.110	0.000	0.000
200-300	0.000	0.000	0.005	0.000	0.000
> 300	0.000	0.000	0.000	0.009	0.589

Table 2.11. $P(m,d)_2$ for average spectral accelerations 5-10 Hz corresponding to the reference probability

Distance Range of Bin (km)	Magnitude Range of Bin				
	5-5.5	5.5-6	6-6.5	6.5-7	>7
0-15	0.437	0.133	0.000	0.000	0.000
15-25	0.147	0.105	0.000	0.000	0.000
25-50	0.053	0.072	0.000	0.000	0.000
50-100	0.001	0.013	0.005	0.000	0.000
100-200	0.000	0.003	0.027	0.000	0.000
200-300	0.000	0.000	0.000	0.000	0.000
> 300	0.000	0.000	0.000	0.000	0.004

2. Determination of Controlling Earthquakes

Table 2.12. $P_{>100}(m,d)_1$ for average spectral accelerations 1-2.5 Hz corresponding to the reference probability

Distance Range of Bin (km)	Magnitude Range of Bin				
	5-5.5	5.5-6	6-6.5	6.5-7	>7
100-200	0.000	0.021	0.151	0.000	0.000
200-300	0.000	0.000	0.007	0.000	0.000
> 300	0.000	0.000	0.000	0.012	0.809

Steps 6 and 7

To compute the controlling magnitudes and distances at 1-2.5 Hz and 5-10 Hz for the example site, the values of $P_{>100}(m,d)_1$ and $P(m,d)_2$ are used with m and d values corresponding to the mid-point of the magnitude of the bin (5.25, 5.75, 6.25, 6.75, 7.3) and centroid of the ring area (10, 20.4, 38.9, 77.8, 155.6, 253.3, and somewhat arbitrarily 350 km). Note that the mid-point of the last magnitude bin may change. This value is dependent on the maximum magnitudes used in the hazard analysis.

Table 2.13 gives the controlling earthquake characteristics for this example site.

Table 2.13. Magnitudes and distances of controlling earthquakes from the LLNL probabilistic analysis

1-2.5 Hz	5-10 Hz
Mc and Dc > 100 km	Mc and Dc
7.25 and 304 km	5.45 and 16 km

2.5 Summary of Results of the Controlling Earthquakes

The methodology outlined in Section 2.4 is applied to all the plant sites using the RP developed in Section 2.2. For this purpose, the software package CE-PA (Short 1995) developed during this project was used.

Table 2.14 gives the list of controlling earthquakes for each site. Figure 2-9 shows a plot of the magnitude and distance values of the controlling earthquake. Note that in Table 2.14 the values for the controlling earthquakes for soil sites are given based on local site conditions using the simplified site correction approach used in the LLNL studies (1989, 1993). In these studies, eight soil type categories were defined and each site was placed into the most appropriate category. The soil category is given for each site in Table 2.14. The impact of this is discussed in Sections 3.5 and 4.5.

Also, Table 2.14 lists the average spectral values at 1 and 2.5 Hz and 5 and 10 Hz obtained at the RP $1E-05$ as discussed in Section 2.2.

We found that for the average of 5 and 10 Hz median seismic hazard results, the controlling earthquake characteristics are within the following ranges:

$$5.29 \leq \underline{M_c} \leq 5.77$$

$$12 \text{ km} \leq \underline{D_c} \leq 22 \text{ km}$$

In Table 2.15, we list the sites for which more than 5 percent of the hazard for the average of 1-2.5-Hz hazard curves comes from distances greater than 100 km. We also list the percent contribution to the hazard for distances greater than 100 km and the controlling earthquakes obtained using the approach outlined in Step 5 of Section 2.3.2.

We see from Table 2.15 that 38 sites have a controlling earthquake associated with the average of the 1-2.5-Hz hazard curves. The percent contribution for distances greater than

100 km ranges from 5 to 85 percent. However, we note that only at 5 sites is the percent contribution greater than 50 percent.

RP case RG list of M_c & D_c
average 5-10hz median hazard curve

Figure 2-9. Plot of M_c and D_c given in Table 2.14 for the 69 NPPs in the central and eastern U.S. based on the average of the 5- and 10-Hz hazard curves

2. Determination of Controlling Earthquakes

Table 2.14. Controlling earthquakes for central and eastern U.S. sites

Site	Soil Category	S _a (g) for 10 ⁻⁵		Magnitude and Distance	
		1-2.5 Hz	5-10 Hz	1-2.5 Hz	5-10 Hz
Arkansas	Rock	0.19	0.42	7.4/274	5.7/14
Beaver Valley	Sand-S1	0.09	0.40	6.4/228	5.4/16
Bellefonte	Rock	0.18	0.51	7.5/342	5.7/14
Big Rock Point	Till-T1	0.06	0.28	-	5.4/18
Braidwood	Rock	0.10	0.29	7.4/342	5.5/14
Browns Ferry	Rock	0.18	0.36	7.5/260	5.7/22
Brunswick	Sand-S1	0.16	0.60	6.7/175	5.6/15
Byron	Rock	0.09	0.29	7.4/337	5.5/14
Callaway	Rock	0.16	0.32	7.3/280	5.6/20
Calvert Cliffs	Deep Soil	0.16	0.33	-	5.5/15
Catawba	Rock	0.14	0.42	6.5/206	5.5/13
Clinton	Till-T3	0.26	0.39	7.1/276	5.5/17
Comanche Peak	Rock	0.07	0.19	6.7/254	5.4/17
Cook	Sand-S2	0.13	0.37	7.0/286	5.4/18
Cooper	Sand-S1	0.12	0.53	-	5.4/15
Crystal River	Rock	0.05	0.16	6.5/311	5.3/17
Davis Besse	Rock	0.10	0.32	-	5.5/15
Dresden	Rock	0.10	0.31	7.4/343	5.5/14
Duane Arnold	Rock	0.07	0.20	7.4/333	5.4/17
Farley	Rock	0.08	0.20	6.9/263	5.4/17
Fermi	Rock	0.09	0.28	-	5.5/15
Fitzpatrick	Rock	0.10	0.28	6.2/166	5.5/19
Ft. Calhoun	Sand-S1	0.10	0.46	-	5.5/16
Ginna	Rock	0.10	0.31	6.2/189	5.5/15
Grand Gulf	Deep Soil	0.15	0.21	7.5/348	5.4/16

Table 2.14. Controlling earthquakes for central and eastern U.S. sites, continued

Site	Soil Category	S _a (g) for 10 ⁻⁵		Magnitude and Distance	
		1-2.5 Hz	5-10 Hz	1-2.5 Hz	5-10 Hz
Haddam Neck	Rock	0.14	0.45	-	5.7/14
Hatch	Deep Soil	0.18	0.28	6.7/237	5.5/15
Hope Creek	Deep Soil	0.19	0.39	-	5.6/16
Indian Point	Rock	0.15	0.51	-	5.7/14
Kewaunee	Till-T1	0.07	0.31	-	5.4/18
Lacrosse	Sand-S2	0.11	0.32	7.0/284	5.5/17
Lasalle	Till-T2	0.18	0.40	7.3/331	5.5/14
Limerick	Rock	0.14	0.49	-	5.7/14
Maine Yankee	Rock	0.15	0.48	-	5.8/14
McGuire	Rock	0.13	0.40	6.5/197	5.5/14
Millstone	Rock	0.14	0.46	-	5.7/13
Monticello	Sand-S1	0.07	0.37	-	5.5/17
Nine Mile Pt.	Rock	0.10	0.28	6.2/166	5.5/19
North Anna	Rock	0.12	0.44	-	5.6/15
Oconee	Rock	0.15	0.48	-	5.6/15
Oyster Creek	Deep Soil	0.17	0.34	-	5.6/16
Palisades	Sand-S2	0.12	0.32	6.9/278	5.4/17
Peach Bottom	Rock	0.14	0.49	-	5.7/14
Perry	Rock	0.08	0.27	-	5.5/16
Pilgrim	Sand-S2	0.27	0.86	-	5.6/13
Point Beach	Till-T1	0.07	0.30	-	5.4/18
Prairie Island	Sand-S2	0.09	0.33	-	5.4/17
Quad Cities	Rock	0.08	0.23	7.4/333	5.5/17
River Bend	Deep Soil	0.11	0.17	7.4/337	5.3/17
Robinson	Deep Soil	0.31	0.47	6.7/157	5.6/14

2. Determination of Controlling Earthquakes

Table 2.14. Controlling earthquakes for central and eastern U.S. sites, continued

Site	Soil Category	S _a (g) for 10 ⁻⁵		Magnitude and Distance	
		1-2.5 Hz	5-10 Hz	1-2.5 Hz	5-10 Hz
Salem	Deep Soil	0.18	0.38	-	5.6/16
Seabrook	Rock	0.17	0.57	-	5.8/13
Sequoyah	Rock	0.17	0.53	7.4/336	5.7/13
Shearon Harris	Rock	0.11	0.34	6.4/206	5.5/14
Shoreham	Deep Soil	0.21	0.43	-	5.7/14
South Texas	Deep Soil	0.07	0.17	-	5.4/17
St. Lucie	Deep Soil	0.07	0.15	-	5.3/17
Summer	Rock	0.15	0.45	6.7/164	5.5/13
Surry	Deep soil	0.16	0.31	-	5.5/15
Susquehanna	Rock	0.11	0.37	-	5.6/15
Three Mile Is.	Rock	0.14	0.48	-	5.7/14
Turkey Point	Rock	0.04	0.16	-	5.3/17
Vermont Yankee	Rock	0.15	0.44	6.2/162	5.7/16
Vogtle	Deep soil	0.30	0.44	6.7/156	5.6/16
Waterford	Deep soil	0.10	0.18	7.3/328	5.4/16
Watts Bar	Rock	0.17	0.53	7.3/320	5.7/14
Wolf Creek	Rock	0.08	0.21	7.2/317	5.5/17
Yankee Rowe	Till-T2	0.25	0.58	6.2/162	5.6/14
Zion	Sand-S2	0.14	0.42	7.3/324	5.5/16

Of the 69 sites studied, 38 have a controlling earthquake for an average of 1-2.5 Hz. Table 2.15 gives a list of the sites with the additional controlling earthquakes and the percent contribution to the hazard at the RP for distances greater than 100 km.

Table 2.15. Sites for which contributions of distances greater than 100 km are more than 5%

Site	Soil Category	Distance > 100 km	Controlling Earthquake	
		Percent Contribution	Magnitude	Distance
Arkansas	Rock	59	7.4	274
Beaver Valley	Sand-S1	8	6.4	229
Bellefonte	Rock	18	7.4	342
Big Rock Point	Till-T1			
Braidwood	Rock	21	7.4	343
Browns Ferry	Rock	85	7.5	260
Brunswick	Sand-S1	35	6.7	174
Byron	Rock	8	7.4	339
Callaway	Rock	77	7.3	280
Calvert Cliffs	Deep Soil			
Catawba	Rock	11	6.5	206
Clinton	Till-T3	62	7.1	274
Comanche Peak	Rock	15	6.7	254
Cook	Sand-S2	15	7.0	287
Cooper	Sand-S1			
Crystal River	Rock	5	6.5	311
Davis Besse	Rock			
Dresden	Rock	17	7.4	343
Duane Arnold	Rock	19	7.4	333
Farley	Rock	19	6.9	271
Fermi	Rock			
Fitzpatrick	Rock	33	6.2	166
Ft. Calhoun	Sand-S1			
Ginna	Rock	11	6.2	188
Grand Gulf	Deep Soil	56	7.5	348

2. Determination of Controlling Earthquakes

Table 2.15. Sites for which contributions of distances greater than 100 km are more than 5%, continued

Site	Soil Category	Distance > 100 km		Controlling Earthquake	
		Percent Contribution	Magnitude	Distance	
Haddam Neck	Rock				
Hatch	Deep Soil	20	6.7	237	
Hope Creek	Deep Soil				
Indian Point	Rock				
Kewaunee	Till-T1				
Lacrosse	Sand-S2	6	7.0	284	
Lasalle	Till-T2	11	7.3	332	
Limerick	Rock				
Maine Yankee	Rock				
McGuire	Rock	9	6.5	197	
Millstone	Rock				
Monticello	Sand-S1				
Nine Mile Pt.	Rock	34	6.2	166	
North Anna	Rock				
Oconee	Rock				
Oyster Creek	Deep Soil				
Palisades	Sand-S2	18	6.9	278	
Peach Bottom	Rock				
Perry	Rock				
Pilgrim	Sand-S2				
Point Beach	Till-T1				
Prairie Island	Sand-S2				
Quad Cities	Rock	16	7.4	334	
River Bend	Deep Soil	22	7.4	337	

Table 2.15. Sites for which contributions of distances greater than 100 km are more than 5%, continued

Site	Soil Category	Distance > 100 km	Controlling Earthquake	
		Percent Contribution	Magnitude	Distance
Robinson	Deep Soil	36	6.7	156
Salem	Deep Soil			
Seabrook	Rock			
Sequoyah	Rock	10	7.4	338
Shearon Harris	Rock	15	6.4	206
Shoreham	Deep Soil			
South Texas	Deep Soil			
St. Lucie	Deep Soil			
Summer	Rock	28	6.7	163
Surry	Deep soil			
Susquehanna	Rock			
Three Mile Is.	Rock			
Turkey Point	Rock			
Vermont Yankee	Rock	8	6.2	161
Vogtle	Deep soil	41	6.7	156
Waterford	Deep soil	11	7.3	329
Watts Bar	Rock	8	7.4	336
Wolf Creek	Rock	19	7.3	320
Yankee Rowe	Till-T2	7	6.2	160
Zion	Sand-S2	8	7.3	323

2.6 Comparison with Seismic Criteria of Existing Sites

It is worthwhile to note that the ranges of values of the controlling earthquakes correspond reasonably well with the current set of SSEs.

This comparison is not as simple to make as it would appear—because for most of the sites being studied, the SSE was set at some maximum site intensity (typically a Modified Mercalli Intensity (MMI) of VII or, for a few sites, a MMI of VII to VII and VIII). The distances from the seismic events to the sites used in the determination of the SSEs were not directly specified. The assigned maximum epicentral intensity was converted into a PGA value and this value was then used to scale a standard spectral shape. Later (Bernreuter et al. 1987), it was generally assumed that a distance of about 15 km was appropriate to estimate the ground motion at a site from an event for which the magnitude was given. There is considerable uncertainty in converting an epicentral intensity into a magnitude. Typically (Bernreuter et al. 1987), spectra were developed for intensity VII by using spectra from events with magnitude between 4.75 and 5.75 (centered at magnitude 5.25). Spectra for intensity VIII were developed by using spectra from events with magnitude of 5.75 plus or minus 0.5. All events used in determining spectra were events for which records were observed at distances less than 25 km and with an average distance of about 15 km.

Based on these considerations, we conclude that the range of magnitudes and distances found for the controlling earthquake given in Section 2.5 is in reasonable agreement with the range of magnitudes and distances for the SSEs.

For a few sites in the operating license review process, the actual magnitude of the design event was established¹ and is given in Table 2.16.

We see from Table 2.16 that there is reasonable agreement between the controlling earthquakes and the SSEs. At some sites, the controlling

earthquakes are larger than the SSEs and at other sites the controlling earthquakes are smaller.

It is convenient to delay examining why some of the larger differences exist and what the implications might be until after we have examined the factors that govern the values for the controlling earthquake. We return to the topic in Section 4.8.

2.7 Return Periods of Controlling Earthquakes

It is not possible to provide the range of return periods for the magnitude M_c of the controlling earthquake. If a few strong assumptions are made, then it is possible to make such estimates. However, it is important to keep in mind how the estimates are made to place them in their proper context. First, for most sites, most of the contribution to the median hazard at the RP developed in Section 2.2 comes from the region within 35 km of the site (in fact, much of it is within 15 km of the site).

Secondly, recall that there are 11 seismicity experts in the LLNL study. For each zone, each expert gave a most likely value for the rate of activity with uncertainty bounds. In Figure 2-10 the most likely value for the rate of earthquake recurrence from each expert for a typical site is plotted using the zones within 35 km of the site. There is considerable uncertainty in the estimate of the rate of earthquakes around a site among the experts. In addition (not shown), each expert expressed considerable uncertainty in his estimates. Because M_c and D_c are based on the median hazard obtained by combining the overall values from the experts, it is reasonable to use the median estimate for rate of activity around the site. This estimate is given in Figure 2-11 by the curve labeled m—m. The curve labeled a—a is the average of the most likely estimate by each expert. The upper (U) and lower (L) bounds are also shown.

Using the above process at each site, it is possible to obtain an estimate for the return period of M_c , which varies from 512,000 years to 10,400 years. In Figure 2-12 the return period of M_c is plotted. If one removes the sites with the $M_c < 5.4$ (sites

¹ Rothman, R.L. 1993. Private Communication.

with low seismic activity around them, which had the minimum fixed acceptable ground motion level assigned to them) then there appears to be little correlation between the return period and $\underline{M}_c$. And given how $\underline{M}_c$ is obtained, there is no reason to expect any correlation between $\underline{M}_c$ and the return period.

In Figure 2-13, $\underline{M}_c$ versus the rate of $M \geq 5.25$ is plotted. Note that the rate is obtained as outlined

above based on the zones within 35 km of each site. Figure 2-13 shows that there is a reasonable degree of correlation between $\underline{M}_c$ and rate of activity around the sites. As expected, the larger numbers for $\underline{M}_c$ are for sites with the highest rate. There is also considerable scatter to the above correlation. The reasons for this scatter are discussed in Sections 3 and 4.

Table 2.16. Comparison of controlling earthquakes to SSEs established at existing sites at operating license review period by NRC Staff

Site	Controlling Earthquakes		SSEs Established at Operating License Review	
	Magnitude	Distance	Magnitude	Distance
Beaver Valley	5.4	16	5.0	15
Bellefonte	5.7	16	5.8	15
Braidwood	5.5	14	5.8	15
Byron	5.5	14	5.8	15
Callaway	5.6	20	5.5	15
	7.3	280	7.3	250
Catawba	5.5	13	5.3	15
Clinton	5.5	17	5.8	15
Fermi	5.5	15	5.3	15
Oyster Creek	5.6	16	5.3	15
Perry	5.5	16	5.3	15
River Bend	5.3	17	4.8	15
	7.4	337	7.3	370
Seabrook	5.8	13	6	15
Sequoyah	5.7	13	5.8	15
Watts Bar	5.7	14	5.8	15

2. Determination of Controlling Earthquakes

Figure 2-10. Most likely yearly recurrence model for earthquakes for a typical site for each of the 11 LLNL seismicity experts based on the zones within 35 km of a site

Figure 2-11. Composite recurrence model for the rate of activity based on the most likely models of the eleven LLNL experts shown in Figure 2-10

a— a = average model
m— m = median model
U— U = upper bound expert
L— L = lower bound expert

2. Determination of Controlling Earthquakes

Figure 2-12. Plot of M_c based on the average of 5-10Hz versus return period for the sites given in Table 2.14. Return period is based on the most likely composite recurrence model for all zones within 35 km of each site.

Figure 2-13. Plot of M_c versus rate of $M \geq 5.25$ earthquakes for the sites given in Table 2.14. Rate of $M \geq 5.25$ is based on the most likely composite recurrence model for all zones within 35 km of each site.

3. ISSUES IN DETERMINING CONTROLLING EARTHQUAKES

3.1 Ground Motion Parameter

Selecting the most appropriate ground motion measure (GMM) to use to establish CEs received considerable discussion at the meetings with the EG. Based on the review of many studies, both the NRC Staff and the EG selected the average of the 5-Hz and 10-Hz spectral velocity hazard curves of the most appropriate Ground Motion Model (GMM) to use to establish the CEs.

To assess the implication of this judgmental choice for GMM, the impact of also using peak ground acceleration (PGA) and the average of 1-Hz and 2.5-Hz hazard curves to determine the CEs was examined. In general, both the $\underline{M}_c$ and $\underline{D}_c$, based on the average of 5 and 10 Hz, were either slightly larger or the same as the $\underline{M}_c$ and $\underline{D}_c$ based on the PGA hazard curves; the hazard surfaces were similar. Thus, no new useful information is gained by computing the CEs based on the PGA hazard curves.

Section 2.5 noted that at 38 sites, for the average of 1–2.5-Hz hazard curves, the magnitude and distance bins greater than 100 km contributed more than 5% of the total hazard. Thus, for these sites, the hazard surface for the average of 1–2.5 Hz case provides useful information. Thus, the methodology given in Section 2.3 includes checking the average of the 1–2.5 Hz hazard and the hazard surface to see if the $\underline{M}_c$, $\underline{D}_c$, for $D > 100$ km is needed.

Figures 3-1, 3-2, and 3-3 show typical hazard surfaces for three cases. Fig. 3-1 shows the hazard surface for the average of 5–10-Hz hazard curves at a ground motion level corresponding to the RP established in Section 2.2. This distribution is typical for most sites for the average of the 5–10-Hz hazard curves. However, as noted above, for the average of the 1–2.5-Hz hazard curves, two cases occur. For sites located sufficiently far from zones like the New Madrid or Charleston source zones (zones characterized by high rates and larger upper bound magnitude M_u), the contribution of distant large events is small and we get a hazard surface similar to Figure 3-2. This

hazard surface is similar to the hazard surface for the average of 5–10-Hz shown in Figure 3-1. However, as noted in Table 2.15, at 38 sites there is significant contribution from large distant earthquakes. We see from Table 2.15 that the contribution for distance bins greater than 100 km ranges from 5 to 85 percent of the hazard at the selected RP. Thus, there is no typical case for the hazard surface for the average of 1–2.5-Hz when distant earthquakes become significant. Figure 2-8 shows a case where large distant earthquakes are very important and Figure 3-3 shows a case where earthquakes in the 100–200 km bin are important.

3.2 Sensitivity of $\underline{M}_c$ and $\underline{D}_c$ to the Reference Probability

In Section 2.2, the process for selecting the RP of exceedance level used to establish the CEs was described. As discussed in Section 2.2, the criteria used was to develop the RP of exceedance from the sites with "modern design," i.e., the sites whose SSE spectra shape was either an RG1.60 shape or a Newmark-Hall shape. Certainly, a number of other choices could have been made. This issue received considerable discussion at the EG meetings. In order to assist the EG and NRC Staff in making the appropriate choice for the RP, the $\underline{M}_c$ and $\underline{D}_c$ for several different choices of RP were computed (see Table 3.1).

The RP level labeled ALL was selected in a similar manner as described in Section 2, except that all the sites were used to form the cumulative distribution of the probability of exceeding the SSE. Cases CP1 and CP0 are bounding choices.

Table 3.1 gives the range for $\underline{M}_c$ and $\underline{D}_c$ for all sites. Taking the RP level $1E-05$ as the base case, referred to as case RG, Table 3.1 also gives the maximum difference at any site between the $\underline{M}_c$ s ($\Delta \underline{M}_c$) and $\underline{D}_c$ s ($\Delta \underline{D}_c$) for each case. In addition, the table shows the median values for $\Delta \underline{M}_c$ and $\Delta \underline{D}_c$ for each case.

Table 3.1 shows that the RP level does not have a significant impact on $\underline{M}_c$. For example, the maximum $\Delta \underline{M}_c$ difference at any site between RP cases RG and ALL is 0.12 units; the median value of $\Delta \underline{M}_c$ (for this, the absolute values of ΔM were

3. Issues in Determining Controlling Earthquakes

used) is 0.01 units. There is more of an impact on Dc.

It is interesting to examine what happens to the Mc and Dc values at the two extreme cases CP1 and CP0. Figure 3-4 shows how the Mc and Dc changed between RP case RG and CP1 and Figure 3-5 shows how they changed between RP case RG and CP0.

Figure 3-4 shows that for all sites, the Dc is smaller for case CP1 than for case RG and Figure 3-5 shows that Dc is larger for case CP0 than case RG. Generally, Mc is somewhat larger for case CP1 than for case RG; however, at four sites, Mc is smaller for case CP1 than case RG. At two of the four sites, the difference is only 0.01 units. At two sites, Browns Ferry $\Delta Mc = 0.11$ larger for case RG than for case CP1 and Callaway $\Delta Mc = 0.08$ larger for case RG than for case CP1.

The change in Mc is a bit more mixed between cases RG and CP0. The largest changes in Mc are for the Browns Ferry and the Callaway sites.

In general, as the RP becomes larger, UHS_a values become smaller and the more distant distance bins and the larger magnitude bins contribute more to the hazard. Hence, Dc becomes larger and in some cases Mc becomes larger. As RP becomes smaller, then Dc becomes smaller. How Mc varies depends on the relative distribution of earthquakes around a site. Table 3.2 illustrates this point. Table 3.2 gives the percent contribution to the total hazard for each magnitude and distance bin for two sites (Seabrook and Browns Ferry) for the three RP cases: CP1, RG and CP0. Also, the Mc and Dc are given as well as the Mc and Dc based only on the distance bins less than 100 km. Table 3.2 shows that for the Seabrook site, Mc is largest for case CP1 and smallest for case CP0, whereas at the Browns Ferry site, for cases RG and CP0 the larger distance and magnitude bins become more important at lower ground motion levels, and hence Mc increases for cases RG and CP0.

It is worthwhile to note that certainly for RP case CP0 for the Browns Ferry site, basing Mc and Dc on all bins is not a good measure of Mc and Dc. Clearly one would want to compute Mc and Dc

for less than 100 km and greater than 100 km. Table 3.2 shows that Mc based on distance less than 100 km remains approximately the same.

To help understand why the percent contribution to the total hazard for different RP levels varies in Table 3.2, it is useful to examine how the rate of activity varies around the two sites. Table 3.3 gives the median activity rate on a yearly basis for each magnitude and distance bin for Seabrook and Browns Ferry.

Table 3.3 shows that the seismic activity at close distance around the Seabrook site is much higher than for the Browns Ferry site, but at large distances the activity around Browns Ferry is much higher than around Seabrook.

3.3 Alternative Techniques to Determine Controlling Earthquakes

3.3.1 Mean Hazard Results

The procedure for determining the controlling earthquakes given in Section 2.3 uses the median hazard curve. Theoretically, it might be better to use the mean hazard curve. The mean hazard curve was rejected for two reasons. First, the mean hazard surface at any RP level is generally much flatter than the median hazard surface, resulting in ambiguity as to the appropriate Mc and Dc. A typical case is shown in Figure 3-6. This figure gives the mean for the Seabrook site. It's difficult to attach any useful interpretation to an Mc, Dc based on the surface shown in Figure 3-6 as contrasted to Figure 3-1. The hazard surfaces shown are typical for most sites at the RP level, RG.

The second reason why Mc and Dc, based on the mean hazard curve, were not used is because the resultant set of Mc and Dc are significantly different than the current set of SSEs for the existing NPP. Figure 3-7 shows the range of Mc and Dc for the RP case RG for the median and mean hazard curves.

Figure 3-7 shows that for the mean hazard curve case the Dc's are large: $20 < Dc < 70$. These values are much different than the distances for most SSEs (see Section 2.6). Figure 3-7 also shows that Mc > 5.6, which is larger than the magnitude of

the SSEs at many sites. On the other hand, the range of $\underline{M}_c$ and $\underline{D}_c$ based on the median hazard curve is in general agreement with the current set of SSEs (see Section 2.6).

3.3.2 Hazard Surface

One could use the relative maximum of the hazard surface for a given RP to select $\underline{M}_c$ and $\underline{D}_c$. However, as can be seen from Figure 3-1, more than one magnitude and distance bin contributes significantly to the hazard. Thus, it is not clear how to include this information in the assessment of $\underline{M}_c$ and $\underline{D}_c$. One approach would be to take $\underline{M}_c$ and $\underline{D}_c$ as the bin with the highest contribution. This would generally lead to slightly smaller $\underline{M}_c$ s than obtained using the procedure outlined in Section 2.3. One could also select the $\underline{M}_c$, $\underline{D}_c$ for the bin giving the largest ground motion at the site provided that the bin contributed more than "x" percent of the hazard at the target ground motion level. The question here is how to select the appropriate value for "x."

The hazard surfaces for all the sites at $RP = 1E-05$ were examined. For the median hazard curve, it was found that the surfaces all had one M, D bin which made the largest contribution. This ranged between a high of 48 percent to a low of 27 percent. The average for all sites is 36 percent. The second highest bin ranged between 35 percent to 14 percent with an average value of 23 percent. In view of this, the EG and NRC Staff determined that it would be better to use the procedure given in Section 2.3 (averaging the nearby bins) than to develop a rule for selecting the appropriate value for $\underline{M}_c$ and $\underline{D}_c$ based on either selecting (1) the bin with the maximum contribution or (2) the bin which contributes at least "x" percent to the hazard and using the M, D values of the bin to determine which choice leads to the maximum ground motion at the site.

3.4 Selection of Parameters in the Deaggregation Process

3.4.1 Magnitude and Distance Intervals

In Bernreuter et al. (1989), the contribution to the hazard for different magnitude intervals (over all distances) and different distance intervals (over all magnitudes) was investigated. Using these

results, the matrix of magnitude and distance given in Table 3.4 was initially selected as a starting point to use to deaggregate the hazard at all of the sites and compute $\underline{M}_c$ and $\underline{D}_c$. It was found that the first distance bin contributed significantly to the hazard at all sites. It was also found that for a number of sites, the distance bins greater than 100 km were important for the average of 1- and 2.5-Hz hazard curves for large magnitude events. Based on these findings, the matrix of magnitude and distances in Table 3.4 was replaced with the set given in Table 3.5. Sensitivity analyses were conducted to assess the choice of the set of discrete magnitude pairs on the controlling earthquake. Table 3.6 summarizes the results of this analysis. Two cases were examined. For Case 1, Table 3.4, 16 bins were used, consisting of 4 magnitude and 4 distance bins. For Case 2, Table 3.5, 35 bins were used, consisting of 5 magnitude and 7 distance bins. Although small changes are observed in the evaluation of magnitudes, the choice of discrete sets of magnitude-distance pairs mainly impacts the distance estimates.

The above results are generally acceptable; however, for some sites, added bins—e.g., more bins greater than 300 km—might be useful to get a better understanding of the most significant zones.

3.4.2 Geometric Versus Arithmetic Mean Calculation for $\underline{D}_c$

In the methodology outlined in Section 2.3, $\underline{D}_c$ is computed as a geometric mean rather than as an arithmetic mean. This choice was made primarily because the magnitude is a log measure; distance should be treated in the same manner. The choice is a bit arbitrary; hence, the impact of this choice on the resultant $\underline{D}_c$ was investigated. In Figure 3-8, $\underline{M}_c$, $\underline{D}_c$ were plotted for the following:

(1) when $\underline{D}_c$ is computed by the equation given in Section 2.3 by taking the log (d) and (2) when $\underline{D}_c$ is computed by the following relation:

$$\underline{D}_{ac} = \frac{\sum_m \sum_d d H_{md}}{\sum_m \sum_d H_{md}}$$

3. Issues in Determining Controlling Earthquakes

In Figure 3-8, we plot $\underline{M_c}$ versus $\underline{D_c}$ and $\underline{D_{ac}}$. We see from this figure that $\underline{D_{ac}} > \underline{D_c}$.

On the average, $\underline{D_{ac}}$ is 3.9 km larger than $\underline{D_c}$. The range for $\underline{D_{ac}}$ is $14.5 < \underline{D_{ac}} \leq 42.5$.

The geometric average method of computing $\underline{D_c}$ was adopted by NRC because, as discussed in Sections 2.6 and 4.8, the resultant $\underline{D_c}$ for the sites is in better agreement with the current set of SSEs from the existing NPP than using $\underline{D_{ac}}$.

3.5 Selection of Site Condition

The methodology in Section 2.3 specifies that the controlling earthquake be determined for actual or assumed rock conditions, i.e., at some hypothetical rock outcrop. Corrections for local soil conditions are to be applied to rock spectrum for the controlling earthquake. The issue here is how much impact this approach would have on the magnitudes and distances of the controlling earthquakes.

To explore the significance of this choice, we computed the controlling earthquakes at five sites both as a rock site and as a soil site. These sites were selected to cover a range of soil conditions and regional seismological conditions. The sites reflected along with the site soil condition and a note relative to the regional seismology conditions are given in Table 3.7. In Table 3.8, we give the results of our analysis for the controlling earthquakes for the average of 5-10-Hz and 1-2.5-Hz cases for both rock and site conditions given in Table 3.7.

We see from Table 3.8 that the change in either $\underline{M_c}$ or $\underline{D_c}$ due to change in site conditions is very small. This is not to say that site conditions are not important. The site type has a significant

impact on the spectral velocities. Because the site amplification effect is so important, the choice was made to determine $\underline{M_c}$ and $\underline{D_c}$ for a rock site, convert this to a rock motion as outlined in RG1.165 or in Section 6 of this report, and then perform a very detailed site amplification analysis to determine the SSE motion.

The effect of site conditions is also discussed further in Section 4.5.

3.6 Stability of the Results Using LLNL and EPRI Seismic Hazard Methodology

If the values for the controlling earthquakes at various sites differed significantly between the LLNL and EPRI methodologies, then the approach would lose much of its usefulness. It is to be expected that at some sites there will be differences but on the average the $\underline{M_c}$ and $\underline{D_c}$ should be in reasonable agreement.

Nuclear Management and Resource Council (NUMARC) provided an estimate for the $\underline{M_c}$ s and $\underline{D_c}$ s for the 16 sites listed in Table 3.9 based on the average of the 5- and 10-Hz hazard curves at a PE level of $1E-05$ for the EPRI hazard. In Table 3.9 we also give the values for $\underline{M_c}$ s and $\underline{D_c}$ s obtained as part of this study. Both sets of results are based on the binning given in Table 3.5.

For the 16 sites listed in Table 3.9, $(\underline{M_c})_{av}=5.49$ for EPRI results and 5.58 for the LLNL results.

The two studies report some differences at individual sites—and this is to be expected. However, on the average, the results for $\underline{M_c}$ s and $\underline{D_c}$ s are in reasonable agreement between the two studies.

Table 3.1. Effect of RP level on $\underline{M_c}$ and $\underline{D_c}$ based on the average of 5- and 10-Hz hazard curves

RP Level	Case Name	Range for $\underline{M_c}$	Range for $\underline{D_c}$	Max ΔM	Med ΔM	Max ΔD	Med ΔD
1E-05	RG	5.3< $\underline{M_c}$ <5.8	12< $\underline{D_c}$ <22	-	-	-	-
2.4E-05	All	5.3< $\underline{M_c}$ <5.8	14< $\underline{D_c}$ <30	0.12	0.01	9.4	3.3
1E-06	CP1	5.3< $\underline{M_c}$ <5.9	10< $\underline{D_c}$ <14	0.15	0.06	8.6	3.7
1E-04	CP0	5.3< $\underline{M_c}$ <6.1	18< $\underline{D_c}$ <57	0.39	0.03	36	14.6

Table 3.2. Percent contribution to the hazard for distance and magnitude bins for three RP cases—Seabrook and Browns Ferry sites

dist	Seabrook					Browns Ferry				
	RP case CP1									
	5.25	5.75	6.25	6.75	7.50	5.25	5.75	6.25	6.75	7.50
10.0	9.9	47.2	29.6	0.0	0.0	32.7	39.1	0.0	0.0	0.0
20.0	0.1	5.6	6.0	0.0	0.0	4.5	12.5	0.0	0.0	0.0
39.0	0.0	0.5	1.1	0.0	0.0	1.0	4.4	2.9	0.0	0.0
78.0	0.0	0.0	0.1	0.0	0.0	0.0	0.4	0.7	0.0	0.0
155.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
253.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.8
350.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

 $\underline{M_c}$ & $\underline{D_c}$ for Dbins <100 km $\underline{M_c}$ = 5.88 $\underline{D_c}$ = 11.1 $\underline{M_c}$ = 5.57 $\underline{D_c}$ = 12.9 $\underline{M_c}$ and $\underline{D_c}$ for all M and D bins $\underline{M_c}$ = 5.88 $\underline{D_c}$ = 11.1 $\underline{M_c}$ = 5.61 $\underline{D_c}$ = 13.7

3. Issues in Determining Controlling Earthquakes

RP case RG

dist	5.25	5.75	6.25	6.75	7.50	5.25	5.75	6.25	6.75	7.50
10.0	18.8	40.0	13.1	0.0	0.0	27.9	18.2	0.0	0.0	0.0
20.0	2.2	10.2	6.8	0.0	0.0	9.6	12.6	0.0	0.0	0.0
39.0	0.3	3.6	4.4	0.0	0.0	4.3	11.0	3.0	0.0	0.0
78.0	0.0	0.1	0.5	0.0	0.0	0.2	2.0	1.9	0.0	0.0
155.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.0	0.0
253.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	8.6
350.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1

Mc & Dc for Dbins <100km Mc = 5.77 Dc = 12.9

Mc & Dc - for all M and Dbins Mc = 5.77 Dc = 12.9

Mc = 5.55 Dc = 17.1

Mc = 5.72 Dc = 21.9

RP case CP0

dist	5.25	5.75	6.25	6.75	7.50	5.25	5.75	6.25	6.75	7.50
10.01	25.3	18.1	3.1	0.0	0.0	11.9	4.4	0.0	0.0	0.0
20.01	8.9	13.0	3.5	0.0	0.0	9.8	6.3	0.0	0.0	0.0
39.01	3.4	12.3	6.2	0.0	0.0	10.3	13.4	1.7	0.0	0.0
78.01	0.2	2.1	3.5	0.0	0.0	1.7	6.5	3.0	0.0	0.0
155.01	0.0	0.1	0.3	0.0	0.0	0.0	0.5	0.9	0.0	0.0
253.31	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	2.2	25.9
350.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1

Mc & Dc for Dbins <100 km Mc = 5.64 Dc = 18.1

Mc & Dc for all M and D bins Mc = 5.64 Dc = 18.3

Mc = 5.54 Dc = 27.1

Mc = 6.11 Dc = 53.8

Table 3.3. Seabrook: median rate of EQ occurrence

	5.25	5.75	6.25	6.75	7.25
10.0	.615E-04	.150E-04	.115E-05	.000E+00	.000E+00
20.4	.118E-03	.251E-04	.215E-05	.000E+00	.000E+00
38.9	.501E-03	.123E-03	.100E-04	.000E+00	.000E+00
77.8	.199E-02	.449E-03	.379E-04	.000E+00	.000E+00
155.6	.379E-02	.780E-03	.911E-04	.000E+00	.000E+00
253.3	.625E-02	.118E-02	.818E-04	.282E-06	.000E+00
350.0	.877E-01	.225E-01	.553E-02	.823E-03	.101E-04

Browns Ferry

	5.25	5.75	6.25	6.75	7.25
10.0	.546E-05	.320E-06	.000E+00	.000E+00	.000E+00
20.4	.275E-04	.129E-05	.000E+00	.000E+00	.000E+00
38.9	.163E-03	.304E-04	.205E-05	.000E+00	.000E+00
77.8	.625E-03	.129E-03	.155E-04	.000E+00	.000E+00
155.6	.347E-02	.689E-03	.984E-04	.000E+00	.000E+00
253.3	.327E-01	.132E-01	.402E-02	.105E-02	.1266E-03
350.0	.107E+00	.262E-01	.659E-02	.172E-02	.185E-03

Table 3.4. Matrix of distances and magnitude bins suggested in RG1.165: 16 bins total

Distance (km)	Magnitude			
	5 to 5.5	5.5 to 6	6 to 6.5	>6.5
0 - 25				
25 - 50				
50 - 100				
>100				

3. Issues in Determining Controlling Earthquakes

Table 3.5. Matrix of distances and magnitude bins currently recommended: 35 bins total

Distance (km)	Magnitude				
	5 to 5.5	5.5 to 6	6 to 6.5	6.5 to 7	>7
0 - 15					
15 - 25					
25 - 50					
50 - 100					
100 - 200					
200 - 300					
>300					

Table 3.6. Estimates of controlling earthquakes

Site No.	Controlling Earthquake (Case 1)		Controlling Earthquake (Case 2)	
	Case 1: Magnitude: 5-5.5, 5.5-6.0, 6.0-6.5, >6.5 Distance : 0-25, 25-50, 50-100, >100		Case 2: Magnitude: 5-5.5, 5.5-6.0, 6.0-6.5, 6.5-7.0, >7.0 Distance : 0-15, 15-25, 25-50, 50-100, 100-200, 200-300, >300	
	Magnitude	Distance (km)	Magnitude	Distance (km)
1	5.7	23	5.7	19
2	5.8	18	5.7	13
3	5.8	18	5.8	14
4	5.5	19	5.5	15
5	5.7	19	5.7	14
6	5.6	18	5.6	14
7	5.5	20	5.5	16
8	5.5	21	5.5	18

Table 3.7. Sites selected to study impact of soil type on the controlling earthquake

Site	Soil Type	Local Seismological Conditions
Clinton	Shallow	Site nearest to New Madrid seismic zone
Pilgrim	Shallow	Located in high seismicity area
River Bend	Deep soil	Located in very low seismicity area
Robinson	Deep soil	Located near Charleston region
Salem	Deep soil	Located in moderate seismicity region
Vogtle	Deep soil	Site nearest to Charleston region

Table 3.8. Controlling earthquakes calculated for the sites listed in Table 3.7. For both soil and rock conditions for the average of 5-10-Hz and 1-2.5-Hz cases.

Site	5-10-Hz				1-2.5-Hz			
	Soil		Rock		Soil		Rock	
Clinton	5.5	17	5.5	16	7.1	276	7.25	304
Pilgrim	5.6	13	5.7	13	None		None	
River Bend	5.3	17	5.4	16	7.4	339	7.4	338
Robinson	5.6	14	5.7	14	6.7	157	6.7	157
Salem	5.6	16	5.6	16	None		None	
Vogtle	5.6	16	5.7	17	6.7	156	6.7	156

3. Issues in Determining Controlling Earthquakes

Table 3.9. Comparison of $\underline{M}_c$ s and $\underline{D}_c$ s based on the average of the 5–10Hz hazard curves at RP=1.–05 using the LLNL and EPRI results

Site	LLNL		EPRI	
	$\underline{M}_c$	$\underline{D}_c$	$\underline{M}_c$	$\underline{D}_c$
Bellefonte	5.7	14	5.4	13
Braidwood	5.5	14	5.3	14
Callaway	5.6	20	5.5	20
Clinton	5.5	17	5.3	13
Comanche Peak	5.4	17	5.3	28
Hope Creek	5.6	16	5.6	13
Limerick	5.7	14	5.7	14
Maine Yankee	5.8	14	5.8	12
Nine Mile Point	5.5	19	5.3	15
Perry	5.5	16	5.3	13
River Bend	5.3	17	5.3	17
Seabrook	5.8	13	5.9	13
Shearon Harris	5.5	14	5.4	16
Vogtle	5.6	16	5.9	16
Watts Bar	5.7	14	5.6	13
Wolf Creek	5.5	17	5.4	15

Figure 3-1. Typical distribution of percent contribution to the total hazard as a function of magnitude and distance bins for the average of the 5-10-Hz hazard curves at the ground motion level corresponding to the RP selected in Section 2.2

3. Issues in Determining Controlling Earthquakes

Figure 3-2. Distribution of the percent contribution to the hazard as a function of the magnitude and distance bins for the average of 1–2.5-Hz hazard curves at the ground motion level corresponding to RP level of Section 2.2 for the Seabrook site

Figure 3-3. Distribution of the percent contribution to the hazard as a function of magnitude and distance bins for the average of 1-2.5-Hz hazard curves at the ground motion level corresponding to the RP level of Section 2.2 for the 1-2.5-Hz Clinton site. For this site, the figure shows the need for an M_c and D_c for the 1-2.5-Hz case.

change in M_c & D_c between RP RG2 & CP1
x RG2 0 CP1

Figure 3-4. Change in M_c and D_c between case RG and case CP1

Figure 3-5. Change in M_c and D_c between case RG and case CP0

Figure 3-6. Mean hazard surface for the average of 5-10-Hz hazard curves for the Seabrook site at the ground motion level corresponding to the RP level RG

M&Dbars MEDIAN & MEAN based on RG2 5-10hz total hazard

X--X MEDIAN

O--O MEAN

Figure 3-7. Comparison of Mc and Dc for RP level RG average of 5-10-Hz median and mean hazard curves

3. Issues in Determining Controlling Earthquakes

Figure 3-8. Comparison of $\bar{M}_c$ and $\bar{D}_c$ based on the average of 5-10 Hz hazard curves for RP case RG between $\bar{D}_c$ computed as a geometric average and an arithmetic average

4. INTERPRETATION OF CONTROLLING EARTHQUAKES

4.1 Introduction

Section 2.5 showed that the range for $\underline{M}_c$ and $\underline{D}_c$ is relatively small. Section 2.6 showed that the range for both $\underline{M}_c$ and $\underline{D}_c$ is consistent with the current set of SSEs. For the sites for which there is an $\underline{M}_c$ and $\underline{D}_c$ for the average of 1–2.5 Hz, the computed $\underline{M}_c$, $\underline{D}_c$ make physical sense and are consistent with the regional geology and seismology. However, it is interesting to examine how $\underline{M}_c$ and $\underline{D}_c$ vary as a function of such parameters as M_u , rate of activity around a site, choice of ground motion models, and lower bound used for magnitude.

Because of the large intra-expert uncertainty (see Figure 2-6, for example) it is difficult to assess the impact of any of the above-mentioned parameters by using the actual models provided by the LLNL experts. So in this section, simple models consistent with the range of inputs provided by the LLNL experts are employed. Section 4.2 summarizes the range of inputs provided by the LLNL experts.

4.2 Range of Rates and Upper Bound Magnitude of LLNL Seismicity Experts

Each of the eleven seismicity experts involved in the LLNL study provided a set of source zones, recommended models, estimates for the upper bound magnitude and a complete description of the uncertainty for each of their source zones. This data is compiled in the tables in Bernreuter et al. (1989) and updated values in Savy et al. (1993). These tables—while of considerable interest—are somewhat difficult to use. In this section, a simpler summary of the inputs—as they impact each site of the existing 69 NPP sites in the central and eastern United States—are provided.

Section 2.5 notes that, for most sites, the major contribution to the average of 5- and 10-Hz median hazard at the RP selected in Section 2.2 comes from the zones within 35 km of each site. Figure 2-10 shows how the preferred value varied

among each of the eleven LLNL seismicity experts for the rate of earthquakes around a typical site. Figure 2-11 summarizes this information by showing the upper and lower bounds, the median and the average rate curves. Because at least one of the LLNL seismicity experts had $M_u \geq 7.5$ for the zones around each site, the M_u for the average rate for each site was at least 7.5.

Table 4.1 gives, for zones within 35 km of each site, the 18th percentile (second lowest expert), the median, and the 82nd percentile estimate for M_u . For the 82nd percentile, eight of the eleven experts had a lower estimate for this preferred estimate for M_u , and two of the eleven had a higher estimate. The median estimate for the rate of $M \geq 5$ for the zones within 35 km of each site is also given.

Table 4.2 summarizes the results for all sites.

4.3 Effect of M_u , b-value, and Rate on $\underline{M}_c$ and $\underline{D}_c$

To help understand how M_u , b-value, and rate impact the computed $\underline{M}_c$ and $\underline{D}_c$, a simple case of a site located in a large zone was examined. For the base case, the rate for the zone was selected such that approximately 1/3 of the NPP sites in the central and eastern United States would have a higher rate in a 35 km region around the sites for $M \geq 5$ events and 2/3 of the NPP sites would have a lower rate for $M \geq 5$ events. The rate for $M \geq 5$ events within a 35 km region around the site is $2.69E-04$ events per year. The b-value was somewhat arbitrarily taken = -1.0.

To reduce the effect of uncertainty, there is only one ground motion model. The model was selected by Ground Motion Experts as discussed in Bernreuter et al. (1989). The model is similar to the Boore-Atkinson (1987) model. In Section 4.7, the sensitivity of $\underline{M}_c$ and $\underline{D}_c$ to the choice in the ground motion model used is explored.

Section 3.2 notes that $\underline{M}_c$ and $\underline{D}_c$ vary with choice of RP used. Because both the rate of activity and the ground motion model used are similar to the rates and ground motion model used in Bernreuter et al. (1989) and Savy et al. (1993),

the use of RP in the range of $1\text{E-}04$ to $1\text{E-}06$ seems appropriate to use to compare the results of the 1-Zone model to the results for the actual sites.

Section 4.2 states that the range of the median estimate for M_U was $5.75 \leq M_U \leq 6.5$ with only one site at the 5.75 level. The $\underline{M}_c$, $\underline{D}_c$ for values of $M_U = 6, 6.25, 6.5$, and 7.25 were computed.

$M_U = 7.25$ was used to see how $\underline{M}_c$ might vary for a site located in a region where most of the seismicity experts thought a large earthquake could occur. The results are given in Table 4.3.

Note that in computing the $\underline{M}_c$ and $\underline{D}_c$ in Table 4.2 and other tables where the 1-Zone model is involved, a value of 7.25 was used for the mid-magnitude of the last magnitude bins rather than 7.5 that was suggested in Section 2 and used for the 69 sites. We made this change because for the 1-Zone model, M_U ranged between 7 and 7.50 with the best estimate of 7.25.

Table 4.3 shows that for any of the three RP levels used, $\underline{M}_c$ increases as M_U increases. As M_U becomes large, the effect of the choice of RP has more impact on $\underline{M}_c$. For example, at $M_U = 6$, changing RP from $1\text{E-}04$ to $1\text{E-}06$ only changes $\underline{M}_c$ by 0.08 units whereas at $M_U = 6.5$, $\underline{M}_c$ changes by 0.2 units and at $M_U = 7.25$, $\underline{M}_c$ changes by 0.4 units. Clearly, M_U is an important parameter.

Figure 4-1 plots, for each of the 69 NPP sites, $\underline{M}_c$ versus the median value of M_U given in Table 4.1. Figure 4-1 also shows the values from Table 4.3. Figure 4-1 shows that there is some correlation between M_U and $\underline{M}_c$ —but clearly, other parameters are also very important.

Figure 4-1 also indicates the $\underline{M}_c$ and M_U for a few sites. They were chosen to illustrate why, for a given M_U , the $\underline{M}_c$ can vary so much between sites.

First, the difference between the $\underline{M}_c$ for the 1-Zone model and the Seabrook Site (the NPP with the largest $\underline{M}_c$), is examined at an RP of $1\text{E-}05$. The median rate for $M \geq 5$ for the region around the Seabrook site is more than a factor of two higher than that used for the single zone case.

However, the “effective b-value” of the recurrence relationship for the 1-Zone model is less steep (more large events relative to the smaller events) than for the Seabrook site. This can be seen from Tables 4.4 (a) and (b). Table 4.4 (a) gives the rate of activity for each of the magnitude and distance bins used (Table 3.5), normalized by area and the rate in the first distance and magnitude bin. Table 4.4 (b) gives the same results for the Seabrook site.

Tables 4.4 (a) and (b) show that the $M = 6.25$ bin will make a larger relative contribution to the hazard for the 1-Zone model than for the Seabrook Site. Thus, $\underline{M}_c$ for the 1-Zone model will be somewhat larger than for Seabrook—5.82 versus 5.77.

Next, the reasons why the North Anna site, which has the same M_U as Seabrook, has a much lower $\underline{M}_c$ than Seabrook is examined. Table 4.5 gives the normalized rates for the North Anna site. It also should be noted that the median rate of activity for $M \geq 5$ at the North Anna site is about a factor of 2 lower than at Seabrook and a little higher than the 1-Zone model.

In comparing Table 4.5 with 4.4 (b), the $M = 6.25$ bin is going to contribute significantly more to the hazard at the Seabrook site than at the North Anna site. Also the $M = 5.75$ bin will contribute more at the Seabrook site than at the North Anna site. Thus the $\underline{M}_c$ at the North Anna site is significantly smaller than at the Seabrook site or for the 1-Zone model. The effective b-value at the North Anna site is much steeper than at the Seabrook site.

Next it is interesting to examine why the $\underline{M}_c$ for Vogtle is so large even though the median M_U is only 6.0. Table 4.6 gives the normalized rates for the Vogtle site.

The rate of $M \geq 5$ events is about a factor 4 higher at Seabrook than Vogtle and the rate at the North Anna Site is about a factor of 2 higher than Vogtle. In comparing Tables 4.5 and 4.6, the $M = 5.75$ bin has a higher relative rate at the Vogtle site. There is some contribution from the 6.25 bin at North Anna, but it is relatively small—only about 9% of the total hazard.

However, at the Vogtle site, the larger distance and magnitude bins contribute to the hazard, the $M = 6.25$ bins contribute 7% and the 6.75 bins contribute 4% which makes the $\underline{M}_c$ at the Vogtle site larger than for the North Anna site.

It is interesting to examine why $\underline{M}_c$ is approximately the same for the North Anna and Calvert Cliffs sites although the M_u for North Anna is 6.5 and only approximately 6 for Calvert Cliffs. The Brunswick site, which would have been the most logical site based on Figure 4-1, was not chosen because it is a very shallow soil site and the large site amplification factors could make the interpretation difficult.

In addition to M_u , the median rate of $M \geq 5$ is approximately a factor of 2.6 higher at North Anna than at Calvert Cliffs. Figure 4-2 plots the normalized recurrence model for the two sites. Note that for this plot, the normalization is arbitrary so that both sites have the same rate of $M \geq 5$ events.

The curve labeled 1-1 is for Calvert Cliffs and 2-2 is for North Anna. This figure shows that at values as high as $M = 5.75$, the b-value for Calvert Cliffs is less steep than for North Anna. Hence, there are more $M = 5.75$ events relative to $M = 5$ events at Calvert Cliffs than at North Anna. The figure also shows that at North Anna, there are many more $M = 6$ events than at Calvert Cliffs. However, the probability of having $M = 6$ events is sufficiently low so that the $M = 6.25$ bins only contribute about 7 percent of the total hazard and the $M = 5.75$ bins contribute 51 percent of the total hazard. At Calvert Cliffs, the $M = 5.75$ bins contribute 56 percent of the hazard. There is a 1 percent contribution to the hazard at Calvert Cliffs in the $M = 6.25$ bins at larger distances. The $\underline{M}_c$ for Calvert Cliffs is 5.54 and for North Anna, 5.57.

The site with the smallest $\underline{M}_c$ in the $M_u = 6$ group is the Turkey Point site. Table 4.7 provides the normalized median rate for each bin for the Turkey Point site. The rate of $M \geq 5$ at Vogtle is about a factor of 11 times higher.

When comparing Tables 4.6 with 4.7, it is apparent why the $\underline{M}_c$ at Vogtle is so much larger than at the Turkey Point Site.

A more interesting comparison is between the Comanche Peak site (median M_u approximately 5.75 and $\underline{M}_c = 5.38$), Palisades (median M_u approximately 6 and $\underline{M}_c = 5.38$), and Turkey Point (median M_u approximately 6 and $\underline{M}_c = 5.29$). Both Comanche Peak and Turkey Point have approximately the same median rate of $M \geq 5$ events. The median rate of $M \geq 5$ at Palisades is approximately 1.7 times higher. Figure 4-3 shows the normalized median recurrence model for each site based on the seismicity out to a distance of 35 km. It is apparent from Figure 4-3 why Turkey Point has the lowest $\underline{M}_c$. The higher rate at $M = 5.5$ at Comanche Peak is enough to make the percent contribution from the 5.75 bins the same for both the Comanche Peak and the Palisades sites. This is a case where a finer set of magnitude bins might have made a slight difference in the final $\underline{M}_c$ s. However, given the large uncertainties in how to go from magnitude to ground motion, the slight difference in $\underline{M}_c$ that might result using a finer magnitude binning is hardly worth the considerable effort.

It is apparent that seismicity rate does not seem to play much of a role in the value for $\underline{M}_c$, and that sites with very different rates can easily have the same $\underline{M}_c$. This is not too surprising, because in the equation for $\underline{M}_c$, the rates are normalized. It is difficult to see if there is some influence from rate using actual sites because of all other uncertainties. The effect of rate for the 1-Zone case was investigated. Three rates were selected: (1) the base rate case which is the same as that used in the above discussion, (2) 8 times the base rate and (3) 0.125 times the base rate for two values of M_u (6.25 and 7.25). Table 4.8 gives the results of this analysis based on an RP of $1E-05$.

Rate has some influence on $\underline{M}_c$ and $\underline{D}_c$ much like the value of RP used (see Table 4.3). At the higher rates, larger events can now contribute to the ground motion hazard for a fixed RP. Recall that for actual sites, it was found that in some cases $\underline{M}_c$ became larger for the RP case $1E-04$ (see Table 3.2). This happened because the ground motion levels became smaller at larger

values for RP and hence the more distant zones contributed to the hazard. These distant zones often have much larger values for M_U than the zone around the site. Hence, for these cases, $\underline{Mc}$ does not follow the trend given in Table 4.8 which was for a single uniform zone.

Figure 4-4 is a repeat of Figure 2-9 with the addition of the identification of four sites. Figure 4-4 plots $\underline{Mc}$ versus the rate of earthquakes $M \geq 5.25$ based on the seismicity out to 35 km. We see from Figure 4-4 that Callaway, Browns Ferry and Catawba are "outlier" sites. Both Browns Ferry and Callaway have a larger $\underline{Mc}$ relative to their rate because there is a significant contribution to hazard at the selected RP from larger distant earthquakes. At Callaway, $M=6-6.5$, 50-100 km bin contributes 12 percent of the hazard and the bin centered at $M > 7$, 253 km contributes 2 percent of the hazard. At the Browns Ferry site, the bin centered at 253 km and $M > 7$ contributes 9 percent of the hazard at the selected RP.

Both Catawba and Millstone sites have approximately the same rate of $M \geq 5.25$ within 35 km of the sites. However, M_U is 6.5 at Millstone and only 6.25 at Catawba. In addition, at the selected RP, the effective b-value is such that at the Millstone site, the $M = 6.25$ bin contributes over 13 percent of the hazard; the $M=5.75$ bin contributes 51 percent of the hazard and the $M = 5.25$ bin contributes only about 35 percent of the hazard. On the other hand, at the Catawba site, the $M = 5.25$ bin contributes over 52 percent of the hazard while the 6.25 bin does not contribute to the hazard at all. Hence, the $\underline{Mc}$ is significantly larger for Millstone than for Catawba.

We performed a simple sensitivity analysis to see what impact changes in the b-value might have on the computed $\underline{Mc}$. We selected three b-values: E-0.8, -1.0 and -1.2. We selected the a-value so that in all three case the rate of $M \geq 5$ would be the same. We also selected two values for M_U , 6.25 and 6.5. In Table 4.9 we give the results.

The effect of changing the b-value has some impact on the computed $\underline{Mc}$. At some actual sites the "b-value effect" appears to be more significant than suggested by Table 4.9. This is

because near M_U , the roll-off of the rate with increasing magnitude is much greater than suggested by comparing two truncated exponential models with different b-values. This is illustrated in Figure 4-5 where we plot the normalized recurrence model for North Anna and Seabrook and the simple truncated exponential model for b-values of -1 and -1.2. We see from Figure 4-5 that the median Seabrook recurrence model out to 35 km around the site is very similar to a truncated exponential model with $b = -1.2$ out to $M = 6$. For $M > 6$, the Seabrook model rolls-off more rapidly out to $M=6.25$, then less rapidly for $M \geq 6.25$.

We also see that between $M=5.25$ and $M=5.5$, the North Anna b-value makes a significant slope change. Between 5.5 and 6, the b-value for North Anna is approximately -1.2. However for $M > 6$, the roll-off of the North Anna median recurrence model is very rapid. The reason why the median LLNL recurrence models appear so different than a simple truncated exponential model is that they are composite models. Each of the models making up the composite model are very different (see Figure 2-6).

Because of the shape of the truncated exponential recurrence model used, the rate of activity starts to depart significantly from a straight line about 0.75 units below M_U (see Figure 4-6). As discussed above, the "roll-off" of rate with increasing magnitude appears to be more rapid for many of the actual sites. Hence $\underline{Mc}$ will be lower than for the simple 1-Zone models relative to M_U . An important parameter is the large uncertainty in the ground motion models. If the uncertainty in the ground motion models is significantly reduced, then for very small RP cases, $\underline{Mc}$ will begin to approach M_U . However, it is highly unlikely that the uncertainty in the ground motion will be reduced enough to have an impact on the results. This is discussed in detail in Section 4.6.

4.4 Effect of Lower Bound Magnitude

The choice was made to start the integration of the hazard at a lower bound magnitude of 5. The basis for this is that earthquakes lower than $M = 5$ will not cause any damage to NPP. Bernreuter et

al. (1989) showed that earthquakes in the 3.75–5 range generally contribute significantly to the PGA hazard at RP of $1E-05$. To see the impact that changing the lower bound of integration on magnitude would have, we performed a sensitivity study using the 1-Zone model discussed in Section 4.3. We determined $\underline{M}_c$ and $\underline{D}_c$ for 12 cases.

The 12 cases were made up of a matrix of runs that have 2 values for M_u (6.25 and 7.25), 3 rates (BR, $8 \times BR$ and $0.125 \times BR$), and two lower bound of integration values (3.75 and 5). The results are given in Table 4.10.

We see from Table 4.10 that the lower the rate and the smaller the M_u , the more that the magnitude bins from $M = 3.75$ to 5 contribute to the hazard and the greater the impact on $\underline{M}_c$ and $\underline{D}_c$. Both $\underline{M}_c$ and $\underline{D}_c$ decrease when the $M = 3.75$ to 5 bins are included.

4.5 Effect of Site Conditions

In Section 3.5, we found that changing site conditions did not have a significant effect on $\underline{M}_c$ and $\underline{D}_c$. However, because of the large uncertainties involved at actual sites, it is possible that there might be some systematic impact of changing site conditions as a function of M_u that was obscured by the scatter of results introduced by the large uncertainties. To examine this, we computed $\underline{M}_c$ and $\underline{D}_c$ for the three site conditions (rock, deep soil, and shallow sand) for the sample 1-Zone model described in Section 4.3. Three values for M_u were selected: 6.25, 6.5, and 7.25.

In Table 4.11, we give the results of our analysis. We see that changing soil type has only a minor impact on $\underline{M}_c$ and $\underline{D}_c$ for a wide range of M_u . These results are similar to the results given in Table 3.7 for the actual sites.

4.6 Effect of the Uncertainty in the Ground Motion Model

Most of the ground motion models used are assumed to have a lognormal distribution about the central tendency. The lognormal distribution is controlled by two parameters, the log of the means and the standard deviation of logs. The mean controls the level of the ground motion and

the standard deviation (σ) controls the distribution of the uncertainty. It is of some interest to see how $\underline{M}_c$ and $\underline{D}_c$ vary as a function of the size of the standard deviation.

In order to explore this issue, we performed a sensitivity analysis for the 1-Zone model described in Section 4.3. In Section 4.3, the σ for the ground motion model was taken as 0.6 (base e) with a range of 0.5 to 0.7 which is a value often used. We call this case the moderate σ (MS) case. We also selected a value of σ as 1.3 with a range of 1. to 1.6 which we called the large σ (LS) case and a value of 0.02 (range 0.01 to 0.03) which we call the Small σ (SS) case.

We also selected three values for M_u : 6.25, 6.5, and 7.25. Each has ± 0.25 units of uncertainty. We performed the analyses for $\underline{M}_c$ and $\underline{D}_c$ at three PE levels ($1E-05$, $1E-06$, and $1E-07$). In Table 4.12, we give the values for $\underline{M}_c$ and $\underline{D}_c$ based on the average of the 5- and 10-Hz hazard curves as a function of M_u , and the PE level used for the three values of σ selected. The values marked with an asterisk (*) in the table were obtained by extrapolation beyond the last calculated value; hence, they are only approximate.

We see from Table 4.12 that $\underline{M}_c$ and $\underline{D}_c$ vary with σ as would be expected. That is, for very large σ , the smaller and more distant earthquakes can contribute; hence, $\underline{M}_c$ is smaller and $\underline{D}_c$ is larger. For very small σ , only the larger nearby earthquakes can contribute; hence, $\underline{M}_c$ is larger and $\underline{D}_c$ is smaller. Of course, how ground motion scales with magnitude and attenuates with distance plays a role as well. The values given in Table 4.12 are for the same scaling with magnitude and same attenuation with distance. Most ground motion models scale much like the model we used; hence, the results should be relatively general.

We see from Table 4.12 that $\underline{M}_c$ only will approach M_u for very small values of σ and generally at very small PE levels. For normal uncertainty levels in the ground motion models used, $\underline{M}_c$ is going to be smaller than M_u . Part of the reason is because, as discussed in Section 4.3

and illustrated in Figure 4.6, the roll-off of the rate as M_u is approached. This roll-off is partly because the scaling of ground motion with magnitude is not stronger, and partly because the b -value is around -1. If the b -value was much less steep, then the larger magnitudes would be somewhat more important as illustrated in Table 4.9.

4.7 Effect of Changing Ground Motion Models

In order to explore the question of how sensitive the value computed for $\underline{M}_c$ and $\underline{D}_c$ might be to changes in the ground motion model used in the analysis, we ran a series of analyses for the 1-Zone model using the composite model developed in Savy (1993) and used to obtain the results for the 69 NPP given in this report. The composite model is developed using the input of the Ground Motion Experts that participated in the LLNL study and represents a composite of all their individual models—one of which was the modified Boore-Atkinson model used in Subsection 4.3 and elsewhere in Section 4. The composite model includes models significantly different from the Boore-Atkinson model.

In Table 4.13, we give the spectral acceleration (S_a) values at 5- and 10-Hz for M_u values of 6.25, 6.5, and 7.25 at an $RP = 1E-05$ for the 1-Zone model for the two different ground motion models. The S_a values for the Boore-Atkinson model are denoted by BA in Table 4.13 and those for the composite model by C. We see from Table 4.13 that indeed the two ground motion models are significantly different. Because of the large differences in results, it is not clear how best to compare the $\underline{M}_c$ and $\underline{D}_c$ for the two cases. Ideally, according to Section 2, we should compute the hazard at all 69 sites using the new ground motion model and then determine the appropriate RP to use with the new ground motion model as outlined in Subsection 2.2.

However, for the sample case, we cannot do this. To get around this issue, we have chosen to compute the $\underline{M}_c$ and $\underline{D}_c$ for the 1-Zone model using the composite ground motion model in two ways:

- 1) at an $RP = 1E-05$
- 2) at the same S_a value as for the Boore-Atkinson case.

Table 4.14 gives the results for these two ways of obtaining the ground motion levels at which the contribution to the hazard is evaluated.

We see from Table 4.14 that in the range of M_u s of most interest (6.25–6.5), the change in the ground motion model did not have a significant impact on $\underline{M}_c$ and $\underline{D}_c$. However, for very large M_u , the impact is somewhat larger.

We also checked to see if changing site conditions would change the results. We found approximately the same small impact as was found in Subsection 4.5.

4.8 Examination of the Differences Between SSEs and CEs

In Section 2.6 and Table 2.16, we compared the CEs to SSEs at 15 sites where an estimate for the SSE had been developed by NRC at the time of the Operating License Review process and noted several significant differences between the CEs and the SSEs. In particular, the CEs for the Braidwood, Byron and Clinton sites are about 0.3 magnitude less than the SSE. The CE at Seabrook is 0.2 units smaller than the SSE, and at several sites, e.g., at River Bend, the CE is larger by 0.3 units than the SSE.

It is of interest to examine the difference between the CE and the SSE in some detail as it contrasts the differences in approach and application between the original Appendix A and the approach given in RG1.165.

In the approach given in RG1.165, the CEs are determined including the relative likelihood of the earthquake occurrence, the likelihood that a smaller earthquake can have a larger ground motion than a larger earthquake, as well as the likelihood of the earthquake being located near the site. Finally, a calibration level is used as outlined in Section 2.2. In the 10 CFR Part 100 Appendix A approach, the SSE is determined by a judgment about the largest earthquake that can reasonably occur within the same source zone as

the site—or moved to the boundary of any nearby source zones. Rate considerations may enter in making a judgment about the largest earthquake that can reasonably occur, but not in any formal or systematic way. All of the other factors are missing and no calibration process is used other than some loose judgmental process about what was done at other sites.

Braidwood and Byron are two nearby sites in northern Illinois where there was a significant difference between the SSE and the CE. In arriving at the SSE for these two sites, the NRC Staff (J.C. Stepp 1996)² was concerned about the fact that there had been several MM VII earthquakes in northern Illinois since 1900. The return period for a large northern Illinois source zone was judged by the Staff to be sufficiently high so that coupled with the MM VII events, the Staff concluded that a MM VIII event (approximately $M = 5.75$) was the appropriate value for the SSE. The procedure in Appendix A then fixed the SSE at approximately 15 km from the site.

The methodology of RG1.165 is significantly different in the way the same data enters into the analysis. The 11 Seismicity Experts involved in the LLNL study developed what in their judgment (for each Expert) was (1) a set of source zones (including alternatives), (2) judgments about the maximum earthquakes and (3) the appropriate occurrence models. Also, the Ground Motion Experts provided the appropriate Ground Motion Models to use. Finally, the appropriate RP to use was determined, as per Section 2.2, and the CE was obtained using this RP to determine the appropriate ground motion level. Finally, the CE is determined by averaging which distance-magnitude intervals contribute most to the ground motion corresponding to the RP.

In Figure 4.7, we give (as described in Section 2.6), the best estimate recurrence model for each of the seismicity experts in the LLNL study for the region within 35 km of the Braidwood site. The models for Byron are very similar. We see

from Figure 4.7 that indeed all but one of the Experts considered a $M_{\text{U}} = 5.75$ or larger earthquake possible. We also see from this figure that for $M > 5.5$, there is considerable roll-off of the rate of activity. As discussed in 4.3, this roll-off controls $\underline{M}_{\text{C}}$, so that for this site $\underline{M}_{\text{C}} = 5.5$.

It is of some interest to compare the recurrence models at Braidwood to sites where both the SSEs and the CEs are in the 5.7–5.8 range such as the Bellefonte, Seabrook, Sequoyah, and Watts Bar sites for the region within 35 km of each site. It is evident from Figure 4.8 why $\underline{M}_{\text{C}}$ for Braidwood is only 5.5 and the $\underline{M}_{\text{C}}$ for the other sites is in the 5.7 to 5.8 range.

The seismicity around the Byron site is very similar to the activity around the Braidwood site—here, the $\underline{M}_{\text{C}}$ for the Byron site is the same as for Braidwood.

The Clinton site is located about 130 km south of the Braidwood site in a different set of source zones and nearer to the New Madrid zone and the Wabash Valley region. The Callaway site is located about 400 km southwest of the Braidwood site. In Figure 4.9, we plot the median composite recurrence model for the Braidwood, Clinton, and Callaway sites based on the region within 35 km of each site, and in Figure 4.10 we plot the recurrence models for the same three sites based on the region within 100 km of each site. We see from these two figures that it is not surprising that $\underline{M}_{\text{C}}$ for the Clinton site is about the same as for the Braidwood site. From Figure 4.9, we might expect that $\underline{M}_{\text{C}}$ for the Callaway site to be lower—but as noted in Section 4.3, the $\underline{M}_{\text{C}}$ for the Callaway site is somewhat larger because of source zones located 35 to 100 km from the site. We see from Figure 4.10 why these more distant zones are more significant at the Callaway site than at the Clinton site and why $\underline{M}_{\text{C}}$ might be larger.

Let us now examine why $\underline{M}_{\text{C}}$ for the Seabrook site is lower than the SSE. We see from Figure 4-8 that the median value for M_{U} at the Seabrook site is approximately 6.5. We also saw from Table 3.2 that at the appropriate RP level, earthquakes greater than magnitude 6 only contribute about 25% of the hazard at the Seabrook site. Even if

² Stepp, J.C. 1996. Private Communication. Dr. Stepp was the lead seismologist at NRC when Byron and Braidwood were under review. D.L. Bernreuter was also on loan to NRC at the time and participated in the review.

4. Interpretation of Controlling Earthquakes

we go to an $RP = 1E-06$, an earthquake greater than magnitude 6 only contributes about 36% of the hazard; hence, M_c is in the 5.8 to 5.9 range at the Seabrook site. One major difficulty with the old Appendix A approach is how to select the magnitude for the SSE. For example, why is $M = 6$ appropriate for Seabrook in light of the recurrence models of the various Experts involved in both the LLNL and EPRI studies?

We see from Table 4.1 that most of the Seismicity Experts involved in the LLNL study thought that $M \geq 5.5$ could occur within 35 km any of the sites. Thus, the CEs are larger at the River Bend and Beaver Valley sites than the SSEs given in Table 2.16. However, as discussed in Section 4.4, the CEs for low seismicity sites are artificially high because the integration is started at $M = 5$ and the center of the first magnitude bin is 5.25. Table 4.10 suggests that M_c would be at least 0.2 units smaller if the contribution of earthquakes less than magnitude 5 were considered.

In general, it was both the EG and the NRC Staff's opinion that the approach given in RG1.165 was more scrutable and defensible than the approach given in Appendix A and provided better estimates for the SSE than those obtained by using the approach given in Appendix A.

Table 4.1. 18th percentile, median, and 82nd percentile for most likely value for maximum magnitude, M_u , within 35 km of each site and rate of recurrence of $M \geq 5$ within 35 km of each site for all 69 NPP sites in the central and eastern U.S.

Site	18% M_u	Median M_u	82% M_u	median rate @ $M=5$
Arkansas	5.75	6.50	7.00	.259E-03
Beaver Vally	5.50	6.00	6.50	.677E-04
Bellefonte	6.25	6.50	7.00	.589E-03
Big Rock Point	5.50	6.00	6.00	.272E-04
Braidwood	5.75	6.00	6.50	.168E-03
Browns Ferry	5.50	6.50	6.50	.175E-03
Brunswick	6.00	6.00	7.00	.928E-04
Byron 1 & 2	5.75	6.00	6.50	.170E-03
Callaway	5.50	6.00	6.00	.452E-04
Calvert Cliffs	5.75	6.00	7.00	.176E-03
Catawba	5.75	6.25	7.00	.460E-03
Clinton	5.50	6.00	6.75	.681E-04
Comanche Peak	5.50	5.75	6.00	.218E-04
Cook 1 & 2	5.75	6.00	6.00	.496E-04
Cooper	5.75	6.00	6.25	.210E-03
Crystal River	5.50	6.00	6.50	.219E-04
Davis Besse 1	6.00	6.00	6.50	.254E-03
Dresden 2&3	5.75	6.00	6.50	.168E-03
Duane Arnold	5.50	6.00	6.25	.439E-04
Farley	5.50	6.00	6.50	.379E-04
Fermi 2	5.75	6.00	6.50	.676E-04
Fitzpatrick	5.50	6.00	6.25	.677E-04
Fort Calhoun	5.75	6.00	6.25	.802E-04
Ginna	5.50	6.00	6.50	.936E-04
Grand Gulf	5.50	6.00	6.50	.381E-04
Haddam Neck	6.00	6.50	6.75	.394E-03
Hatch	6.00	6.25	7.00	.819E-04
Hope Creek	6.00	6.50	7.00	.178E-03
Indian Point	6.00	6.50	6.75	.403E-03
Kewaunee	5.50	6.00	6.00	.301E-04
La Crosse	5.50	6.00	6.00	.381E-04

4. Interpretation of Controlling Earthquakes

Table 4.1. 18th percentile, median, and 82nd percentile for most likely value for maximum magnitude, M_u , within 35 km of each site and rate of recurrence of $M \geq 5$ within 35 km of each site for all 69 NPP sites in the central and eastern U.S., continued

Lasalle	5.75	6.00	6.50	.168E-03
Limerick	6.00	6.50	6.75	.428E-03
Maine Yankee	6.00	6.50	6.75	.455E-03
Mcguire	5.75	6.25	7.00	.339E-03
Millstone	6.00	6.50	6.75	.396E-03
Monticello	5.50	6.00	6.25	.421E-04
Nine Mile Point	5.50	6.00	6.25	.683E-04
North Anna	6.00	6.50	7.00	.464E-03
Oconee	6.25	6.50	7.00	.454E-03
Oyster Creek	6.00	6.50	7.00	.176E-03
Palisades 1	5.50	6.00	6.00	.378E-04
Perry	5.75	6.00	6.50	.143E-03
Pilgrim	5.75	6.50	6.75	.397E-03
Point Beach	5.50	6.00	6.00	.301E-04
Prairie Island	5.50	6.00	6.00	.379E-04
Quad Cities	5.50	6.00	6.50	.682E-04
River Bend	5.50	6.00	6.50	.276E-04
Robinson	5.75	6.50	7.00	.284E-03
Salem	6.00	6.50	7.00	.173E-03
Seabrook	6.00	6.50	6.75	.715E-03
Sequoyah	6.25	6.50	7.00	.596E-03
Shearon Harris	5.75	6.00	7.00	.178E-03
Shoreham	6.00	6.50	7.00	.36E-03
South Texas	5.50	6.00	6.00	.277E-04
St. Lucie	5.50	6.00	6.50	.217E-04
Summer	5.75	6.25	7.00	.409E-03
Surry	6.00	6.25	7.00	.962E-04
Susquehanna	5.50	6.50	6.50	.285E-03
Three Mile Island	6.00	6.50	6.75	.336E-03
Turkey Point	5.50	6.00	6.50	.219E-04
Vermont Yankee	6.00	6.50	6.75	.287E-03
Vogtle	6.00	6.00	7.00	.178E-03
Waterford	5.50	6.00	6.50	.380E-04

Table 4.1. 18th percentile, median, and 82nd percentile for most likely value for maximum magnitude, M_U , within 35 km of each site and rate of recurrence of $M \geq 5$ within 35 km of each site for all 69 NPP sites in the central and eastern U.S., continued

Watts Bar	6.25	6.50	7.00	.594E-03
Wolf Creek	5.50	6.00	6.25	.602E-04
Yankee Rowe	6.00	6.50	6.75	.291E-03
Zion	5.75	6.00	6.00	.781E-04

Table 4.2. Summary of values for all sites

	Median Value for all sites	Range
Median M_U	6.0	5.75 to 6.5
82% M_U	6.5	6.0 to 7.0
18% M_U	5.75	5.5 to 6.25
Median rate $M \geq 5$	1.7E-04	2.2E-05 to 7.2E-04

Table 4.3. Effect of M_U and RP on $\underline{M}_c$ and $\underline{D}_c$ for the 1-Zone model

	$M_U = 6$		$M_U = 6.25$		$M_U = 6.5$		$M_U = 7.25$	
RP Level	$\underline{M}_c$	$\underline{D}_c$	$\underline{M}_c$	$\underline{D}_c$	$\underline{M}_c$	$\underline{D}_c$	$\underline{M}_c$	$\underline{D}_c$
1. - 04	5.48	25.4	5.61	25.2	5.71	27.3	6.07	28.0
1. - 05	5.52	15.7	5.7	16.1	5.82	16.9	6.25	20.1
1. - 06	5.56	12.5	5.73	12.2	5.91	13.4	6.48	15.1

4. Interpretation of Controlling Earthquakes

**Table 4.4. Normalized median rate of activity in each distance and magnitude bin
normalized by area and rate of the M=5.25, D=10 km bin
(a) 1-Zone model**

	5.25	5.75	6.25	6.75	7.25
10	1	.28	0.047	0	0
20	1	.28	0.047	0	0
39	1	.28	0.047	0	0
78	1	.28	0.047	0	0
156	1	.28	0.047	0	0
253	1	.28	0.047	0	0
>350	1	.28	0.047	0	0

(b) Seabrook site

	5.25	5.75	6.25	6.75	7.25
10	1.0	0.24	0.019	0	0
20	1.0	0.23	0.02	0	0
39	0.98	0.24	0.02	0	0
78	0.97	0.22	0.019	0	0
156	0.46	0.10	0.011	0	0
253	0.46	0.09	0.006	0.00002	0
>350	0.45	0.11	0.028	0.004	0.00005

Table 4.5. Normalized median rate of activity in each distance and magnitude bin for the North Anna site

	5.25	5.75	6.25	6.75	7.25
10	1.0	0.13	0.002	0	0
20	0.93	0.14	0.002	0	0
39	0.89	0.11	0.01	0	0
78	0.73	0.10	0.01	0	0
156	0.74	0.13	0.02	0	0
253	0.76	0.15	0.009	0	0
>350	0.75	0.19	0.02	0.001	0.000005

Table 4.6. Normalized median rate of activity in each distance and magnitude bin for the Vogtle site

	5.25	5.75	6.25	6.75	7.25
10	1.0	0.20	0.00	0	0
20	0.96	0.19	0.00	0	0
39	0.98	0.21	0.027	0	0
78	2.15	0.59	0.15	0.009	0
156	3.93	1.28	0.42	0.04	0.0001
253	1.72	0.33	0.08	0.006	0.00004
>350	2.11	0.54	0.14	0.04	0.008

4. Interpretation of Controlling Earthquakes

Table 4.7. Normalized median rate of activity in each distance and magnitude bin for the Turkey Point site

	5.25	5.75	6.25	6.75	7.25
10	1.0	0.018	0	0	0
20	0.92	0.009	0	0	0
39	0.93	0.008	0	0	0
78	1.15	0.045	0	0	0
156	0.9	0.053	0	0	0
253	0.71	0.044	0	0	0
>350	2.15	0.65	0.21	0.02	0.0001

Table 4.8. $\underline{M_c}$ and $\underline{D_c}$ for average of 5-10 Hz as a function of rate and M_u

Case	$M_u = 6.25$			$M_u = 7.25$	
	Rate $M > 5$	$\underline{M_c}$	$\underline{D_c}$	$\underline{M_c}$	$\underline{D_c}$
BR	2.69E-04	5.7	16	6.3	20
8 x BR	2.15E-03	5.7	12	6.5	16
.125 x BR	3.36E-05	5.6	24	6.1	31

Table 4.9. Effect of b -value on $\underline{Mc}$ and $\underline{Dc}$ for the 1-Zone model for two values of M_u .
The rates of $M \geq 5$ are the same for all b -values.

b-value	$M_u = 6.25$		$M_u = 6.5$	
	$\underline{Mc}$	$\underline{Dc}$	$\underline{Mc}$	$\underline{Dc}$
-0.8	5.74	15.7	5.87	16.2
-1.0	5.7	16.1	5.82	16.9
-1.2	5.63	15.6	5.73	16.3

Table 4.10. Comparison of $\underline{Mc}$ and $\underline{Dc}$ between lower bound of integration of 3.75 and 5 for six cases using the 1-Zone model at RP level of $1E-05$ for average of 5-10Hz

Case	Lower Bound = 3.75		Lower Bound = 5	
	$\underline{Mc}$	$\underline{Dc}$	$\underline{Mc}$	$\underline{Dc}$
BR				
$M_u = 6.25$	5.5	15	5.70	16
BR				
$M_u = 7.25$	6.2	19	6.25	20
8xBR				
$M_u = 6.25$	5.6	12	5.7	12
8xBR				
$M_u = 7.25$	6.5	16	6.5	16
.125BR				
$M_u = 6.25$	5.2	19	5.6	24
.125BR				
$M_u = 7.25$	5.8	25	6.1	31

4. Interpretation of Controlling Earthquakes

Table 4.11. Effect of site soil condition on the controlling earthquake based on the average of 5-10-Hz hazard curves as a function of M_u

M_u	Rock		Deep Soil		Shallow Soil	
6.25	5.7	16	5.7	14	5.7	14
6.5	5.8	17	5.8	15	5.8	15
7.25	6.3	20	6.3	18	6.3	18

Table 4.12. Effect of the sigma of the Ground Motion Model on $\underline{M}_c$ and $\underline{D}_c$ for the simple 1-Zone Model

PE = 1E-05

Sigma case	$M_u = 6.25$		$M_u = 6.5$		$M_u = 7.25$	
	$\underline{M}_c$	$\underline{D}_c$	$\underline{M}_c$	$\underline{D}_c$	$\underline{M}_c$	$\underline{D}_c$
LS	5.6	26	5.7	28	6.1	32
MS	5.7	16	5.8	17	6.25	20
SS	5.9	10	6.0	11	6.6	15

PE = 1E-06

Sigma case	$M_u = 6.25$		$M_u = 6.5$		$M_u = 7.25$	
	$\underline{M}_c$	$\underline{D}_c$	$\underline{M}_c$	$\underline{D}_c$	$\underline{M}_c$	$\underline{D}_c$
LS	5.7	19	5.8	20	6.2	22
MS	5.7	12	5.9	13	6.5	15
SS	6.2	10	6.25	10	6.9	10

PE = 1E-07

Sigma case	$M_u = 6.25$		$M_u = 6.5$		$M_u = 7.25$	
	$\underline{M}_c$	$\underline{D}_c$	$\underline{M}_c$	$\underline{D}_c$	$\underline{M}_c$	$\underline{D}_c$
LS	5.7*	15	5.9*	14	6.4*	17
MS	5.7	11	6.0	11	6.6	12
SS	6.25	10	6.25	10	7.25	10

* Values obtained by extrapolation only approximate.

Table 4.13. Median S_a values at $RP = 1E-05$ for 1-Zone Model for two different ground motion models for selected M_u values

M_u	5-Hz BA	5-Hz C	10-Hz BA	10-Hz C
6.25	308	408	509	515
6.5	342	547	565	578
7.25	430	785	685	798

S_a values in cm/s/s

BA = Boore-Atkinson Model

C = Composite ground motion model

Table 4.14. $\underline{M}_c$ and $\underline{D}_c$ for 1-Zone Model for various M_u for the case of the composite ground motion model for two cases discussed in text. $\underline{M}_c$ and $\underline{D}_c$ are based on the average of 5-10-Hz median hazard curves.

M_u	BA case		Composite 1E-05		Composite at same S_a	
6.25	5.7	16	5.7	17	5.7	19
6.5	5.8	17	5.9	19	5.9	22
7.25	6.3	20	6.5	26	6.5	32

Figure 4-1. Plot of $\bar{M}_c$ versus M_u for all 69 NPPs in the central and eastern U.S. based on average of 5-10-Hz hazard curves at RP level RG. Also shown are the results for the simple case given in Table 4.1.

Figure 4-2. Comparison of the median composite normalized recurrence models for the North Anna and Calvert Cliffs sites based on the zones within 35 km of each site

4. Interpretation of Controlling Earthquakes

Figure 4-3. Comparison of the median composite normalized recurrence models for the Palisades, Comanche Peak and Turkey Point sites based on the zones within 35 km of each site

Figure 4-4. Plot of M_c versus rate of $M \geq 5.25$ earthquakes. Several sites have been identified for reference.

4. Interpretation of Controlling Earthquakes

Figure 4-5. Comparison of the normalized recurrence models for the Seabrook and North Anna sites. Also shown is the normalized recurrence models for the 1-Zone model with b-values = -1 and -1.2.

Figure 4-6. Comparison of a simple truncated exponential model with $\mu = 6.5$ to the Richter $\log N = a - bM$ model

4. Interpretation of Controlling Earthquakes

Figure 4-7. Median recurrence model for each LLNL seismicity expert for the Braidwood site based on the region within 35 km of the site

Figure 4-8. Comparison of the median composite recurrence models based on the region within 35 km of the sites for the 1—1 Braidwood, 2—2 Watts Bar, 3—3 Seabrook, 4—4 Sequoyah, and 5—5 Bellefonte sites

4. Interpretation of Controlling Earthquakes

Figure 4-9. Comparison of the median composite recurrence models based on the region out to 35 km of the 1—1 Braidwood, 2—2 Clinton, and 3—3 Callaway sites

Figure 4-10. Comparison of the median composite recurrence models based on the region out to 100 km of the 1—1 Braidwood, 2—2 Clinton, and 3—3 Callaway sites

5. GUIDELINES TO DETERMINE WHEN UPDATING IS NEEDED

5.1 Background

Appendix E of RG1.165 discusses issues of evaluation of new geosciences information and the potential need to update the source models to incorporate this new information. In this section, we examine this issue to provide some helpful insights as to when it would be appropriate to update the input source models.

There are a number of reasons why a region would be subdivided into a set of distinct source zones such as:

- 1) Newly observed differences in geology
- 2) Newly determined existence of some type of geophysical anomaly
- 3) Newly discovered data which would introduce a contrast in the earthquake recurrence model (e.g., a change in estimate for rate or in the largest earthquake)

The first two reasons for a new zone are not addressed in this study as they are very difficult to quantify. However, one must determine if the observed differences are from geology or geophysical anomalies and are sufficiently significant to introduce a new source zone. From the practical point of view, a new zone is needed only if it has some impact on the computed seismic hazard at the site of interest. The computed seismic hazard will only change if the recurrence model for earthquakes or the estimate for the upper bound magnitude M_u in the new zone are sufficiently different from the other zones to impact the computed seismic hazard at the site of interest. The purpose of this section is to provide some sensitivity results which will help determine if the introduction of a new zone leads to an earthquake recurrence model sufficiently different to warrant the new zone. It will also assist in determining how much effort one needs to expend in refining estimates of the parameters of the earthquake recurrence model and or geometry of the zone.

A new zone is needed only if the introduction of the zone will increase the estimate for $\bar{M}_c$ sufficiently and/or the average of 5- and 10-Hz estimates of the ground motion at the site at an RP

of $1E-05$ enough to have a significant impact on the design of the NPP's structures. This report does not attempt to address this issue except to note that, because of the very large uncertainties in the estimation of the ground motion, the increase in the ground motion estimate would have to be greater than 5 to 10 percent.

5.2 Approach

To keep the results relatively simple for ease of interpretation, the geometry of the problem is kept very simple, and the recurrence model is assumed to have a truncated exponential distribution characterized by three parameters: a , b , and M_u . The a -value gives the rate of earthquake at lower bound value of magnitude, the b -value gives the slope of the curve, and M_u gives the truncation value for magnitude. We start with a large source zone referred to as Zone L. The question to address is, under what conditions should a new smaller zone, say Zone S, be introduced in Zone L? As indicated above, there are a number of reasons to suspect that a new, smaller zone may need to be introduced. However, the need for a new zone depends upon several factors:

- 1) the distance between the site and boundary of the new Zone S
- 2) rate of activity in Zone S as compared to Zone L
- 3) the estimate for the largest earthquake, M_u , in Zone S compared to M_u in Zone L
- 4) the estimate for the b -value in Zone S as compared to Zone L

Figure 5-1 shows the geometry of the problem considered in this study. Two source zones are considered. Zone L is a large zone and Zone S is a 50×50 km zone embedded in Zone L. The hazard is computed at 7 sites:

- 1) Site 5L is 200 km from the boundary of Zone S and is within Zone L
- 2) Site 4L is 100 km from the boundary of Zone S and is within Zone L
- 3) Site 3L is 60 km from the boundary of Zone S and is within Zone L
- 4) Site 2L is 25 km from the boundary of Zone S and is within Zone L

5. Guidelines to Determine when Updating is Needed

- 5) Site 1L is 12.5 km from the boundary of Zone S and is within Zone L
- 6) Site B is on the boundary between the two zones
- 7) Site 1S is 12.5 km from the boundary of Zone S and is within Zone S
- 8) Site 2S is 25 km from the boundary of Zone S and is within Zone S

Clearly, the shape of Zone S could have some influence on the results. For example, if Zone S were a longer narrow zone, one would expect that this might change the results somewhat, but it would be a second-order effect. One could also introduce multiple zones, but this would make interpretation of the results very difficult. Hence, these complexities have not been studied.

The rate of activity in Zone L was selected so that the rate of $M > 5$ was at approximately the 67% level of existing NPP—i.e., 33% of the sites had a higher rate and 67% had a lower rate within 35 km of the sites. The 35 km radius was used because, for most sites, most of the hazard comes from this region. This is the same base rate used in Sections 4.3 and 4.4.

The largest event (M_U) for Zone L was selected as $M_U = 6.25$ which is typical for many zones. The b -value was taken as $b = -1$.

For all of the runs made, the seismicity parameters for Zone L were kept fixed at the base rate, $M_U = 6.25$ and $b = -1$. The following cases were run:

- 1) Base case - same base rate (BR) and $b = -1$ in both Zone L and S with $M_U = 6.25$ in both zones.
- 2) A matrix of runs were made with $b = -1$ in Zone S. The rate and M_U in Zone S were varied. Rates of 1.25, 1.5, 1.75, 2, 4, and 8 times the base rate were used. M_U in Zone S was varied with values of 6.25, 6.5, 6.75, 7, and 7.25.
- 3) A matrix of runs was made with the base rate in both Zone L and S. In Zone S, b -values of -0.8 , -0.9 , -1 , -1.1 and -1.2 were used with M_U values of 6.25, 6.5, 6.75, 7 and 7.25.

For the matrix of runs with varying " b -values" in Zone S (case 3), the rate in Zone S was varied so that, for all values for b , the number of $M > 3.75$ earthquakes were the same as in Zone L. A value of $M = 3.75$ was chosen because it is likely that experts can establish a reasonable estimate for the rate of earthquakes in this magnitude range.

The above sets of runs make a large number of combinations. Various conclusions can be reached depending on whether the ground motion measure is low or high frequency. To examine this, we developed results for both 1 and 10 Hz.

Two measures assess the impact of introducing a new zone on the seismic hazard at a site. The first measure is in terms of probability of exceedance (PE) of a given ground motion level. Figure 5-2 illustrates this choice. We selected the following three ground motion levels (in cm/s/s) to make assessments:

	1 Hz	10 Hz
low S_a	38	138
Moderate S_a	132	627
high S_a	357	1880

The plots give the ratio of the

$$\frac{\text{PE case of interest}}{\text{PE base case}}$$

The second measure is the ratio of ground motion between the case of interest and the base case for a given RP level. Figure 5-3 illustrates this choice. Three RP levels were used ($1E-04$, $1E-05$ and $1E-07$).

There is an approximate equivalence between the three ground motion levels used to evaluate the ratios of RPs and the three RP levels selected to evaluate the ratio of ground motion.

5.3 Effect of the New Zone on Hazard

The data discussed above is organized by several sets of cross-plots. Each set will contain information contained in other sets but presented in a different manner which allows for additional insights. In this report, we will only select a subset of the above set of runs and data to illustrate the important points. Most of the time

the choice will be for the moderate ground motion level and RP level of $1E-05$. This appears to correspond most closely to the case of interest for the existing NPP.

In addition, we note that four seismicity parameters are examined: distance from boundary of Zone S, rate in Zone S relative to Zone L, M_U in Zone S and the b-value in Zone S. The first set of plots uses distance from the boundary as the ordinate variable and either the ratio of PEs or the ratio of ground motion as the abscissa variable. The next set of plots is per individual site with M_U in Zone S as the ordinate variable. The third set of plots is per individual site with rate in Zone S as the ordinate variable; the last set of plots is per site with b-value in Zone S as the ordinate variable.

5.3.1 Effect of Distance from a New Zone's Boundary

The ordinate variable in Figures 5-4 to 5-11 is *distance from the boundary of Zone S*. The negative distances are in Zone L and the positive distances are in Zone S. Figures 5-4 to 5-7 show the effect of distance from the boundary of Zone S for various rates in Zone S. The upper magnitude, M_U , is 6.25 for both zones. Figure 5-4 and 5-5 are for 10 Hz and Figs. 5-6 and 5-7 are for 1 Hz. Figures 5-8 to 5-11 show the effect of distance from a boundary of Zone S and for various M_{US} in Zone S. The rate is the same for both zones. Figures 5-8 and 5-9 are for 10 Hz and Figures 5-10 and 5-11 are for 1 Hz.

One of the most interesting aspects of all of these figures is that if one is 10–25 km from the boundary, the effect of the new zone is lost relative to the 10-Hz hazard curve. For example, at site 2L (25 km from boundary S), the hazard hardly changes due to the introduction of a Zone S—even when M_U in Zone S has increased from 6.25 to 7.25. We also see that there is very little increase in the hazard between site 1S (12.5 km from the boundary of S) and site 2S in the middle of Zone S. The message here is clear. If a zone boundary is within 10–15 km of a site, it is very important to know the boundary location. However, the importance of knowing the exact boundary location diminishes significantly for distances greater than 15 km.

Figures 5-12 to 5-15 illustrate more clearly how the influence of a new zone diminishes with

distance from the boundary. For these figures we plot the results for sites 1L, 2L, 3L and 4L (distance 25 km to 200 km from the boundary between the two zones). The abscissa variable is the ratio of S_a/S_{abc} at the PE level of $1E-05$.

Both Figures 5-12 and 5-13 are for 10 Hz. For Figure 5-12, the same rate was used in both zones but a range of M_U from 6.25 to 7.25 was used in Zone S. For Figure 5-13, Zone S had 8 times the base rate with the same range of M_U in Zone S as used in Figure 5-12. We see that the influence of a new zone rapidly diminishes. We see from Figure 5-12 that changing M_U in Zone S from 6.25 to 7.25 only results in about a 3 percent change in the spectral acceleration (S_a) at 10 Hz at site 2L (25 km from the boundary). We see from Figure 5-13 that increasing the rate in Zone S by 8x only results in a 7 percent increase in S_a at site 2L for a $M_U = 6.5$ in Zone S. We also see that if both M_U and rate increase significantly in Zone S, then the influence of these changes extends farther out. However, by 60 km (site 3L) the increase in S_a is only about 5 percent.

The figures show that for the 1-Hz hazard curve, the influence of changes in a new Zone S extends farther out. However, since the SSE ground motion is scaled at the average of 5 to 10 Hz, it reduces the importance of the lower attenuation at 1 Hz. It should be noted that the behavior of the 10-Hz hazard curve is very similar to the 5-Hz case as can be seen by comparing Figures 5-14 (10 Hz) to 5-16 (5 Hz). In fact, the behavior of the 2.5-Hz hazard case is closer to the 5-Hz case than the 1-Hz case which can be seen by comparing Figures 5-17 (2.5 Hz) to 5-16 (5 Hz) and 5-14 (1 Hz).

Figures 5-18 through 5-21 show the effect of distance from one boundary for various b-values in Zone S. The same M_U was used in both zones. Figures 5-18 and 5-19 are for 10 Hz and Figures 5-20 and 5-21 are for 1 Hz.

Changes in b-values are a bit more complex to evaluate as they impact the larger earthquakes more than the smaller earthquakes. This is illustrated in Table 5.1.

Recall that we kept the number of events for $M=3.75$ the same for all b-values. If we had kept just the a-value the same, then the changes would

5. Guidelines to Determine when Updating is Needed

be much larger; conversely, if we had kept the number of events at $M=5$ the same, the effects would be smaller.

5.3.2 Effect of Source Characteristics

The plots with distance as the ordinate variable are useful to give overall trends and to see the impact of distance from the boundary of Zone S. However, to gain added insights and a more precise measure of the sensitivity of the results to the variations in seismicity parameters considered, it is useful to cross-plot for each individual site.

In Figures 5-22 to 5-33 we provide such plots for three sites, 2L (Figures 5-22 through 25), B (Figures 5-26 through 29), and 2S (Figures 5-30 through 33). Each site has the same four figures. For example, for site 2L, Figure 5-22 gives the effect of increasing M_u (in Zone S) on the ratio of

$$\frac{(\text{PE})}{(\text{PE base case})}$$

at a high ground motion level (see Figure 5-2) for several different rates in Zone S relative to the BR. Figure 5-23 shows the same information except at a moderate level of ground motion. Figure 5-24 shows the effect of increasing M_u in Zone S relative to Zone L on the ratio of S_a at a PE level of $1E-07$ (see Figure 5-3). Figure 5-24 shows the same information as Figure 5-23 except at a PE level of $1E-05$.

Where M_u is involved, the ground motion (GM) level or PE level at which the ratios are evaluated makes a significant difference. This can be seen not only by the change in ratios, but also by the change in shape of the curves between figures a and b and between figures c and d.

Figures 5-24 and 25 show that a new zone 25 km or more away from a site can be introduced with significantly different seismicity parameters in terms of both M_u and rate, and result in less than a 5 percent change in the estimate of S_a at 10 Hz at PE levels of interest. However, if the site is very close to the new zone, then there can only be relatively minor changes in the seismicity parameters or some updating is needed. Finally, Figures 5-30 through 33 show that if the site is in the new zone, only small changes can be introduced.

Note that the above conclusions are based only on the single simple model. In the actual case, where a number of experts are involved, it is likely that the range of estimates for rates and M_u for a number of experts at any site will be much larger from the changes suggested by the new data (see Section 4.2). However, only a few expert models might need updating and hence the actual impact would be much less.

5.4 Effect of New Zone on $\underline{Mc}$ and $\underline{Dc}$

In Section 5.3, we examined the impact that a new zone had on the hazard and, more importantly, on the estimate of the ground motion at the average of the 5- and 10-Hz hazard curve at a PE of $1E-05$. This is important because it impacts the scaling of the SSE spectral shape. However, changes in $\underline{Mc}$ —and to some extent $\underline{Dc}$ —could impact the spectral shape used. It is possible that a new zone might not increase the estimate of the ground motion at the site sufficiently to require updating, but $\underline{Mc}$ could be increased enough to be significant. Or, in addition, a new zone might increase both the level of ground motion and $\underline{Mc}$.

As discussed in Section 2.6, there is considerable uncertainty in the set of earthquakes used to determine an appropriate spectral shape. Thus, it would appear that unless $\underline{Mc}$ is changed by more than 0.25 units through the introduction of a new zone, updating may not be needed. Naturally we must also examine the impact on the estimate of the ground motion.

To investigate the potential impact of a new zone on $\underline{Mc}$ and $\underline{Dc}$ for a site, we computed the $\underline{Mc}$ and $\underline{Dc}$ for sites 5L, 3L, 2L, B, 1S and 2S for two cases:

BR (see Section 4.3) in both zones S and L (see Figure 5-1.), $M_u = 6.25$ in Zone L and $M_u = 7.25$ in Zone S.

BR in Zone L, 8xBR in Zone S, $M_u = 6.25$ in Zone L and $M_u = 7.25$ in Zone S.

Table 5.2 gives the analysis results for $\underline{Mc}$ and $\underline{Dc}$ based on the average of the 5-10-Hz hazard average at an RP level of $1E-05$. In Table 5.3, taken from Table 4.8, we give the $\underline{Mc}$ and $\underline{Dc}$ for three 1-Zone models. The first represents the base case without a Zone S. The other two cases are

given to see how different the results are for (1) a site located in a small zone with higher seismicity parameters than the surrounding regions and (2) a site located in a large zone with the same seismicity parameters as the small zone.

We concluded from Figure 5-12 that for case 1, the induction of a new Zone S with $M_u = 7.25$ with the same rate as Zone L would not have a significant impact at sites more than 25 km from the boundary of the new zone. Even at a site 12 km from the boundary (site 1L), the impact is relatively small—only about a 5 percent increase in the average of the 5-10-Hz ground motion level; M_c increases by 0.17 units. We also see that if Zone S were to become a major seismic zone with $M_u = 7.25$ and a rate of activity 8x the rate in the original Zone L, then this new zone would be important for sites to distances of about 60 km from the boundary.

5.5 Examples at Actual Sites

The sensitivity analysis using the Z zone model is useful; however, it does not include the large uncertainties that exist in the LLNL seismicity and ground motion input data supplied by various experts.

In this section, we examine the possible impact of new data on the need to update using actual sites and the seismicity and ground motion models used in the LLNL analysis.

The most likely case that we might encounter in the future is the discovery of paleo-liquefaction data that would suggest that larger earthquakes had occurred in a region than are recorded in the historical record. For example, recent studies (Obermeier 1997) have discovered paleo-liquefaction features in the Wabash Valley which were not known at the time the LLNL and EPRI studies were performed. We do not want to get into a discussion of the issues of just how large an earthquake caused the paleo-liquefaction features but only examine what impact this discovery might have. The largest historical earthquake in the Wabash Valley was approximately magnitude 5.5 or less event. For the purposes of this study, we examine two additional cases: (M) where the most likely estimate for M_u of the zone which contains the Wabash Valley Zone is set to $M_u \geq 6.5$ for each of the seismicity experts involved in the LLNL study and (L) where the most likely estimate for M_u is set to $M_u \geq 7$. By

this we mean that if the best estimate for M_u for the zone containing the Wabash Valley zone for any given expert was less than 6.5, for example, for case (M), the estimate was raised to 6.5 and the uncertainty bounds adjusted accordingly.

Because there are no existing NPP sites in the Wabash Valley, we selected a hypothetical site near Vincennes, Indiana. The location for the hypothetical Wabash Valley site is at the northeast end of the Valley and for some experts the zone which would contain most of the Wabash Valley might not include the site. Except for Expert 10, the zone which included most of the Wabash Valley either included the site or was within 35 km of the site. For Expert 10, the zone was within 40 km of the site.

We generated the hazard and controlling earthquakes for three cases given in Table 5.4.

Figures 5.34, 5.35, and 5.36 show the most likely yearly recurrence model for the region within 50 km of the Wabash Valley site for the cases given in Table 5.4. Figure 5.34 is for the base case. We see from Figure 5.34 that many of the experts considered it possible that M_u in the Wabash was as large as $M=6.5$. Figure 5.35 shows the same data as Figure 5.34 except the upper magnitude cut-offs for some experts have been raised to 6.5. Finally, Figure 5.36 shows case (L) when the upper magnitude cut-offs have been raised to $M_u \geq 7$.

There are two elements to the CR. The first is the magnitude and distance of the CE which controls the spectral shape and the second is the level of the acceleration average of the 5- and 10-Hz hazard curves which are used to scale the spectral shape corresponding to the CE.

Table 5.5 gives the computed controlling earthquakes based on both the average of the 5-10 Hz hazard curves and for the 1-2.5 Hz hazard curves for the three cases given in Table 5.4. It should be noted that these results for an actual site showing the effects of increasing M_u on the CE are consistent with the results given in Table 4.3 for a similar 1-zone model.

We noted above that relative to Figure 5.34, most of the seismicity experts thought a much larger than historical earthquake could occur in the Wabash Valley; hence, the discovery of the paleo-liquefaction features would have little impact on their estimates of the hazard provided that the

5. Guidelines to Determine when Updating is Needed

most likely estimate for the paleo-earthquake is around $M=6.5$ with an upper bound around $M=7$. We see from Table 5.5 that this is the case as there is little change in the CE in terms of magnitude and distance between Case B and Case M.

Figure 5.37 addresses the second element of the definition of the CR—namely the ground motion level. Figure 5.37 gives the UHS_a for the PE level corresponding to the CE for the three cases listed in Table 5.4 and the CEs in Table 5.5. As expected, there is very little change in the average of the 5 and 10 Hz S_a between Case B and Case M. However, if the median estimate for the magnitude of the paleo-earthquake is $M \geq 7$ (Case L), we see from both Table 5.5 and Figure 5.37 that the controlling earthquake would be impacted by the new information and the LLNL seismicity input would have to be updated to account for the paleo-liquefaction data.

The Wabash Valley site is a region of elevated seismicity; in fact, even for the base case (Case B), the UHS_a is higher than any of the existing sites. To see what impact this might have on the above conclusions, we also consider a site with lower seismicity. We selected the Vogtle site. Figure 5.38 gives the individual experts' most likely recurrence models for the region within 35 km of the Vogtle site. We see that a number of experts chose an $M_L \geq 6.0$. As with the Wabash Valley site, we examine three cases given in Table 5.6.

It should be noted that for the Vogtle site, Cases M and L are totally hypothetical, as at this time, there is no evidence for any paleo-liquefaction in the region.

Figures 5.39 and 5.40 give the modified recurrence models for each expert for Cases M and L. Table 5.7 gives the computed controlling earthquakes for the three cases in Table 5.6. For this analysis, the site conditions for Vogtle were taken as rock.

Figure 5.41 shows the UHS_a for the three cases listed in Table 5.6 and the CEs given in Table 5.7. If we compare Figure 5.41 to 5.37, we see that the change in the UHS_a between cases M and BC are slightly larger for Vogtle than for the Wabash Valley site. This is to be expected because, as can be seen by comparing Figure 5.34, 5.35, 5.38, and 5.39, more extensive modification of recurrence

models occurred for the Vogtle than for the Wabash Valley site. Interestingly enough, the damage in the UHS_a for Case L is larger for the Wabash Valley site than for the Vogtle site even though the change in recurrence models is more significant for the Vogtle site than for the Wabash Valley site. However, the overall rate of activity is much lower around the Vogtle site than around the Wabash Valley site. Because the UHS_a are for the same PE level, the larger earthquakes around the Vogtle site may not be contributing to the hazard at the PE level used to select the CE. Clearly, Case L would require modification of the seismicity parameters around the site and a careful reanalysis to determine the CEs. Case M is less clear. Going from a CE of 5.7 to 5.9 would suggest a slight modification of the spectral shape—but so slight that it would most likely be lost in the uncertainty in selecting the records to use to determine the appropriate spectral shape for the CE. The scaling of the S_a at the average of the 5 and 10 Hz spectral value increases by approximately 6% from 451 cm/s^2 to 479 cm/s^2 . It is interesting to note that even for Case L, where a massive change has been introduced, the scaling of the CE between Case BC and L is only an increase of approximately 12%.

It should be noted that these values are consistent with the sensitivity studies given in this section using a simple 2-zone model.

The above examples for the Vogtle and Wabash Valley sites assumed a worse case scenario where the change in M_L was in the zone containing the site. If the change was for some zone at some distance from the site, e.g., was greater than 20 km based on these results and the other sensitivity studies in Section 5, it is unlikely that the new information would have an impact on the CE and either the LLNL or EPRI model could be used.

EPRI obtained similar results using their model. Their results were presented at a meeting between NUMARC and NRC on February 4, 1993 held at the NRC facility in Rockville, MD and summarized by A. Murphy (1993).

5.6 Conclusions on When Updating is Needed

The goal of this section was to provide some guidance relative to the question of when it is necessary to subdivide a region into several source zones. We noted that there are a number of

possible indications for introducing a new source zone, e.g., changes in or new knowledge about the geology. We also noted that there was no way to assess such factors except as they impact the rate of activity in a zone, M_u , or the b-value. Thus the sensitivity studies in this section only address the changes in the parameters of the earthquake recurrence model and the distance from the site to the zone of interest. Thus, if geological changes or other geophysical factors do not suggest a change in either M_u , rate, or b-value, then they have no impact on the results and no computational updating is needed.

There are two types of seismic hazard studies: (1) site-specific—where the site location is known and (2) regional—where the site can be located anywhere in the region. For site-specific studies, distance from the source zone is very helpful in determining if a new zone is going to impact the hazard at a site and/or in determining how much effort is required for refining the location of the boundary, the zone, or the parameters of the earthquake recurrence model. For regional studies, the distance from a new zone is not known and hence cannot be used to determine if new data needs to be included in the model.

The results in Section 5.3 and 5.4 indicate that distance from the boundary is a very important parameter and that the influence of a zone doesn't extend more than 15–25 km from the zone boundary unless M_u is very large. The results suggest that beyond 25 km or 50 km, little care is needed and—unless very major changes in both M_u and rate are suggested by the new data—no updating is needed. However, for credibility, it is important to carefully define the source zones so that a reviewer has confidence in the study. The results of this study are useful to evaluate how much effort is needed to determine the location of

a source boundary—or if it is highly uncertain that several alternatives are needed.

The sensitivity results indicate that unless the new information suggests the need for a new zone with a relatively large increase in rates or M_u , it will have little effect on the hazard unless the data suggest that the new zone is very close (less than 10 km) from the site. The results of this section clearly indicate that if the boundary is more than 15–20 km from the site of interest, then alternative locations for a boundary are not needed and just a best estimate to the location of the boundary is all that is required.

One possible problem not addressed by the sensitivity studies in this section is that with the introduction of multiple source zones in a region, the historical activity will be subdivided into several zones making it more difficult to estimate the a- and b-values. This must be kept in mind when doing a source zonation. If too many zones are introduced, it may be very difficult to estimate the a- and b-values for any of the zones. If these zones are very near the site, then the uncertainty in the estimate of the a-values could inflate the rate in zone which would have a direct impact on hazard. If the site is within a zone, then the hazard varies directly as the rate if it is on the boundary between the zones at about the average of the rate of the two zones.

When comparing the figures that show the ratio of the PE to those figures that show the ratio of ground motion, it is apparent that changes in rates, M_u s, etc., have a more significant impact on the ratio of the PEs compared to the ratio of ground motion. For design purposes, it is the level of ground motion that is important. This could be helpful in assessing whether the introduction of a new zone is significant.

5. Guidelines to Determine when Updating is Needed

Where changes in M_u or b-values are involved, it is important to consider the level at which the assessment of the importance of the change is measured. For most cases, the most significant level to assess the importance of a change is at the moderate ground-motion level or at a PE of 1E-05, as these levels contribute most of the risk.

Table 5.1. Change in the number of earthquakes in Zone S as compared to Zone L as a function of the b-value in Zone S

b	Magnitude			
	5.25	6.25	6.75	7.25
-0.8				
-1.2	0.5x	0.32x	0.25x	0.2x

Table 5.2. M_c and D_c for average of 5-10-Hz hazard curve for selected sites for 2-Zone models shown in 5-1 at RP level of 1E-05

Case	Site 5L	Site 3L	Site 2L	Site 1L	Site B	Site 1S	Site 2S
BR in both zones							
$M_u = 6.25$ in Zone L	5.7	5.73	5.79	5.87	5.97	6.05	6.06
$M_u = 7.25$ in Zone S	16.1	16.5	16.9	17.3	16.2	15.4	15.3
BR in Zone L							
8xBR in Zone S	5.7	5.90	6.17	6.32	6.38	6.43	6.48
$M_u = 6.25$ in Zone L	16.1	20.5	24.9	21.7	14.6	12.8	12.9
$M_u = 7.25$ in Zone S							

Table 5.3. 1-Zone results from Table 4.8

Case	
BR	5.7
$M_u = 6.25$	16.1
BR	6.28
$M_u = 7.25$	20.1
8xBR	6.54
$M_u = 7.25$	15.6

Table 5.4. Three cases for the value of M_u in the Wabash Valley zone

(B)	Base Case—results based on using each expert's seismicity input
(M)	$M_u \geq 6.5$ in the zone containing the Wabash Valley zone
(L)	$M_u \geq 7$ in the zone containing the Wabash Valley zone

Table 5.5. Effect of possible modification of M_u on the CE for the hypothetical Wabash Valley site for the three cases given in Table 5.4

Case	av 5-10 Hz		av 1-2.5 Hz	
	magnitude	distance	magnitude	distance
B	5.8	17	7.4	268
M	5.9	18	7.4	266
L	6.2	22	7.3	234

5. Guidelines to Determine when Updating is Needed

Table 5.6. Three cases for M_u in the Zone containing the Vogtle Site

(B)	Base Case—results based on using each expert's seismicity input
(M)	For those experts whose most likely estimate for M_u in the zone containing the site was less than 6.5, the M_u was modified to 6.5 and the uncertainty of M_u expressed by the expert was modified to be consistent with the changed value for the most likely estimate for M_u .
(L)	Similar to (M) except $M_u=7$ was used as the minimum value for the most likely estimate for M_u for any expert.

Table 5.7. Effect of possible modification of M_u on the CE for the Vogtle site

Case	av 5-10 Hz		av 1-2.5 Hz	
	magnitude	distance	magnitude	distance
BC	5.7	17	6.7	156
M	5.9	18	6.7	157
L	6.1	21	6.7	157

Figure 5-1. Geometry of the 2-Zone model used and location of the sites relative to the boundary between Zone L and Zone S

5. Guidelines to Determine when Updating is Needed

Figure 5-2. Illustration of how the PEs are determined. The PE for the moderate level S_a is determined by entering the hazard curve for the case of interest at the S_a value given in the text. The corresponding PE level (1) is read-off at the same S_a value, the hazard curve for the base case is entered, and the corresponding PE level (2) is read off the curve. The ratio plotted is $\frac{(PE)_1}{(PE)_2}$.

Figure 5-3. Illustration of how the S_a s are determined. The hazard curves are entered at the desired PE level, for example $1E-05$. The corresponding ground motion value (S_a) for the case of interest (1) and the base case (2) are read off the curves. The ratio of S_a s plotted is $\frac{(S_a)_1}{(S_a)_2}$.

5. Guidelines to Determine when Updating is Needed

Figure 5-4. 10-Hz effect of distance and rate $M_H = 6.25$ in Zone S with a moderate GM level and a ratio of $\frac{(PE)}{(PE \text{ base case})}$

Figure 5-5. 10-Hz effect of distance and rate $M_H = 6.25$ in Zone S with PE of $1E-05$ and a ratio of $\frac{(S_a)}{(S_a \text{ base case})}$

Figure 5-6. 1-Hz effect of distance and rate $M_U = 6.25$ in Zone S with a moderate GM level and a ratio of $\frac{(PE)}{(PE \text{ base case})}$

Figure 5-7. 1-Hz effect of distance and rate $M_U = 6.25$ in Zone S with PE of $1E-05$ and a ratio of $\frac{(S_a)}{(S_a \text{ base case})}$

5. Guidelines to Determine when Updating is Needed

Figure 5-8. 10-Hz effect of distance and M_u for the same rate in both Zone L and S with a moderate GM level and a ratio of $\frac{(PE)}{(PE \text{ base case})}$

Figure 5-9. 10-Hz effect of distance and M_u for the same rate in both Zone L and S with a PE of $1E-05$ and a ratio of $\frac{(S_a)}{(S_a \text{ base case})}$

Figure 5-10. 1-Hz effect of distance and M_u for the same rate in both Zone L and S with a moderate GM level and a ratio of $\frac{(PE)}{(PE \text{ base case})}$

Figure 5-11. 1-Hz effect of distance and M_u for the same rate in both Zone L and S with a PE of $1E-05$ and a ratio of $\frac{(S_a)}{(S_a \text{ base case})}$

5. Guidelines to Determine when Updating is Needed

Figure 5-12. 10-Hz base rate in both zones with a PE of 1E-05 and a ratio of $\frac{(S_a)}{(S_a \text{ base case})}$

Figure 5-13. 10-Hz 8x base rate in Zone S with a PE of 1E-05 and a ratio of $\frac{(S_a)}{(S_a \text{ base case})}$

Figure 5-14. 1-Hz base rate in both zones with a PE of 1E-05 and a ratio of $\frac{(S_a)}{(S_a \text{ base case})}$

Figure 5-15. 1-Hz 8x base rate in Zone S with a PE of 1E-05 and a ratio of $\frac{(S_a)}{(S_a \text{ base case})}$

5. Guidelines to Determine when Updating is Needed

Figure 5-16. 5-Hz base rate in Zone S with a PE of 1E-05 and a ratio of $\frac{(S_a)}{(S_a \text{ base case})}$

Figure 5-17. 2.5-Hz 8x base rate in Zone S with a PE of 1E-05 and a ratio of $\frac{(S_a)}{(S_a \text{ base case})}$

Figure 5-18. 10-Hz effect of distance and b-value with the same M_u (6.25) in both zones with a moderate GM level and a ratio of $\frac{(PE)}{(PE \text{ base case})}$

Figure 5-19. 10-Hz effect of distance and b-value with the same M_u (6.25) in both zones with a PE of $1E-05$ and a ratio of $\frac{(S_a)}{(S_a \text{ base case})}$

5. Guidelines to Determine when Updating is Needed

Figure 5-20. 1-Hz effect of distance and b-value with the same M_H (6.25) in both zones with a moderate GM level and a ratio of $\frac{(PE)}{(PE \text{ base case})}$

Figure 5-21. 1-Hz effect of distance and b-value with the same M_H (6.25) in both zones with a PE of $1E-05$ and a ratio of $\frac{(S_a)}{(S_a \text{ base case})}$

Figure 5-22. Site 2L 10-Hz effect of M_u and rate changes in S with a high GM level and a ratio of $\frac{(PE)}{(PE \text{ base case})}$

Figure 5-23. Site 2L 10-Hz effect of M_u and rate changes in S with a moderate GM level and a ratio of $\frac{(PE)}{(PE \text{ base case})}$

5. Guidelines to Determine when Updating is Needed

Figure 5-24. Site 2L 10-Hz effect of M_u and rate changes in S with a PE of $1E-07$ and a ratio of $\frac{(S_a)}{(S_a \text{ base case})}$

Figure 5-25. Site 2L 10-Hz effect of M_u and rate changes in S with a PE of $1E-05$ and a ratio of $\frac{(S_a)}{(S_a \text{ base case})}$

Figure 5-26. Site B 10-Hz effect of μ and rate changes in S with a high GM level and a ratio of $\frac{(PE)}{(PE \text{ base case})}$

Figure 5-27. Site B 10-Hz effect of μ and rate changes in S with a moderate GM level and a ratio of $\frac{(PE)}{(PE \text{ base case})}$

5. Guidelines to Determine when Updating is Needed

Figure 5-28. Site B 10-Hz effect of M_u and rate changes in S with a PE of $1E-07$ and a ratio of $\frac{(S_a)}{(S_a \text{ base case})}$

Figure 5-29. Site B 10-Hz effect of M_u and rate changes in S with a PE of $1E-05$ and a ratio of $\frac{(S_a)}{(S_a \text{ base case})}$

Figure 5-30. Site 2S 10-Hz effect of M_u and rate changes in S with a high GM level and a ratio of $\frac{(PE)}{(PE \text{ base case})}$

Figure 5-31. Site 2S 10-Hz effect of M_u and rate changes in S with a moderate GM level and a ratio of $\frac{(PE)}{(PE \text{ base case})}$

5. Guidelines to Determine when Updating is Needed

Figure 5-32. Site 2S 10-Hz effect of M_u and rate changes in S with a PE of $1E-07$ and a ratio of $\frac{(S_a)}{(S_a \text{ base case})}$

Figure 5-33. Site 2S 10-Hz effect of M_u and rate changes in S with a PE of $1E-05$ and a ratio of $\frac{(S_a)}{(S_a \text{ base case})}$

Figure 5-34. Most likely yearly recurrence model for each of the seismicity experts based on the zones within 50 km of the hypothetical Wabash Valley site (base case).

Figure 5-35. Most likely yearly recurrence model for each of the seismicity experts for Case M based on the zone within 50 km of the hypothetical Wabash Valley site.

5. Guidelines to Determine when Updating is Needed

Figure 5-36. Most likely yearly recurrence model for each of the seismicity experts for Case L based on the zone within 50 km of the hypothetical Wabash Valley site.

Figure 5-37. Comparison of the UHS_a at a PE level of 1E-05 for the hypothetical Wabash Valley site for the three cases of modified M_u given in Table 5.4.

Figure 5-38. Most likely yearly recurrence model for each of the seismicity experts based on the zones within 35 km of the Vogtle site.

Figure 5-39. Most likely yearly recurrence model for each of the seismicity experts for Case M based on the zones within 35 km of the Vogtle site.

5. Guidelines to Determine when Updating is Needed

Figure 5-40. Most likely yearly recurrence model for each of the seismicity experts for Case L based on the zones within 35 km of the Vogtle site.

UHS_a for the Vogtle Site (rock site category)
1---1 base case 2---2 case M 3---3 case L

Figure 5-41. Comparison of the UHS_a at a PE level of 1E-05 for the Vogtle site for the three cases of modified M_u given in Table 5.6 and CEs on Table 5.7. For this plot, the soil category was used as rock.

6. DETERMINATION OF THE SSE GROUND MOTION

6.1 Design Spectra

In the past, the SSE ground motion was used to design the facility. However, this may not be the case in the future as the next generation of nuclear power plants will most likely be licensed under 10 CFR Part 52. These nuclear power plants will have a certified design spectrum chosen to make them suitable at most possible sites in the central and eastern U.S.

For these type of facilities, the primary role of the SSE ground motion obtained following the approach used in RG1.165 will be to determine if the design spectra used are adequate for the site, and to determine a site-specific SSE for the design of structures and other facilities that are seismic category 1 but are not part of the standardized design package, e.g., dams, pump houses, etc.

6.2 Issues in Determining the SSE Ground Motion

The PSHA results in a uniform hazard spectrum at any given site for any selected RP. In Section 2, the appropriate RP was selected as 1E-05 probability of exceedance per year for the average of the 5- and 10-Hz hazard curves.

It is interesting to examine how well the 5% damped median spectral acceleration (S_a) for the average of 5- and 10-Hz hazard curves at an RP of 1E-05 correlates with rate of activity and with the computed $\underline{M}_c$. In Figure 6-1, we plot the average of 5-10-Hz spectral acceleration (S_a) at an RP of 1E-05 based on the median hazard curves for all existing rock sites versus the median rate of $M \geq 5.25$ earthquakes based on the zones within 35 km of each site. We see from this figure that as one might expect, there is a good correlation between rate and S_a . The scatter is due to such factors as variations in M_u between sites and/or effective b-value.

In a few cases, there is scatter because 35 km is not the appropriate region to use to compute the rate. For example, the site labeled "c" in Figure

6-1 has a much higher S_a than indicated by the rate of $M > 5.25$ within 35 km of the site. This site is the Callaway site. In Section 4 we noted that the distribution of the percent contribution to the hazard at the Callaway site was significantly different than most in that 16% of the hazard at the selected RP came from larger earthquakes in a zone centered 78 km from a site.

In Figure 6-2 we plot S_a versus the computed $\underline{M}_c$ for rock sites. We see that there is a reasonable correlation but a somewhat greater scatter. This scatter is due to variations in M_u , rate and effective b-value between sites.

The methodology outlined in Section 2 results in an estimate of at least one $\underline{M}_c$ and $\underline{D}_c$ for any site. For some sites, a second $\underline{M}_c$ and $\underline{D}_c$ exists based on the average of 1-2.5-Hz hazard curves for distances greater than 100 km.

The question now is how to use the above information to determine the SSE ground motion. Sections 3 and 4 show that although $\underline{M}_c$ is correlated with rate of activity around the site, other factors such as the value for M_u or effective b-value as a function of magnitude also play a very important role in establishing the value for $\underline{M}_c$. We saw in Section 2.7 that the "return period" of $\underline{M}_c$ varied significantly between sites. Thus, if one were to directly use $\underline{M}_c$ and $\underline{D}_c$ to estimate the ground motion at a site, it might well be much larger than that obtained from the PSHA at the selected RP. In general, the estimated ground motion from $\underline{M}_c$ and $\underline{D}_c$ would be the highest relative to the PSHA at low-seismicity sites and lowest relative to the PSHA at the high-seismicity sites.

In the past, the use of site-specific spectra (SSS) (Bernreuter et al. 1987) without scaling would also lead to the same problem. That is, the use of $\underline{M}_c$ and $\underline{D}_c$ to develop an SSS could lead to an estimate of ground motion much higher than that calculated from a PSHA at the RP used to determine $\underline{M}_c$ and $\underline{D}_c$. Thus, the ground motion from $\underline{M}_c$ and $\underline{D}_c$ would be highest relative to the PSHA at the low seismicity sites and lowest relative to the PSHA at higher seismicity sites. In Section 4 we indicated how the relative distribution of the hazard around the site plays a

6. Determination of the SSE Ground Motion

very important role in the value for $\underline{M}_c$. In addition, the $\underline{M}_c$ is (for low-seismicity sites) artificially high because integration was for $M \geq 5$. Section 5 shows that for lower-seismicity sites, the $\underline{M}_c$ is much lower if earthquakes of magnitude 3.75 to 5 are included.

Thus, there is a valid argument that $\underline{M}_c$ and $\underline{D}_c$ should be used to (1) obtain the appropriate spectral shape and (2) establish the appropriate level of the SSE by scaling the spectral shape to the S_a at the average of the 5- and 10-Hz hazard curves.

There is another argument to make in favor of scaling the spectral shape obtained from $\underline{M}_c$ and $\underline{D}_c$ by the results of the PSHA. The additional reason for scaling is that different ground motion models and/or site-specific spectra types of approaches can result in significantly different estimates of the ground motion at a site for the same $\underline{M}_c$ and $\underline{D}_c$. Scaling ensures that in the 5- to 10-Hz range, the range of most interest, the required spectral level will be approximately the same no matter what approach is used to obtain the SSE spectral shape.

In summary, one of the main issues in using $\underline{M}_c$ and $\underline{D}_c$ for a site to estimate the SSE ground motion is whether to use just $\underline{M}_c$ and $\underline{D}_c$ to define the appropriate spectral shape and obtain the level by scaling the shape by the results of the PSHA at the selected RP, or to use $\underline{M}_c$ and $\underline{D}_c$ to directly estimate the ground motion.

Another important issue is how to treat an $\underline{M}_c$ and $\underline{D}_c$ associated with the average of 1-2.5-Hz hazard curves. This is not a simple issue to address. Table 2.15 gives the percent contribution to the total hazard for the average of 1-2.5-Hz hazard curves at RP case RG for distance ≥ 100 km for the sites where this contribution is $\geq 5\%$. Here, the percent contribution ranges from 85% to 5%. However, of the 38 sites in the table, only 5 sites have a contribution to the hazard for the average of 1-2.5-Hz hazard curves for distances ≥ 100 km greater than 50%. For the most part, the percent contribution is in the 20-30% range. Thus, it does not seem to be reasonable to scale a spectral shape obtained from the $\underline{M}_c$ and $\underline{D}_c$ for the average of 1-2.5-Hz hazard curves and

distances ≥ 100 km to the average of 1-2.5-Hz hazard curve obtained from the PSHA at RP case RG. It would make some sense to scale it to the average of the 1-2.5-Hz hazard curves for distances ≥ 100 km at PE level RG. However, such an approach would require a significant amount of additional computation and not really provide any useful information.

An alternative approach to scaling would be to use $\underline{M}_c$ and $\underline{D}_c$ based on the average of 1-2.5-Hz hazard curves for distance ≥ 100 km to directly estimate the ground motion. One could make the same arguments against this approach as we made above relative to using $\underline{M}_c$ and $\underline{D}_c$ based on the average of 5-10-Hz hazard curves to directly compute the spectral level for the SSE. However, the decision was made that it would be best to accept the increased estimate for ground motion for those few sites where the use of $\underline{M}_c$ and $\underline{D}_c$ to compute the ground motion directly leads to an estimate of larger ground motion in the 1-2.5-Hz range than the estimate obtained in the same 1-2.5-Hz range from the spectral shape based on $\underline{M}_c$ and $\underline{D}_c$ for 5-10 Hz and scaled by the PSHA results at RP case RG.

Lastly, the approach suggested in DG1032 for obtaining the spectral level for the SSE by scaling a spectral shape obtained from $\underline{M}_c$ and $\underline{D}_c$ to the spectral acceleration level for the average of the 5- and 10-Hz hazard curves at the RP level RG, is only useful if it leads to approximately the same results independent of the ground motion models used in the hazard analysis and/or opinions from the set of seismicity experts.

It is important to note that if the hazard analyses are performed using very different models than those used to develop the LLNL or EPRI results, then an appropriate value for PE must be obtained using the approach given in Section 2.2.

6.3 Discussion of Issues

Let us first address the last issue raised in Section 6.2. Will the same estimate for the SSE be calculated if the level for the SEE ground motion is set by scaling the spectral shape obtained from $\underline{M}_c$ and $\underline{D}_c$ by the average of S_a from the 5- and 10-Hz hazard curves at the appropriate RP level?

By appropriate RP level, we mean that the RP level used to obtain the S_a values from the hazard curves is computed for each PSHA study following the approach given in Section 2.2.

First, to address this issue, we note that $\underline{M}_c$ and $\underline{D}_c$ are approximately the same for various studies. Our results showed only minor changes for the $\underline{M}_c$ and $\underline{D}_c$ for each site between the results given in Bernreuter et al. (1989) and Savy (1993) although there was about a factor of 5 difference in the PE level and very different ground motion models being used in each study. We also noted in Section 2.8 that the differences in $\underline{M}_c$ and $\underline{D}_c$ for a selected set of sites based on the Savy et al. (1993) and EPRI (1993) results were small. Thus, different PSHA studies will lead to approximately the same spectral shape for each site in the 5-10-Hz range. If the same approach is used to convert $\underline{M}_c$ and $\underline{D}_c$ into a spectral shape, then the shape will be the same for various studies. The same is true for the spectral level. For example, as noted, there is about a factor of 5 difference in PE for the PE level RG between the LLNL study (Bernreuter et al. 1989) and the updated results given in Savy et al. (1993). Very different sets of ground motion models were used. For each of the 69 sites listed in these studies, we entered the hazard curves at the appropriate PE level for each set of results and computed the ratio of S_a at 7.5 Hz. For the 69 sites, the average of this ratio is 0.99. The range of the ratio varied between 0.75 to 1.21. Only at 3 sites was there more than a 20% difference and for 37 sites the difference in the ratio of S_a was 10% or less.

It should be noted that at 1 Hz, for example, the differences in the ratio of S_a between two studies with very different ground models can become much larger.

Section 6.2 argues that the approach suggested in RG1.165 uses only $\underline{M}_c$ and $\underline{D}_c$ to obtain a spectral shape and to obtain the spectral level by scaling to the S_a level obtained from the PSHA. How does this compare to directly using the $\underline{M}_c$ and $\underline{D}_c$ to obtain both the shape and level of the SSE? This is a somewhat difficult issue to address. We have tried to address this issue in the following way.

We selected two different ground motion models considered appropriate for use in the central and eastern U.S. Both models were assumed to have a lognormal distribution. Thus, it was possible to compare the estimate for S_a at 7.5 Hz (average of 5 and 10 Hz) obtained from the PSHA at the PE level determined in Section 2.2, and estimate the percentile that this value represented relative to using $\underline{M}_c$ and $\underline{D}_c$ and the selected ground motion model to estimate the ground motion directly. Ideally, we would like for this percentile to be above the 50 percentile level and nearer to the mean plus 1-sigma level.

Note that the results given below are made only at rock sites. Soil amplification factors introduce a much larger uncertainty and make it very difficult to interpret the results.

The two ground motion models used are (1) a slightly modified version of the Boore-Atkinson (1987) model (modification provided by D. Boore as part of the Bernreuter et al. 1989 study) and (2) a model recently developed for EPRI (1993). We found relative to the Boore-Atkinson model that the S_a value of 7.5 Hz obtained from the PSHA at the PE level RG would be, on the average, at the 91 percentile level compared to computing the S_a using the Boore-Atkinson model at the $\underline{M}_c$ and $\underline{D}_c$ for each site. The range of the percentile varied from 97% to 77%. The lower percentiles were for the sites with low seismicity.

Figures 6-3a and b help clarify the above statements. In Figure 6-3a, we plot, using the symbol P-P, the S_a values obtained from the PSHA for the Limerick site at RP RG. We plot, using the symbol C-C, the estimate of the S_a values using the modified Boore-Atkinson equations for S_a as a function of magnitude and distance. We see from Figure 6-3a that the PSHA estimate is significantly higher than the 1-sigma estimate of the Boore-Atkinson model at 7.5 Hz. In fact, to make the Boore-Atkinson estimate equal to the PSHA at 7.5 Hz would require going to the 94 percentile. In Figure 6-3b, we show the case for the low-seismicity site. We see from Figure 6-3b that the estimate of S_a obtained at the 1-sigma level of the Boore-Atkinson model using $\underline{M}_c$ and $\underline{D}_c$ as the magnitude and distance is somewhat larger than the estimate of ground

motion obtained from the PSHA. In this case, to have the estimate of ground motion from the Boore-Atkinson model equal to the PSHA would require only using the 78 percentile level which is slightly smaller than the 1-sigma level.

We found, relative to the EPRI (1993) model that the S_a value at 7.5 Hz obtained from the PSHA at the PE level RG would on the average be at the 77 percentile level (the median at the 80 percentile level) compared to computing the S_a using the EPRI model and $\underline{M}_c$ and $\underline{D}_c$ for each site. The range of the percentiles varied from 88% to 59%. The lower percentiles correspond to the lower seismicity sites.

Based on these results, the EG and the NRC Staff concluded that the approach given in RG1.165 for setting the level of SSE by scaling using the results of PSHA was the best overall approach to use and provided the level of protection needed.

Let us now examine the role of the CE associated with the 1-2.5-Hz hazard curves for distances greater than 100 km. In Section 6.2, we made an argument that, unlike the 5-10-Hz case where the CE would be scaled to the results of the PSHA at the RP, we should not scale the CE for the 1-2.5-Hz case to the results of the PSHA. One of the main arguments we gave was that for most sites the contribution to the hazard for distances greater than 100 km is much less than 50%. However, one could argue that the magnitude-distance bin of the CE for the 5-10-Hz case also is generally less than 50%. The big difference is that for the 5-10-Hz case, the adjacent bins also contribute significantly. The spectral shape of nearby 5.25 earthquakes is not significantly different than 5.75 earthquakes. However, the spectral shape of 7.25 earthquakes at 300 km is very different. This point is illustrated in Figures 6-4a and b. In Figure 6-4a we plot the UHS_a obtained from the PSHA for the Browns Ferry site at the RP RG (plot symbol P), the estimate of the ground motion based on $\underline{M}_c$ and $\underline{D}_c$ for the average of the 5- and 10-Hz hazard curves (plot symbol C) and the estimate of the ground motion based on the $\underline{M}_c$ and $\underline{D}_c$ for the average 1-25-Hz hazard curves for distances greater than 100 km (plot symbol C3). The estimated ground motions are based on the EPRI model at the 1-sigma level.

Also plotted on the figure are two vertical lines: one at 1.75 (average of 1-2.5) and one at 7.5 (average of 5-10).

We see from this figure that, even for this case, when most of the hazard for the average of 1-2.5-Hz case is from far field, the spectral shape of this distant earthquake is significantly different than that of the UHS_a obtained from the PSHA. We also note that in the 5-10-Hz range, the spectral shape of the UHS_a is similar to that of the EPRI ground motion model.

In Figure 6-4b we plot the same information as in Figure 6-4a except for the Shearon Harris site. We see from Table 2.5 that the magnitude and distance bins greater than 100 km only contribute 15% of the hazard at the Shearon Harris site. We see from Figure 6-4b that the spectral shape of UHS_a is significantly different than the spectral shape of the EPRI ground motion model. Also in this case, because distant earthquakes only contribute 15% of the hazard, the UHS_a is significantly higher than from the estimate based on $\underline{M}_c$ and $\underline{D}_c$ at 1-2.5 Hz.

It is interesting to contrast the shape of the UHS_a between Shearon Harris and Browns Ferry. Above 5 Hz, the shapes are not too different, reflecting that earthquakes in the 5.5-6 range within 0-25 km contribute most to the hazard for both sites. Below 5 Hz, we see that the UHS_a shape for Browns Ferry is strongly influenced by the large distant events; whereas, for the Shearon Harris site, the large distant earthquake only contributes 15%. Hence, they hardly influence the spectral shape. It is also worthwhile to note that at the Browns Ferry site, the large distant events contribute almost 100% of the hazard at 1 Hz but only about 60% at 2.5 Hz and only 18% at 5 Hz. Thus, the shape of UHS_a is different from any real earthquake.

If a site has a CE for the 1-2.5 Hz hazard curves, the CE is used to assess the adequacy of the SSE based on the spectral shape corresponding to the CE and scaled to the UHS_a at 7.5 Hz.

According to the Standard Review Plan Section 2.5.2.6, the preferred way to obtain the spectral shape is to use actual records and develop a site

specific spectra (SSS). For purposes of illustration, we use the SSS developed in Bernreuter et al. (1987). It should be noted that these shapes are outdated and could be considerably improved. The earthquake ground motion recordings used in Bernreuter et al. (1987) are primarily western U.S. earthquakes which, because of local soil and rock conditions in the west as compared the east, have more longer-period energy and much less short-period energy than observed in strong eastern U.S. ground motion recordings. However, for purposes of illustration, they are adequate.

In Bernreuter et al. (1987) four sets of spectra were developed:

- rock sets
- deep soil sets
- $M = 5.25$ sets
- and $M = 5.75$ sets

All four sets, as noted in Section 2.6, correspond to the distance ranges of the CEs for the average of 5-10 Hz.

In Figures 6-5a and b, we plot the UHS_a (plot symbol P), the appropriate SSS based on $\underline{M_c}$ and $\underline{D_c}$ scaled to the UHS_a at 7.5 Hz (plot symbol x), and the estimate of the spectra evaluated at $\underline{M_c}$ and $\underline{D_c}$ for the average of 1-2.5 Hz CE using the

EPRI model at the 1- sigma level (plot symbol C3) for the Browns Ferry Site (Figure 6-5a) and the Wolf Creek Site (Figure 6-5b).

We see from Figure 6-5a that the scaled SSS does not require any long period modification.

However, from Figure 6-5b we see that the SSE for the site would have a modified SSS to account for the long period motion from the CE based on the 1-2.5 Hz hazard curves.

It is important to note here that different GMMs often give much different estimates of GM. For example, had we used the modified Boore-Atkinson model instead of the EPRI model, no alteration would be required.

We also see from Figures 6-5a and b that the spectral shape of the SSS is significantly different from both the UHS_a and the EPRI GMM. We see from Figure 6-5b that the shape of the SSS for the $M = 5.25$ case is closer to the UHS_a and the EPRI GMM. This is because the set of earthquakes used to obtain this spectral shape had more eastern U.S. earthquakes than the 5.75 bin (which had none). There is still a lack of eastern U.S. earthquake GMM data recording in the magnitude and distance ranges of interest; however, here now exist models which can be used to correct the western U.S. data to account for the soil/rock differences between the two regions. The issues of what the appropriate spectral shapes should be are being studied by NRC at this time.

6. Determination of the SSE Ground Motion

Figure 6-1. Plot of the average of 5-10 Hz S_a values at RP level RG versus rate of $M \geq 5.25$ earthquakes within 35 km of each site. Only S_a values for rock sites plotted.

Figure 6-2. M_c versus S_a (average of 5-10-Hz at RP level RG) for all rock NPP sites in the central and eastern U.S.

6. Determination of the SSE Ground Motion

Figure 6-3a. Comparison between the Uniform Hazard Acceleration Spectra (UHS_a) at RP RG obtained from the PSHA and a 1-Sigma estimate of the UHS_a using the Boore-Atkinson model evaluated at M_c and D_c for a higher-seismicity site

Figure 6-3b. Comparison between the UHS_a at RP RG obtained from the PSHA and a 1-Sigma estimate of the UHS_a using the Boore-Atkinson model evaluated at $\underline{M_c}$ and $\underline{D_c}$ for a low-seismicity site

6. Determination of the SSE Ground Motion

Figure 6-4a. Comparison between the UHS_a (P—P), an estimate of S_a using the EPRI GMM at the 1-Sigma level evaluated at M_c and D_c based on the average of the 5-10-Hz hazard curves (C—C), and the estimate of S_a using the EPRI GMM at the 1-Sigma level evaluated at M_c and D_c based on the average of 1-2.5-Hz hazard curves for distances greater than 100 km (C3—C3) for RP level RG for the Browns Ferry site

Figure 6-4b. Same curves plotted as in Figure 6-4a except for the Shearon Harris site

6. Determination of the SSE Ground Motion

Figure 6-5a. Comparison between the UHS_a (P—P) and the SSS scaled to the UHS_a at 7.5 Hz (X—X) and 1-Sigma estimate of the S_a based on the EPRI GMM evaluated at the M_c and D_c based on the average of 1-2.5-Hz hazard curves for distances greater than 100 km for the Browns Ferry site. The SSS shape is for the M=5.25 set given in Bernreuter et al. 1987.

Figure 6-5b. Same curves plotted as in Figure 6-5a except for the Wolf Creek site. The SSS shape is for the $M=5.25$ set given in Bernreuter et al. (1987).

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APPENDIX A. SEISMIC HAZARD CHARACTERIZATION OF A SITE IN THE WESTERN U.S.

Summary

A seismic hazard characterization was performed for the Idaho National Engineering and Environmental Laboratory (INEEL) site to determine the controlling earthquakes (CE) associated with the PE level used in the central and eastern U.S. This site is of interest because of the relatively low rate of seismic activity on the nearby faults. The return period of large earthquakes is well over 1,000 years—closer to 10,000 years.

A sensitivity analysis was performed on different PE levels. Preliminary conclusions are given based on the available results.

Parameters of the Seismic Hazard Analysis

Location

The proposed INEEL site location for the new Production Reactor is:

- Longitude: 112.875 degrees west
- Latitude: 43.5833 degrees north

Input Parameters

The seismicity (zonation and recurrence modeling) and ground motion input used in this analysis are those used by LLNL in the DOE study for the NPR study (1992).

The proposed INEEL NPR site is located near the northwestern edge of the Eastern Snake River Plain (ESRP) at the border with the basin and range province (see Figure A-1). The middle Rocky Mountains east and northeast and the northern Rocky Mountains north and northwest complete the overall tectonic environment around the site. The INEEL site is located close to the Centennial Tectonic Belt (CTB). Also close to the site is the Intermountain Seismic Belt (ISB) which shows a high level of seismicity. The ISB has had repeated episodes of surface rupture, associated with large

earthquakes, the largest of which was the 1959 Hegben Lake, Montana, earthquake with an estimated moment magnitude of $M_W = 7.3$. The 1983 Borah Peak earthquake occurred in the CTB with an estimated $M_W = 6.8$. Figure A-2 shows the locations of earthquakes with magnitude greater than five (Note: surface magnitude) within 200 miles of the INEEL site.

Although there is a large diversity of zonation models between the seismicity experts (nine experts), there are a few elements common to most of them.

- For most experts, the highest contributors to the hazard at the site are the two existing faults running northwest-southeast, in the form of the Lehmi Fault and the Lost River Fault (see Figure A-3).
- The next dominant features are the volcanic rift zones within the ESRP, with some of them within the INEEL property boundaries. In the opinions of the seismicity experts, these rifts are capable of producing earthquakes in the range of 4.5 to 5.5 magnitude with return periods as low as 1000 years and as high as 10,000 years (see Figure A-4).
- Most experts do not believe that any of the three ranges' faults (i.e., Lost River, Lehmi, and Beaverhead) extend east-westward across the ESRP under the INEEL site. This is very important because it eliminates, for these experts, the possibility of a large earthquake near or at the site. The experts who considered these fault extensions as physically possible associated very little likelihood to those scenarios (one to five percent degree of belief).

The ground motion models provided by the experts include those developed for the western U.S. by Boore (1982, 1983, 1986) and Campbell (1990) as well as Sadigh (1990), and Trifunac and Lee (1987). In addition, the latest ground motion models developed by Woodward and Clyde Consultants (1991), and region-specific random vibration models were used.

Site Conditions

The site is considered as a generic western U.S. rock and is represented by the ground motion models selected. These conditions are those considered in the 1992 NPR study.

Lower Magnitude of Integration

The lower magnitude of integration was set at $M_0 = 5.0$.

Variability Estimates on Ground Motion Modeling

The range of sigma (logarithmic standard deviation) values used with the ground motion are those given in the 1992 NRP study as best estimates, that is, sigma from 0.37 to 0.65.

Determination of the Controlling Earthquakes

The steps used to characterize the CEs (Magnitude [Mbars] and distance [Dbars]) at a given exceeding probability are those described in Section 2 of this report.

First, a site-specific seismic hazard analysis has been performed for five frequencies (1.0, 2.5, 5.0, 10, and 25 Hz). Figure A-5 shows the median exceeding probability curves for these frequencies. Plots of the median uniform hazard spectra are shown in Figure A-6.

The Mbars and Dbars have been calculated for the RG2 case used in the eastern U.S. study with the 1993 LLNL seismic hazard results. For this case, the exceeding probability values are 1.0×10^{-5} and 7.5×10^{-5} for the median and mean hazard calculations, respectively.

Thirty-five pairs of magnitude intervals (five) and distance intervals (seven) were used to de-aggregate the seismic hazard results. These are:

Magnitude	$5.0 \leq M < 5.5$
	$5.5 \leq M < 6.0$
	$6.0 \leq M < 6.5$
	$6.5 \leq M < 7.0$
	$M \geq 7.0$

Distance	$0 \leq d < 9$
	$9 \leq d < 25$
	$25 \leq d < 49$
	$49 \leq d < 106$
	$106 \leq d < 206$
	$206 \leq d < 356$
	$d \geq 356$

Results of this de-aggregation were used to calculate the Mbars and Dbars at average of 1-2.5 Hz and 5-10 Hz frequencies. The CEs for the RG2 case are:

	av 5-10 Hz		av 1-2.5 Hz			
			<100 km		>100 km	
	mag.	dist.	mag.	dist.	mag.	dist.
median	6.5	19.2	6.6	20.3	N/A	
mean	6.4	29.0	6.5	31.0	N/A	

Tables A.1 to A.4 summarize these calculations. Each table lists the ground motion level for the exceeding probability of reference, the contribution of each magnitude-distance interval to the total seismic hazard, and the Mbar and Dbar values.

One notes from Table A.1 that most of the contribution to the seismic hazard at the site in the 5-10 Hz frequency range is due to the magnitude-distance interval [M: 6.5-7.0; D: 9-25]. This CE would correspond to an earthquake occurring within the fault segment of the Lemhi Fault the closest to the site (see Figure A-3). Conclusions are similar for the average of 1 and 2.5 Hz (see Table A.3). These conclusions are similar to those reached by the seismicity experts in the 1992 NRP study.

Sensitivity

First Test

The CEs were calculated using an exceeding probability value 100 times lower than the PE level for RG2 case. The objective of this test was to check the relative influence of the PE level on the characteristic earthquakes.

The characteristic earthquakes for this case are:

	av 5-10 Hz		av 1-2.5 Hz			
			<100 km		>100 km	
	mag.	dist.	mag.	dist.	mag.	dist.
median	6.6	17.9	6.6	18.2	N/A	
mean	6.6	13.9	6.7	15.8	N/A	

Tables A.5 to A.8 summarize the calculations performed with this new PE level.

It is observed that magnitude values do not change relatively to the change of the PE levels. Distances have decreased by about 2 km or less than 10%.

Second Test

The location of the site has been moved about 30 km southeast to the following coordinates (see Figure A-7). This site is about 30 miles from the southern segment of the Lehmi Fault:

Site 2:

- Longitude: 112.50 degrees west
- Latitude: 43.50 degrees north

For this site, the total seismic hazard is lower than for the original site. Plots of the uniform hazard spectra are shown in Figure A-8.

The CEs at this site for the RG2 case are:

	av 5-10 Hz		av 1-2.5 Hz			
			<100 km		>100 km	
	mag.	dist.	mag.	dist.	mag.	dist.
median	5.9	16.8	6.5	33.9	N/A	
mean	6.2	15.7	6.4	20.4	N/A	

Tables A.9 and A.10 summarize the contributions to magnitude and distance bins to the total seismic hazard for median hazard results. It is noted that for 5-10 Hz frequency band contributions of lower magnitude earthquakes at close distances have increased, as expected. However, the characteristic magnitude for the 1-2.5 Hz frequency band does not vary much although the distance increases from 20 to 30 km.

Third Test

The location of the site has been moved about 30 km northwest to the following coordinates (see Figure A-7). This site is about five miles from the southern segment of the Lehmi fault.

Site 3:

- Longitude: 113.00 degrees west
- Latitude: 43.75 degrees north

For this site, the total seismic hazard is higher than for the original site. The seismic hazard is dominated by the seismicity of the Lehmi fault. Plots of the uniform hazard spectra are shown in Figure A-9.

The CEs at this site for the RG2 case are:

	av 5-10 Hz		av 1-2.5 Hz			
			<100 km		>100 km	
	mag.	dist.	mag.	dist.	mag.	dist.
median	6.5	8.6	6.6	8.1	N/A	
mean	6.4	17.3	6.6	18.2	N/A	

Tables A.11 and A.12 summarize the contributions of magnitude and distance bins to the total seismic hazard for median hazard results. Contributions of earthquakes at close distance have increased, as should be expected, for both 5-10 Hz and 1-2.5 Hz frequency bands.

Fourth Test

We re-ran the seismic hazard analysis for the NPR site but performed the de-aggregation per magnitude and distance intervals by using more refined upper magnitude intervals. We replaced the magnitude bins:

Magnitude	5.0≤M<5.5
	5.5≤M<6.0
	6.0≤M<6.5
	6.5≤M<7.0
	M≥7.0

with

Magnitude	5.0≤M<5.5
	5.5≤M<6.0
	6.0≤M<6.5
	6.5≤M<6.85
	6.85≤M<7.2

and re-calculated the characteristic earthquakes for the RG2 case, which are:

	av 5-10 Hz		av 1-2.5 Hz			
			<100 km		>100 km	
	mag.	dist.	mag.	dist.	mag.	dist.
median	6.6	19.4	6.7	20.5	N/A	
mean	6.4	28.3	6.5	30.3	N/A	

We note that there is a negligible upward change in the magnitude and distance values.

Table A.1 Contribution of Magnitude-Distance Intervals to Total Seismic Hazard—Median Hazard; 5-10 Hz RG2 case; PE = 1.0×10^{-5} Sv (5Hz) = 29.18 cm/s; SV (10 Hz) = 13.20 cm/s

Distance (km)	Magnitude				
	5 - 5.5	5.5 - 6.0	6.0 - 6.5	6.5 - 7.0	> 7.0
0 - 9	0.76	0.19	0.00	0.00	0.00
9 - 25	1.48	7.47	25.14	56.13	0.00
25 - 49	0.00	0.15	1.52	6.53	0.62
49 - 106	0.00	0.00	0.00	0.00	0.00
106 - 206	0.00	0.00	0.00	0.00	0.00
206 - 356	0.00	0.00	0.00	0.00	0.00
> 356	0.00	0.00	0.00	0.00	0.00
Mbar = 6.51					Dbar = 19.23

Table A.2 Contribution of Magnitude-Distance Intervals to Total Seismic Hazard—Mean Hazard; 5-10 Hz
 RG2 case; $PE = 7.5 \times 10^{-5}$ $S_v(5\text{Hz}) = 23.70 \text{ cm/s}$; $S_v(10 \text{ Hz}) = 9.95 \text{ cm/s}$

Distance (km)	Magnitude				
	5 - 5.5	5.5 - 6.0	6.0 - 6.5	6.5 - 7.0	> 7.0
0 - 9	2.49	3.94	2.95	0.47	0.18
9 - 25	2.10	8.91	8.91	10.23	4.35
25 - 49	1.80	6.95	13.09	16.92	3.57
49 - 106	0.30	1.30	2.78	4.69	4.19
106 - 206	0.00	0.02	0.21	0.99	1.61
206 - 356	0.00	0.00	0.00	0.00	0.03
> 356	0.00	0.00	0.00	0.00	0.00
Mbar = 6.43		Dbar = 28.95			

Table A.3 Contribution of Magnitude-Distance Intervals to Total Seismic Hazard—Median Hazard; 1-2.5 Hz
 RG2 case; $PE = 1.0 \times 10^{-5}$ $S_v(1\text{Hz}) = 41.88 \text{ cm/s}$; $S_v(2.5 \text{ Hz}) = 40.29 \text{ cm/s}$

Distance (km)	Magnitude				
	5 - 5.5	5.5 - 6.0	6.0 - 6.5	6.5 - 7.0	> 7.0
0 - 9	0.20	0.09	0.00	0.00	0.00
9 - 25	0.08	2.61	19.36	62.38	0.00
25 - 49	0.00	0.03	1.48	12.05	1.70
49 - 106	0.00	0.00	0.00	0.02	0.01
106 - 206	0.00	0.00	0.00	0.00	0.00
206 - 356	0.00	0.00	0.00	0.00	0.00
> 356	0.00	0.00	0.00	0.00	0.00
Mbar = 6.63		Dbar = 20.33			

Table A.4 Contribution of Magnitude-Distance Intervals to Total Seismic Hazard—Mean Hazard; 1-2.5 Hz
 RG2 case; PE = 7.5×10^{-5} Sv (1Hz) = 30.59 cm/s; SV (2.5 Hz) = 33.21 cm/s

Distance (km)	Magnitude				
	5 - 5.5	5.5 - 6.0	6.0 - 6.5	6.5 - 7.0	> 7.0
0 - 9	1.18	3.10	2.72	0.49	0.19
9 - 25	0.98	3.78	7.80	11.21	5.03
25 - 49	1.54	6.68	14.06	19.76	4.76
49 - 106	0.25	1.20	2.77	5.08	4.73
106 - 206	0.00	0.01	0.17	0.92	1.60
206 - 356	0.00	0.00	0.00	0.00	0.03
> 356	0.00	0.00	0.00	0.00	0.00
Mbar = 6.53			Dbar = 30.98		

Table A.5 Contribution of Magnitude-Distance Intervals to Total Seismic Hazard—Median Hazard; 5-10 Hz
 Test case; PE = 1.0×10^{-7}

First Test
 Sv (5Hz) = 84.31 cm/s; SV (10 Hz) = 40.87 cm/s

Distance (km)	Magnitude				
	5 - 5.5	5.5 - 6.0	6.0 - 6.5	6.5 - 7.0	> 7.0
0 - 9	1.12	0.62	0.00	0.00	0.00
9 - 25	0.08	1.94	23.36	72.80	0.00
25 - 49	0.00	0.00	0.00	0.08	0.00
49 - 106	0.00	0.00	0.00	0.00	0.00
106 - 206	0.00	0.00	0.00	0.00	0.00
206 - 356	0.00	0.00	0.00	0.00	0.00
> 356	0.00	0.00	0.00	0.00	0.00
Mbar = 6.59			Dbar = 17.86		

Table A.6 Contribution of Magnitude-Distance Intervals to Total Seismic Hazard—Mean Hazard; 5-10 Hz
 Test case; PE = 7.5×10^{-7}

First Test

Sv (5Hz) = 120.16 cm/s; SV (10 Hz) = 49.04 cm/s

Distance (km)	Magnitude				
	5 - 5.5	5.5 - 6.0	6.0 - 6.5	6.5 - 7.0	> 7.0
0 - 9	4.33	14.24	15.12	5.96	4.44
9 - 25	0.16	1.61	5.11	12.02	11.17
25 - 49	0.01	0.40	3.47	11.39	6.88
49 - 106	0.00	0.02	0.19	1.16	2.19
106 - 206	0.00	0.00	0.00	0.02	0.10
206 - 356	0.00	0.00	0.00	0.00	0.00
> 356	0.00	0.00	0.00	0.00	0.00
Mbar = 6.59		Dbar = 13.91			

Table A.7 Contribution of Magnitude-Distance Intervals to Total Seismic Hazard—Median Hazard; 1-2.5 Hz
 Test case; PE = 1.0×10^{-7}

First Test

Sv (1Hz) = 108.39 cm/s; SV (2.5 Hz) = 129.93 cm/s

Distance (km)	Magnitude				
	5 - 5.5	5.5 - 6.0	6.0 - 6.5	6.5 - 7.0	> 7.0
0 - 9	0.14	0.21	0.00	0.00	0.00
9 - 25	0.00	0.77	17.51	80.91	0.07
25 - 49	0.00	0.00	0.02	0.34	0.05
49 - 106	0.00	0.00	0.00	0.00	0.00
106 - 206	0.00	0.00	0.00	0.00	0.00
206 - 356	0.00	0.00	0.00	0.00	0.00
> 356	0.00	0.00	0.00	0.00	0.00
Mbar = 6.65		Dbar = 18.19			

Table A.8 Contribution of Magnitude-Distance Intervals to Total Seismic Hazard—Mean Hazard; 1-2.5 Hz
 Test case; PE = 7.5×10^{-7}

First Test
 $S_v(1\text{Hz}) = 151.49 \text{ cm/s}$; $S_v(2.5 \text{ Hz}) = 179.32 \text{ cm/s}$

Distance (km)	Magnitude				
	5 - 5.5	5.5 - 6.0	6.0 - 6.5	6.5 - 7.0	> 7.0
0 - 9	1.63	9.19	12.36	7.01	5.05
9 - 25	0.16	1.46	5.48	14.33	13.95
25 - 49	0.02	0.48	3.92	13.11	7.50
49 - 106	0.00	0.02	0.23	1.36	2.61
106 - 206	0.00	0.00	0.00	0.02	0.12
206 - 356	0.00	0.00	0.00	0.00	0.00
> 356	0.00	0.00	0.00	0.00	0.00
Mbar = 6.72					Dbar = 15.84

Table A.9 Contribution of Magnitude-Distance Intervals to Total Seismic Hazard—Median Hazard; 5-10 Hz
 RG2 case; PE = 1.0×10^{-5}

Second Test
 $S_v(1\text{Hz}) = 19.08 \text{ cm/s}$; $S_v(10 \text{ Hz}) = 9.82 \text{ cm/s}$

Distance (km)	Magnitude				
	5 - 5.5	5.5 - 6.0	6.0 - 6.5	6.5 - 7.0	> 7.0
0 - 9	34.63	2.65	0.00	0.00	0.00
9 - 25	11.0	4.78	3.27	0.07	0.00
25 - 49	0.02	1.47	12.81	27.56	0.68
49 - 106	0.00	0.00	0.07	0.68	0.30
106 - 206	0.00	0.00	0.00	0.00	0.00
206 - 356	0.00	0.00	0.00	0.00	0.00
> 356	0.00	0.00	0.00	0.00	0.00
Mbar = 5.90					Dbar = 16.78

**Table A.10 Contribution of Magnitude-Distance Intervals to Total Seismic Hazard—
Median Hazard; 1-2.5 Hz RG2 case; PE = 1.0×10^{-5}**

Second Test
 $S_v(1\text{Hz}) = 26.42 \text{ cm/s}$; $S_v(2.5 \text{ Hz}) = 26.15 \text{ cm/s}$

	5 - 5.5	5.5 - 6.0	6.0 - 6.5	6.5 - 7.0	> 7.0
0-9	9.29	1.35	0.00	0.00	0.00
9-25	1.99	2.06	2.13	0.05	0.00
25-49	0.00	0.57	15.75	48.34	2.15
49-106	0.00	0.00	0.59	9.26	6.48
106-206	0.00	0.00	0.00	0.00	0.00
206-356	0.00	0.00	0.00	0.00	0.00
>356	0.00	0.00	0.00	0.00	0.00

Mbar = 6.51 Dbar = 33.93

**Table A.11 Contribution of Magnitude-Distance Intervals to Total Seismic Hazard—
Median Hazard; 5-10 Hz RG2 case; PE = 1.0×10^{-5}**

Third Test
 $S_v(5\text{Hz}) = 55.06 \text{ cm/s}$; $S_v(10 \text{ Hz}) = 25.90 \text{ cm/s}$

	5 - 5.5	5.5 - 6.0	6.0 - 6.5	6.5 - 7.0	> 7.0
0 - 9	1.71	5.18	18.85	41.64	0.00
9 - 25	0.19	2.23	10.30	19.84	0.00
25 - 49	0.00	0.00	0.00	0.05	0.01
49 - 106	0.00	0.00	0.00	0.00	0.00
106 - 206	0.00	0.00	0.00	0.00	0.00
206 - 356	0.00	0.00	0.00	0.00	0.00
> 356	0.00	0.00	0.00	0.00	0.00

Mbar = 6.50 Dbar = 8.62

**Table A.12 Contribution of Magnitude-Distance Intervals to Total Seismic Hazard—
Median Hazard; 1-2.5 Hz RG2 case; PE = 1.0×10^{-5}**

Third Test

S_v (1Hz) = 77.43 cm/s; S_v (2.5 Hz) = 83.57 cm/s

	5 - 5.5	5.5 - 6.0	6.0 - 6.5	6.5 - 7.0	> 7.0
0 - 9	0.17	2.22	19.13	51.13	0.00
9 - 25	0.00	0.47	6.05	20.62	0.00
25 - 49	0.00	0.00	0.01	0.16	0.04
49 - 106	0.00	0.00	0.00	0.00	0.00
106 - 206	0.00	0.00	0.00	0.00	0.00
206 - 356	0.00	0.00	0.00	0.00	0.00
> 356	0.00	0.00	0.00	0.00	0.00

$M_{bar} = 6.59$

$D_{bar} = 8.14$

Figure A-1 Seismotectonic Setting of the ESRP

Figure A-2 Map showing the locations of earthquakes ($M > 5.5$) within 200 miles of INEEL

Figure A-3 Map showing locations of the faults closest to INEEL

Figure A-4 Map showing the locations of the basaltic rift zones at INEEL

Figure A-5 INEEL Spectra Hazard Estimates, $M_g > 5$, 9-sx, 6-gx, $\sigma = .037, 0.48, 0.65$

50-th percentile spectra for all return periods

Figure A-6 INEEL Spectra Hazard Estimates, 2/12/92, 9-Sx, 6-Gx, sigma = 0.37, 0.48, 0.65

Figure A-7 Seismotectonic Setting of the ESRP

Figure A-8 INEEL Spectra Hazard Estimates, for Site 2, 9-Sx, 6-Gx, sigma = 0.37, 0.48, 0.65

Figure A-9 INEEL Spectra Hazard Estimates, for Site 3, 9-Sx, 6-Gx, sigma = 0.37, 0.48, 0.65

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11. ABSTRACT (200 words or less)

The Nuclear Regulatory Commission asked Lawrence Livermore Laboratory to form a group of experts to assist them in revising the seismic and geologic siting criteria for nuclear power plants, Appendix A to 10 CFR Part 100. This document describes a deterministic approach for determining a safe Shutdown Earthquake (SSE) Ground Motion for a nuclear power plant site. One disadvantage of this approach is the difficulty of integrating differences of opinions and differing interpretations into seismic hazard characterization. In answer to this, probabilistic seismic hazard assessment methodologies incorporate differences of opinions and interpretations among earth science experts. For this reason, probabilistic hazard methods were selected for determining SSEs for the revised regulation, 10 CFR Part 100.23. However, because these methodologies provide a composite analysis of all possible earthquakes that may occur, they do not provide the familiar link between seismic design loading requirements and engineering design practice. Therefore, approaches used to characterize seismic events (magnitude and distance) which best represent the ground motion level determined with the probabilistic hazard analysis were investigated. This report summarizes investigations conducted at 69 nuclear reactor sites in the central and eastern U.S. for determining SSEs using probabilistic analyses. Alternative techniques are presented along with justification for key choices.

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