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TECHNICAL SUPPORT DOCUMENTS

for

SAR-001 (Rev. 2) Project Overview and General Information

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for
SAR-001 (Rev. 2) Project Overview and General Information

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TECTONIC PROVINCES OF THE SITE REGION

(Revision B)

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Tectonic Provinces of the Site Region

1.0 Introduction

The identification of tectonic features which may act as potential sources of seismicity is fundamental to the quantification of seismic risk. A tectonic framework is a geographical description and interpretation of those tectonic features that could potentially generate seismicity under the current stress regime. A tectonic feature is any geologic structure or crustal element which is either directly observable on the Earth's surface, or which may be inferred from geophysical investigation. These features may be grouped into tectonic provinces based on similar physical characteristics or geologic history. Those tectonic features, or groups of similar features, which may be considered to have seismologic potential are on the order of several tens to hundreds of kilometers in extent. The seismogenic potential of the various categories of tectonic features in the present (geologic sense) stress regime may then be assessed, often in terms of the probability of occurrence of a certain magnitude earthquake.

The definition of tectonic provinces consists of three steps: (1) identifying potentially seismogenic features, (2) defining the physical characteristics or criteria, based on available, observable data which are diagnostic of earthquake activity, and, (3) assessing the probability of activity for each tectonic feature.

The development of a tectonic framework is accomplished by first identifying tectonic features and structures with no attempt to assess the probability of activity or the associated uncertainty. Once these features are identified, the probability of activity may be assigned. The criteria used to assess the potential for seismic activity of a tectonic feature, or class of features, is derived from expert opinion based on current scientific understanding and consensus. Those features potentially active may be geographically depicted to yield a tectonic framework of the site region.

In many cases a seismic source zone may be associated with the location of tectonic features within a given tectonic province. However, some seismic sources may be defined on the basis of a spatial distribution of seismicity with no obvious tectonic association. This is particularly true for the eastern United States, where the Charleston earthquake of 1886 is an example of a strong motion event for which there is no apparent association with a causative tectonic feature. The USGS, acting as consultant to the NRC, has stated:

> "Because the geologic and tectonic features of the Charleston region are similar to those in other regions of the eastern seaboard, we conclude that although there is no recent or historical evidence that other regions have experienced strong earthquakes,

the historical record is not, of itself, sufficient grounds for ruling out the occurrence in these other regions of strong seismic ground motions similar to those experienced near Charleston in 1886. Although the probability of strong ground motion due to an earthquake in any given year at a particular location in the eastern seaboard may be very low, deterministic and probabilistic evaluations of the seismic hazard should be made for individual sites in the eastern seaboard to establish the seismic engineering parameters for critical facilities." (Perkins et al. 1988)

Several studies have attempted to define the tectonic provinces and seismic source zones which may influence the hazard which earthquakes pose to the WVDP site. These studies are described in the following sections.

2.0 Dames & Moore Site Environmental Studies - Seismotectonics (1970)

This report investigated the seismotectonic influence on the proposed expansion of the fuel reprocessing facility at West Valley, NY. The Clarendon-Linden Structure and the St. Lawrence River Valley were identified as historical seismic source zones which may be potentially important sources of future earthquakes. The study also noted the occurrence of several small shocks in the region which could not be associated with any known geologic structure. Such events were attributed to local stress-related crustal re-adjustments, or to some structural feature not identifiable from the existing data.

This deterministic analysis suggested a 0.12 g maximum horizontal ground acceleration, based on an earthquake of MMI VII-VIII occurring about 37 km from the site near the Clarendon-Linden Structure. The maximum magnitude was assumed to be equal to the largest historical event.

3.0 EDAC Seismic Hazard Analysis (1975)

The EDAC study defined five source zones. The most important in terms of hazard posed to the WVDP was their Source 1, which combined a structure trending east-west across the Niagara Peninsula with the Clarendon-Linden Structure. The other source zones used included the Adirondacks, the Eastern Mesozoic Basins / Appalachian fold belts, the Ohio River Valley, and the Anna, Ohio area. The attenuation relationship used (with no uncertainty considered) resulted in only the earthquakes from Source 1 defined as contributing to the seismic hazard. The recurrence relationships were not conservative as they were obtained from a straight line fit through the entire data set, rather than the cumulative number of events. The maximum magnitude was assumed to be equal to the largest historic event, the Attica, N.Y. earthquake of 1929, and the resulting site intensity was described as appropriate for the length of the historical record of the Attica source.

The methodology employed resulted in a value of peak ground acceleration that does not increase with a longer return period. EDAC obtained a value of 0.042 g for peak ground acceleration for any period greater than or equal to the return period of 135 years (EDAC 1975).

4.0 NRC Hazard Study (1977)

The NRC used a unique source of uniform seismicity, the so-called Central Stable Region, in the 1977 study. The model employed was a deterministic one in which the mean rate of occurrence of an intensity greater than or equal to the site intensity was determined, then subsequently converted into peak ground acceleration with no regard for uncertainty. The effects of the simplified source zonation and neglected uncertainty in the attenuation relationship, which tend to reduce calculated hazard, are offset by conservatively specified attenuation coefficients and by the assumption that the mean rate of exceedance of the site intensity is equal to the peak ground acceleration.

The NRC determined a value of 0.10 - 0.13 g for maximum ground acceleration with a return period of 1000 years (NRC 1977, in Dames & Moore 1983).

5.0 TERA Corporation Seismic Hazard Analysis (1981)

The TERA Corporation seismic hazard analysis identified four zones which were believed to contribute to the seismicity of the site region. The Buffalo-Attica zone, as identified by TERA, was further subdivided into three sub-zones because of the proximity of the zone to the site. The first included the Clarendon-Linden Structure and the inferred westward trending structure of Hadley and Devine (1974). The second sub-zone included only the Clarendon-Linden Structure. The third sub-zone identified by TERA covered a wider area which assumed that the Buffalo-Attica source extends under the WVDP site. The second seismic source was identified as a Background Source zone and was defined as the host region for the WVDP. This zone is intended to account for the diffused seismicity of the region. The third source zone defined by TERA was termed the Southern St. Lawrence zone, an area typified by continuous, moderate seismicity. The Central Appalachian Fold Belt, a zone of low activity, was the fourth zone used in the TERA study.

TERA used a probabilistic methodology which explicitly considered the uncertainties associated with assessing the zonation, the selection of the maximum earthquake, and the determination of the recurrence relationship for the WVDP site. The best-estimate curve determined from the study indicated a 0.06 g maximum acceleration for the site with a return period of 100 years, and a 0.14 g maximum acceleration in 1000 years (TERA 1981).

Based on the above studies, the WVDP requested Department of Energy approval of a 0.12 g peak ground acceleration level (Knabenschuh 1982).

6.0 Dames & Moore Seismic Hazard Analysis (1983)

The Dames & Moore probabilistic seismic hazard analysis used seismic source zones defined by several models of the regional tectonic framework. For the purpose of deriving the curves that identify the level of hazard associated with a specified return period subjective weights were assigned to the various models. These weights reflected the subjective judgement that a particular tectonic model is the correct one for describing seismic hazard, and are indicated in the following descriptions of each model.

Tectonic Lithofacies Province

This tectonic model is a generalization of the work complied by Williams (1978) for the entire Appalachian Orogen from Alabama to Newfoundland, and the Tectonic Map of Canada (1968). Williams' (1978) model is based upon surface geologic relations within the orogen. This model implies that the location of contemporary seismicity in the northeastern US region is in some way fundamentally controlled by the lithofacies distribution characterizing the tectonic evolution of the continental crust of the eastern US. Basically, the same concept is employed in the development of "tectonic provinces" for the determination of the Safe Shutdown Earthquake for a nuclear power plant (US CFR 1989).

The dominant zone in this model (with respect to seismic hazard at WVDP) is the Appalachian Basin, with a maximum historic magnitude of m_b = 5.8, the Cornwell-Massena 1945 (MMI-VIII) earthquake. The $m_{b,max}$ used for the analysis was 6.3 ± 0.5.

The tectonic lithofacies model was given a weight of 0.10 in the final calculation of the risk curves.

Hadley and Devine Provinces

This seismic source zone model was developed by Hadley and Devine (1974) in conjunction with the Atomic Energy Commission (later the NRC) as a means to evaluate the distribution of seismic activity in relation to geologic structures and tectonic provinces in the eastern US. Hadley and Devine prepared a seismotectonic model that combines both seismicity and an inferred level of geologic structural control. They investigated information regarding more than 60 earthquakes to identify whether there was any basis for structural control as influencing both the size mechanism and frequency of earthquakes within a particular region. Historical earthquake intensities were not used, as Hadley and Devine were interested in the areal distribution of seismic events, not total seismic energy release.

The specific zones used in the hazard study are:

- Edge of Precambrian: The boundary of this province reflects the edge of Precambrian rocks of the Adirondack massif and the Laurentian shield.

- Central Stable Region: This region embodies the bulk of the Appalachian Basin (partly folded) and related successor basins, the Michigan and Illinois Basins. While much of the seismicity within this province is areally diffuse, there are several seismic areas that have obvious structural control. These include the Mississippi embayment (New Madrid region); Anna, Ohio; the Clarendon-Linden Structure in Western New York and; the Ottawa Basin - Lower St. Lawrence zone. The WVDP site lies within the Central Stable Region in this model.

- Piedmont - Blue Ridge - Green Mountain Belt - New England Maritimes: Seismicity within this province cannot generally be related to specific geologic structures, although certain areas (i.e., Central Virginia Seismic Zone, the Ramapo Fault zone, and the Connecticut River Basin) stand out as having a higher frequency of seismic activity and epicentral trends suggesting some geologic structural influence.

- Faulted Fold Belt: The faulted part of the Appalachian fold belt has a higher frequency of earthquake occurrence than the remainder of the Appalachian folded belt. Generally considered to be the southernmost portion of the Appalachians, where faulting has predominated over folding as the dominant tectonic mode, epicentral alignments in several areas suggest geologic structural control in the release of seismic energy.

- Atlantic Coastal Plain: In general, the Atlantic Coastal Plan has a much lower seismic frequency than other areas of the eastern United States. One anomalous exception to this record of earthquake occurrence in the Coastal Plain is the Charleston, S.C. area, site of the 1886 earthquake (MMI = X, estimated $m_b = 6.8$).

The dominant zone in this model was the Central Stable Region, with an estimated maximum historic event of $m_b = 5.8$ (Cornwell-Massena, 1944, and Montreal, 1732). For purposes of the seismic hazard analysis, an $m_{b,max} = 6.3 \pm 0.5$ was used in this paper.

The Hadley and Devine (1974) seismic source zone model was given a subjective weighting of 0.25.

Seismic Source Zone Map - A Neotectonic Approach

Dames & Moore (1983) developed empirical seismic source zones based upon considerations of many factors which are believed to be important in the geneses of intraplate seismicity. These factors may be grouped into three broad categories:

- Geophysical, including in situ stress, gravity, the geomagnetic field, seismic travel-time residuals, and heat flow.
- Kinematic, e.g., differential vertical crustal movements obtained from releveling and related data.
- Structural, including paleotectonic deformation deduced from evaluation of the erosion resistance of rocks, the occurrence of Cretaceous and Cenozoic deformation features, the distribution of fundamental tectonic lithofacies boundaries, i.e., the evolution of the continental margin, and cross-strike structure.

This model was assigned a weight of 0.15 in the calculation of seismic hazard.

New York State Electric and Gas (NYSEG) Regional Tectonic Provinces

NYSEG (1979) prepared a Preliminary Safety Analysis Report for a proposed nuclear power plant site at New Haven, New York about 24 km east of Oswego, New York. The determination of province boundaries was based on three factors, including structural geology, Bouguer gravity gradient, and the distribution of earthquake epicenters since 1930. The dominant zone in this model for WVDP was the Clarendon-Linden Structure, with a maximum historic earthquake of $m_b = 5.3$ (MMI VII-VIII at Attica).

This model was assigned a weight of 0.15 in the calculation of seismic hazard.

Niagara Mohawk Power Corporation (NMPC) Tectonic Province Model

NMPC (1983) issued the Final Safety Analysis Report (FSAR) for the Nine Mile Point Nuclear Station, Unit 2 near Oswego, New York. The seismic source zone model used by NMPC to determine seismic hazard is a modified version of Hadley and Devine's (1974) seismotectonic model of the eastern United States, discussed earlier, that defines subprovinces on the basis of structural geology.

The dominant zone contributing to the seismic hazard at the site was the Clarendon-Linden Structure, with a maximum historic magnitude of $m_b = 5.3$. This model is a special case of the tectonic lithofacies model.

Dames & Moore assigned a weight of 0.15 to for this model.

Cross-Strike Lineaments

Odom and Hatcher (1980) classify two types of structural lineaments, basement-controlled and supra-crustal. There are two types of basement-controlled structural lineaments, active (reflecting motion of the basement) and passive (reflecting basement surface irregularities). Supra-crustal cross-strike structural discontinuities are broad, diffuse, transverse zones of structural disruption in the "overthrust belts" such as those characteristic of the Appalachian Basin (Wheeler 1980). Where structural lineaments have been studied, they have been found to have very long histories extending back to late Precambrian-Cambrian time (Odom and Hatcher 1980). Six prominent cross-strike features are postulated in West Virginia, Virginia, Maryland, Pennsylvania, New York, and Southern Ontario (Diment et al. 1980; Chaffin, 1981) based principally on the regional configuration of simple Bouguer gravity anomalies and the regional aeromagnetic signature.

Crustal Block Seismic Source Zones

This set of zones combines the arguments posed by Diment et al. (1980) with those of Wentworth et al. (1981). Earthquakes are assumed to occur within northwesterly trending crystal blocks and along the boundaries of northeast trending Mesozoic rift basins. The dominant zone for this model is Zone 5, north and east of the site. The largest historical event in this zone was the 1929 MMI VII-VIII Attica shock (m_b = 5.3).

This model was assigned a weight of 0.15 in the calculation of seismic hazard.

United States Geological Survey (USGS) Seismic Source Zones

The seismic source zones delineated by Algermissen et al. (1976, 1982) were derived using a combination of geologic data, historical earthquake occurrences and expert judgment, and as such, they represent one interpretation of tectonics for the eastern United States. The WVDP site lies within Zone 093, close to the boundaries of Zones 116 and 115 which represent the Clarendon-Linden Structure. The largest historical earthquake in Zone 115, the dominant zone in this model in the analysis, was the 1929 Attica MMI VII-VIII (estimated magnitude of m_b 5.3).

Dames & Moore assigned a weight of 0.05 to this model.

The Hadley and Devine model was weighted highest of any single set of zones because it was the most general interpretation and considered the historical earthquake record. The NYSEG and Niagara Mohawk sources were weighted somewhat higher because they follow zonation practices based on 10 CFR 100 (Appendix A) deterministic practices.

The Crustal Block and Neotectonic models were weighted higher because they were thought to represent timely thinking regarding the origin of seismicity in the eastern US.

The minimum magnitude bound considered was $m_b = 4.5$; uncertainty in the maximum magnitude was accounted for by equally weighting three values including the best-estimate and ± 0.5 magnitude units. Two attenuation functions were employed in the determination of acceleration at the site.

In all, forty-two seismic hazard curves were generated in this study. Based on the subjective weight of each model, the median, 0.16 and 0.84 (± approximately one standard deviation) fractile curves were calculated.

The study found a hazard of less than 0.07 g at the 0.84 fractile for a return period of 3×10^{-2} to 3×10^{-3} years (Dames & Moore 1983).

7.0 Dames & Moore Seismic Hazard Analysis (1992)

In 1983 the Electric Power Research Institute (EPRI) and the Seismicity Owners Group (SOG) implemented a Seismic Hazard Research program to develop a methodology using expert opinion to complement existing data. A parallel effort was undertaken in 1982 by the Lawrence Livermore National Laboratory (LLNL). These methodologies represent an assemblage of the comprehensive analysis of geologic and geophysical data, combined with the opinions of professional earth scientists with broad experience in those properties that may influence the seismicity of the eastern United States.

The development of the EQHAZARD methodology of EPRI/SOG results largely from the position of the Geological Survey regarding the Charleston, South Carolina earthquake of 1886 stated previously. Research efforts have not yet identified a specific, causative structure for the 1886 earthquake. No tectonic feature has been identified that is capable of such a relatively large earthquake, and that is sufficiently unique to preclude the possibility of a similarly large earthquake elsewhere in the eastern United States. Probabilistic seismic hazard methodology is based on the premise that the available data are not sufficient to fully characterize the seismicity and resulting ground motion of earthquakes in the eastern United States. The EQHAZARD program is designed to be applicable to any site in the central and eastern United States. The EQHAZARD methodology has been reviewed for the NRC by the USGS (Perkins et al. 1988). The NRC (1988) issued a Safety Evaluation Report (SER) for the use of the methodology in determining the seismic hazard at sites in the central and eastern US. The EQHAZARD computer code was developed during an intensive fifteen-month research effort by EPRI/SOG and six Earth Science Teams (EST). The six ESTs involved in the development were:

- Bechtel Group, Inc.
- Dames & Moore, Inc.

- Law Engineering Testing Company
- Roundout Associates, Inc.
- Weston Geophysical Corporation
- Woodward-Clyde Consultants

The teams were chosen to achieve the interdisciplinary expertise necessary to evaluate the various data sets, and to minimize interpretation bias. A series of developmental workshops were held among the ESTs to consider the following topics:

- Data requirements
- Tectonic processes of the eastern US and their contribution to crustal stresses
- Crustal stress regime
- Geomechanical processes of failure
- Tectonic framework
- Estimation of seismicity parameters

A Methodology Development Team provided guidance for these workshops, and the methodology was evaluated by a Senior Review Panel. Using the same input data, each team developed independent models of the tectonic framework of the eastern US, and from these models specified a series of seismic source zones to be used in the calculation of seismic hazard for a particular site.

The EPRI/SOG methodology provided the six ESTs with a high degree of flexibility in the expression of alternative interpretations of earthquake causes and seismicity. Tectonic features were identified from an examination of several data sets. The data included geologic structure maps, potential field data (e.g., magnetic field, Bouguer gravity, free-air gravity, isostatic gravity), and interpretive maps of crustal structure. As only moderate-to-large earthquakes are capable of causing damage to structures, these candidate features must be examined for specific characteristics required to generate such events. Such features must also have a finite probability of activity in the present stress regime.

The development of a tectonic framework was accomplished by first identifying tectonic features and structures with no attempt to assess the probability of activity or associated uncertainty. Once these features were identified, the probability of activity was assigned by means of a formalized decision model employing criteria developed by each of the ESTs.
The criteria employed were selected to be as diagnostic of activity as the current state of earth science practice permitted, and to be as independent as possible. The criteria selected by the teams are discussed below.

- Spatial association.

A spatial association with seismicity was the most commonly used criterion. Spatial association of small-magnitude earthquakes with a tectonic feature may indicate that the feature has the potential to generate larger earthquakes. The ESTs felt that the location of future moderate-to-large earthquakes is characterized by small magnitude events rather than by an absence of seismicity. The occurrence of smaller magnitude events may be indicate crustal loading in the vicinity of an impending larger earthquake. Although the different teams used various definitions of spatial association, the judgements were consistent by team for all features analyzed.

- Crustal scale expression.

In order for a candidate feature to have the potential to generate damaging earthquakes it was assumed that it must have significant rupture dimensions, and so the crustal scale expression or vertical extent of that feature must be indicative of activity. The hypocenters of moderate-to-large earthquakes have been shown to lie near the base of the seismogenic zone of the crust, and this is thought to indicate that a feature with a deep crustal expression is more likely to be seismogenic than one with a more shallow expression. Additional evidence of a deep-seated feature, or one with a wide areal extent, may be inferred from various potential field data, or from deep reflection or refraction profiling.

- Fault orientation relative to stress field.

Favorable fault orientation within the existing stress field may indicate the probability of slip on a pre-existing fault. For such a fault, slip will coincide with the direction of maximum resolved shear stress dependent on the ratio between principal stresses. This judgment requires detailed knowledge of the three-dimensional state of stress and of feature geometry, which is lacking for much of the central and eastern US. Most ESTs used more qualitative estimates of the potential for fault activation under the assumed NE-SW horizontal stress orientation.

- Geologically recent strain and paleoseismicity.

Evidence of geologically recent strain and paleoseismicity was also considered to be indicative of potential activity. This evidence includes the stratigraphic and geomorphic relationships near active fault zones, which enable fault displacement and recurrence intervals to be estimated.

- Brittle reactivation.

Any geologic evidence of brittle reactivation, occurring when uplift and erosion brings a structure into the seismogenic regime of the upper crust, may be discerned from older episodes of ductile deformation.

- High deviatoric stress.

Evidence of locally high deviatoric stress may be an indication of activity. Local strength contrasts and structural complexities, e.g., an ultramafic pluton, may produce stresses above normal ambient levels. However, the scarcity of in situ measurements and the relatively shallow (1-2 km) depth of this data leads to problems in applying this criterion to most localities.

- Crustal strength.

The ESTs also examined crustal strength as a criterion for controlling the occurrence of earthquakes. Areas of low strength or spatial and temporal changes in crustal strength may be a factor in seismicity, but, as in the case of in situ stress, may be difficult to evaluate. (McCann et al. 1988; McGuire et al. 1988)

The first three criteria were selected as the most readily identifiable and useful in quantifying the activity of specified tectonic features and were included as primary criteria by most of the ESTs. The other criteria were used as secondary criteria that may be important in the case of a particular feature, but may not be readily associated with most features in the East. Using these physical criteria the probability of activity of each of the candidate tectonic features was assessed by means of a Physical Characteristic Matrix.

The Physical Characteristic Matrix is comprised of cells that represent a particular combination of the characteristic criteria identified above, e.g., crustal scale expression of the candidate feature, spatially-associated moderate-to-large earthquakes, or a favorable geometry and sense of slip in relation to the existing stress field. A probability of from 0.0 to 1.0 is assigned, reflecting the confidence of the EST in the hypothesis that a tectonic feature having the characteristics associated with a specific cell of the matrix is active. The probability of activity P^a is independent of time as long as the stress regime is assumed constant. P^a is a marginal probability, assigned to the feature without considering other source zones that may be active.

The ESTs also assessed the probability of each tectonic feature exhibiting a particular combination of physical characteristics. As these characteristics were assumed to be independent, the probability that any tectonic feature has a specific set of physical characteristics can be assessed by separately examining each characteristic.

After first determining the probability that a candidate tectonic feature belonging to a specific cell of the Physical Characterization Matrix is active, and then assessing the probability that a particular tectonic feature belongs to each cell, these two probabilities were combined to yield the probability that a feature is active (McCann et al. 1988; McGuire et al. 1988, 1989a,b).

The majority of the seismic sources defined by the ESTs are related directly to specific tectonic features and fall into three general categories:

- Single feature - single source, in which a single tectonic feature is interpreted as an individual seismic source. The assigned probability that the source is active is equal to the probability that the feature represented by the source is active.

- Class of features - single source, in which a class of features represents several sources of similar tectonic origin and current tectonic setting. A single value of dependent, marginal probability is made for the class as the characteristics of any member are attributable to all members.

- Group of features - single source, in which a group of several small features in close proximity, and having the same probability distribution of maximum magnitude, are treated as a single source. The probability that the source is active is equal to the probability that at least one of the member features is active.

There are regions of historical seismicity that have been interpreted to contain at least one active feature. In the EPRI/SOG methodology these so-called default sources account for seismicity that cannot be attributed to other identified sources. If the sum of the probabilities of activity of the identified sources is less than unity, then some presently unidentified feature must be active with a probability equal to the probability of none of the known features being active.

Some areas of potentially damaging seismicity may not be associated with any identifiable tectonic feature and are therefore modeled as an area source encompassing the observed seismicity. The Physical Characteristic Matrix described previously does not apply in these cases of featureless seismicity, and the probability of activity of the area must be directly assessed on a subjective basis.

Background sources are specified to represent a region where no distinguishable tectonic features or pattern of seismicity have been identified, but are considered to be capable of potentially damaging earthquakes. As in the case of the featureless seismicity zone described above, the probability of activity must be assessed directly. The probability of activity of a background source is modeled as a spatial average representing that fraction of the source area that is capable of generating earthquakes with magnitudes larger than the lower bounding value. A background source is modeled as always active.

The development of the source zones is described on a team-by-team basis in Seismic Hazard Methodology: Volumes 5 through 10 (Barstow et al. 1986; Klimkiewicz et al. 1986; Litehiser et al. 1986; McWhorter et al. 1986; Statton et al. 1986; White et al. 1986).

Previous studies (Dames & Moore 1983) of the risk posed to the WVDP have used 10 CFR Part 100, Appendix A ("Seismic and Geologic Siting Criteria for Nuclear Power Plants") for guidance in selecting criteria to be used for seismic hazard investigation. These criteria include the correlation of historical earthquakes with tectonic structures, or any part of these structures, within 200 miles (323 kilometers) of the subject site. Originally, EPRI considered only sources within 62 miles (100 kilometers) of a site for inclusion in the calculation of seismic hazard. The USGS, in a review of the EPRI/SOG methodology, noted that the 100-kilometer distance may not be adequately conservative (Perkins et al. 1988). The USGS (and the NRC) have suggested a minimum inclusion distance of 200 kilometers. EPRI suggests including all sources within 100 kilometers of a site, and highly active sources within 200 kilometers of the site, in the hazard calculations (McGuire et al. 1989a). The inclusion of the New Madrid, Charleston, and La Malbaie source zones is recommended if any of these sources are within 500 kilometers of the site. The source zones selected for inclusion in this study were chosen considering the more conservative 200-mile radius criterion. Some zones initially selected as input to the hazard calculation on the basis of this criterion were eliminated from the final calculation by an examination of the source-by-source hazard calculations. For those source zones discarded, the calculations showed no contribution by these sources to the seismic hazard at the WVDP at an appropriate annual frequency of exceedance level. For most of the ESTs the main contributor to the seismic hazard at the site was the Clarendon-Linden Structure acting in combination with a background source.

In the EQHAZARD program the parameters used to described seismicity, the a-value (activity rate) and the b-value (relative frequency of different magnitudes), are allowed to vary spatially within a large source. For each of the source zones listed in the tables below the ESTs have specified smoothing options on the a- and b-values. Each option specifies the degree of smoothing of the a- and b-values, including any prior distribution of the b-value, with an associated degree of probability. The smoothing options, estimated maximum magnitudes, probability of activity, and any source interdependencies are listed in Tables 1 through 6.

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Table 1 - Summary of Bechtel Sources

Source	Description	Smoothing Options [probability]	Maximum Magnitudes [probability]	P[a]	Interdependencies
11	Clarendon-Linden	1[0.33] 2[0.34] 3[0.33]	5.4[0.10] 5.7[0.40] 6.0[0.40] 6.6[0.10]	0.40	Overlaps D
D	Niagara Peninsula	1[0.33] 2[0.34] 4[0.33]	5.4[0.10] 5.7[0.40] 6.0[0.10]	0.35	Overlaps 11
C05	D + 11	1[0.33] 2[0.34] 4[0.33]	5.4[0.10] 5.7[0.40] 6.0[0.40] 6.6[0.10]	NA	NA
BZ6	Southeast Craton Region	1[0.33] 2[0.34] 3[0.33]	5.4[0.10] 5.7[0.40] 6.0[0.40] 6.6[0.10]	1.00	Background P[b] = 1.00

Smoothing options are defined as follows:

1 = Constant a, constant b (no prior)
2 = Low smoothing on a, high smoothing on b (no prior)
3 = Low smoothing on a, low smoothing on b (no prior)
4 = Low smoothing on a, low smoothing on b (weak prior of 1.05)

(Litehiser et al. 1986; McGuire et al. 1989a)

Table 2 - Summary of Dames & Moore Sources

Source	Description	Smoothing Options [probability]	Maximum Magnitudes [probability]	P^a	Interdependencies
08	Eastern Marginal Basin	1[0.75] 2[0.25]	5.6[0.80] 7.2[0.20]	0.08	Default for 5,6,7
09	Clarendon-Linden	1[0.37] 2[0.12] 3[0.38] 4[0.13]	6.5[0.75] 7.2[0.25]	1.00+	None
C02	08 - 09	1[0.75] 2[0.25]	5.6[0.80] 7.2[0.20]	NA	NA

+ P^a of source and its default which has the same geometry

Smoothing options are defined as follows:

1 = No smoothing on a, no smoothing on b (strong prior of 1.04)
2 = No smoothing on a, no smoothing on b (weak prior of 1.04)
3 = Constant a, constant b (strong prior of 1.04)
4 = Constant a, constant b (weak prior of 1.04)

(McWhorter et al. 1986; McGuire et al. 1989a)

Table 3 - Summary of Law Engineering Sources

Source	Description	Smoothing Options [probability]	Maximum Magnitudes [probability]	P[a]	Interdependencies
20	Clarendon-Linden	1c[1.00]	5.0[0.50] 5.5[0.50]	0.70	
111	Laurentian Block	1c[1.00]	5.5[0.50] 6.0[0.50]	1.00	Background P[b] = 0.90
112	Ohio-Pennsylvania Block	1a[1.00]	4.6[0.20] 5.1[0.50] 5.5[0.30]	1.00	Background P[b] = 0.85

Smoothing options are defined as follows:

1a = High smoothing on a, constant b (strong prior of 1.05)
1c = High smoothing on a, constant b (strong prior of 0.95)

(White et al. 1986; McGuire et al. 1989a)

Table 4 - Summary of Roundout Sources

Source	Description	Smoothing Options [probability]	Maximum Magnitudes [probability]	P[a]	Interdependencies
33	Niagara-by-the-Lake	1[1.00] (a= -1.120, b= 1.000)	5.2[0.30] 6.3[0.55] 6.5[0.15]	1.00	
C02	Grenville Province	3[1.00]	4.8[0.20] 5.5[0.60] 5.8[0.20]	NA	

Smoothing options are defined as follows:

1 = Constant a value, constant b value as listed above
3 = Low smoothing on a, constant b (strong prior of 1.0)

(Barstow et al. 1986; McGuire et al. 1989a)

Table 5 - Summary of Weston Geophysical Sources

Source	Description	Smoothing Options [probability]	Maximum Magnitudes [probability]	P[a]	Interdependencies
07	Niagara Peninsula	1b[1.00]	5.4[0.62] 6.0[0.29] 6.6[0.09]	0.36	Overlaps 08
08	Clarendon-Linden	1b[1.00]	5.4[0.26] 6.0[0.50] 6.6[0.24]	0.83	Overlaps 07
101	Southern Ontario Ohio-Indiana	1a[0.20] 2a[0.80]	5.4[0.19] 6.0[0.68] 6.6[0.13]	1.00	Background P[b] = 1.00
102	Appalachian Plateau	1a[0.20] 2a[0.80]	5.4[0.62] 6.0[0.29] 6.6[0.09]	1.00	Background P[b] = 1.00
C12	101 - 07	1a[0.70] 2a[0.30]	5.4[0.19] 6.0[0.68] 6.6[0.13]	NA	NA
C13	101 - 08	1a[0.70] 2a[0.30]	5.4[0.19] 6.0[0.68] 6.6[0.13]	NA	NA
C15	101 - 07 - 08	1a[0.70] 2a[0.30]	5.4[0.19] 6.0[0.68] 6.6[0.13]	NA	NA
C32	07 + 08	1b[1.00]	5.4[0.26] 6.0[0.50] 6.6[0.24]	NA	NA

Smoothing options are defined as follows:

1a = Constant a, constant b (medium prior of 1.0)
1b = Constant a, constant b (medium prior of 0.9)
2a = Medium smoothing on a, medium smoothing on b (medium prior of 1.0)

(Klimkiewicz et al. 1986; McGuire et al. 1989a)

Table 6 - Summary of Woodward-Clyde Sources

Source	Description	Smoothing Options [probability]	Maximum Magnitudes [probability]	P[a]	Interdependencies
32	Clarendon-Linden	3[0.33] 4[0.34] 5[0.33]	5.7[0.33] 6.3[0.34] 7.3[0.33]	0.133	Independent of 33, 34, 35
33	Western New York & Southern Ontario	2[0.25] 3[0.25] 4[0.25] 5[0.25]	5.5[0.33] 6.5[0.34] 7.0[0.33]	0.439	Independent of 33, 34
34	Attica, NY	3[0.33] 4[0.34] 5[0.33]	5.6[0.33] 6.3[0.34] 7.4[0.33]	0.486	Independent of 32, 33
34A	Attica, NY NOTA zone	3[0.33] 4[0.34] 5[0.33]	5.6[0.33] 6.3[0.34] 7.4[0.33]	0.250	Default for 32, 33, 34
C05	32 + 33	2[0.25] 3[0.25] 4[0.25] 5[0.25]	5.5[0.33] 6.3[0.34] 6.8[0.33]	NA	NA
C06	33 + 34	2[0.25] 3[0.25] 4[0.25] 5[0.25]	5.5[0.33] 6.3[0.34] 7,0[0.33]	NA	NA
C10	32 + 34	2[0.25] 3[0.25] 4[0.25] 5[0.25]	5.6[0.33] 6.3[0.34] 7.4[0.33]	NA	NA
C11	32 + 33 + 34	2[0.25] 3[0.25] 4[0.25] 5[0.25]	5.6[0.33] 6.3[0.34] 7.4[0.33]	NA	NA
BG	East Coast Backgrounds	1[0.25] 6[0.25] 7[0.25] 8[0.25]	5.8[0.33] 6.2[0.34] 6.6[0.33]	NA	NA

Table 6 - Summary of Woodward-Clyde Sources
(Concluded)

Smoothing options are defined as follows:

1 = Low smoothing on a, high smoothing on b (no prior)
2 = High smoothing on a, high smoothing on b (no prior)
3 = High smoothing on a, high smoothing on b (moderate prior of 1.0)
4 = High smoothing on a, high smoothing on b (moderate prior of 0.9)
5 = High smoothing on a, high smoothing on b (moderate prior of 0.8)
6 = Low smoothing on a, high smoothing on b (moderate prior of 1.0)
7 = Low smoothing on a, high smoothing on b (moderate prior of 0.9)
8 = Low smoothing on a, high smoothing on b (moderate prior of 0.8)

(Statton et al. 1986; McGuire et al. 1989a)

TECHNICAL SUPPORT DOCUMENT A.3.6-D

TECTONIC PROVINCE MAXIMUM EARTHQUAKE

(Revision B)

TSD A.3.6-D
TECTONIC PROVINCE MAXIMUM EARTHQUAKE

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Supplement A.3.6-D

Tectonic Province Maximum Earthquake

1.0 Introduction

The recently completed seismic hazard assessment for the WVDP used hazard methodology developed by the Electric Power Research Institute (EPRI), in conjunction with the Seismicity Owners Group (SOG).

The EPRI/SOG methodology is a structured procedure for making tectonic interpretations of regional data and fully documented definitions of seismic source zones. The methodology represents a compilation of state-of-the-art expert opinion regarding the seismicity of the central and eastern United States. The output of the EPRI/SOG computer program is a series of fractile hazard curves which relate a peak horizontal ground acceleration to an annual frequency of exceedance. In 1988, after review by experts at the US Geological Survey (Perkins et al. 1988), the Nuclear Regulatory Commission issued a Safety Evaluation Report (SER) judging the methodology to be acceptable for evaluating seismic hazard for the central and eastern United States (NRC 1988).

Probabilistic analyses yield valuable information regarding the potential for seismicity at a particular site, but the natural processes associated with the input parameters are subject to a degree of uncertainty. In the central and eastern United States three major factors contribute to this uncertainty:

- the short time record, in a geologic sense, of the historical earthquake record,
- the general absence of surface expression of the causative faults, as contrasted to the familiar example of the San Andreas feature in the western US, and,
- a lack of complete understanding of the causative relationship between the candidate geologic features and mid-plate earthquakes.

The sources of uncertainty are explicitly accounted for in the EPRI/SOG methodology.

2.0 Probabilistic Seismic Hazard Methodology

Probabilistic methods attempt to predict future earthquakes occurrences from tectonic theories, geologic evidence, analogies with other regions, and historical seismicity. These methods are preferred for regions where the processes which generate earthquakes are not well constrained, e.g., the central and eastern United States.

The probabilistic methodology may be summarized as follows:

- Contributing source zones of potential future activity are delineated from geological and geophysical evidence, and from patterns of historical seismicity;
- The distribution of earthquakes in time and space is described in terms of the rate of occurrence greater than some lower magnitude bound (a-value), an exponential magnitude distribution with a slope parameter (b-value), and a maximum magnitude;
- Adopt or derive one or more attenuation functions which allow estimation of the amplitude of ground motion as a function of earthquake magnitude and distance form the source;
- Mathematically integrate over all earthquake magnitudes and locations, and calculate the distribution of a specified ground motion measure for each magnitude and location.

The EPRI/SOG program requires that explicit subjective probabilities to be assigned to potential sources and to the characteristics of these sources which are deemed to be seismogenic. All available information and expert opinion regarding the causes of earthquakes, and the uncertainties associated with this information, can be accommodated. The methodology incorporates a earthquake recurrence model which assumes that all possible sources of future earthquakes can be described and weighted, according to the relative capability of that source, based on current evidence.

The various alternatives are represented computationally by a logic tree with the various nodes representing a point of choice between alternative values (seismicity parameters a and b, different values of maximum magnitude, and several attenuation functions) for each measure of ground motion and each branch representing one possible parameter value. The branches are assigned a probability that assesses the relative likelihood of that branch being the correct value of the input parameter. The sum of the probabilities assigned to all branches at each node are equal to one, under the assumption that the various alternatives represent all possible choices of that parameter. The output files

contain calculated hazard for a single measure of ground motion for all combinations of the above input parameters for each seismic source (McGuire 1989).

The total seismic hazard at a particular site is the sum of the hazard from the various combinations of simultaneously active sources. The spatial distribution of future seismicity in the specified sources is assumed to be derivable from the historical seismicity, the state of crustal stress, geophysical data, by analogy with other regions, and from earth science interpretations. For each set of active sources the resulting hazard is a function of the alternative sets of seismicity parameters, maximum magnitudes, and attenuation functions.

Technical Support Document A.3.6-C describes the tectonic models used in previous earthquake hazard studies for the WVDP, and the development of the tectonic province model used as input to the most recent hazard analysis using the EPRI/SOG methodology.

Six multidisciplinary teams (Earth Science Teams, or ESTs) comprised of geologists, seismologists, and geophysicists were convened to aggregate the various alternative interpretations of earthquake causes and seismicity. The development of the tectonic framework and seismic source zones is described on a team-by-team basis in Seismic Hazard Methodology: Volumes 5 through 10 (Barstow et al. 1986; Klimkiewicz et al. 1986; Litehiser et al. 1986; McWhorter et al. 1986; Statton et al. 1986; White et al. 1986).

3.0 Tectonic Framework and the Specification of Seismic Source Zones

The development of a tectonic framework is fundamental to the identification of seismic sources and the specification of seismicity parameters. A tectonic framework is a geographical description and interpretation of those tectonic features which may potentially generate seismicity under the current stress regime. The procedure of assessing a tectonic framework consists of three steps:

- the identification of potentially seismogenic features,
- the definition of physical characteristics or criteria, based on available, observable data which are applicable and diagnostic of activity, and,
- the assessment of the probability of activity for each tectonic feature.

Tectonic features were identified from an examination of several data sets including geologic structure maps, potential field data (e.g., magnetic field, Bouguer gravity, free-air gravity, isostatic gravity), and interpretive maps of crustal structure. As only moderate-to-large earthquakes are capable of causing damage to structures, these candidate features must be examined for specific characteristics required to generate such events. Such features must also have a finite probability of activity in the present stress regime.

The criteria employed were selected to be as diagnostic of activity as the current state of earth science practice permitted, and to be as independent as possible. The selected criteria are discussed below.

- Spatial association.

  Spatial association of small-magnitude earthquakes with a tectonic feature may indicate that the feature has the potential to generate larger earthquakes.

- Crustal scale expression.

  In order for a candidate feature to have the potential to generate damaging earthquakes it was assumed that it must have significant rupture dimensions, and so the crustal scale expression or vertical extent of that feature must be indicative of activity.

- Fault orientation relative to stress field.

  Favorable fault orientation within the existing stress field may indicate the probability of slip on a pre-existing fault.

- Geologically recent strain and paleoseismicity.

  This evidence includes the stratigraphic and geomorphic relationships near active fault zones which enable estimates of displacement and recurrence interval.

- Brittle reactivation.

  Any geologic evidence of brittle reactivation, occurring when uplift and erosion brings a structure into the seismogenic regime of the upper crust, may be discerned from older episodes of ductile deformation.

- High deviatoric stress.

  Local strength contrasts and structural complexities, e.g., an ultramafic pluton, may produce stresses above normal ambient levels.

- Crustal strength.

  Areas of low strength or spatial and temporal changes in crustal strength may be an factor in seismicity.

The EPRI methodology assigns a probability of activity to each of the features according to whether the candidate feature has crustal scale expression, if the feature has spatially-associated moderate-to-large earthquakes, or, if the feature has a favorable geometry and sense of slip in relation to the existing stress field. A probability of from 0.0 to 1.0 is assigned, reflecting the confidence of the EST in the hypothesis that a tectonic feature having the characteristics associated with a specific cell of the matrix is active. The probability of activity P^a is independent of time as long as the stress regime is assumed constant (McCann 1988; McGuire 1988).

The majority of the seismic sources defined by the ESTs are related directly to specific tectonic features and fall into three general categories:

- Single feature - single source, where a single tectonic feature is interpreted as an individual seismic source.

- Class of features - single source, in which a class of features represents a number of sources of similar tectonic origin and current tectonic setting.

- Group of features - single source, where a group of several small features in close proximity, and having the same probability distribution of maximum magnitude, are treated as a single source.

There are regions where historical seismicity has occurred which have been interpreted to contain at least one active feature. In the EPRI/SOG methodology these so-called default sources account for seismicity which cannot be attributed to other identified sources.

Some areas of potentially damaging seismicity may not be associated with any identifiable tectonic feature, and are therefore modeled as an area source encompassing the observed seismicity. Background sources are specified to represent a region where no distinguishable tectonic features or pattern of seismicity have been identified, but are considered to be capable of potentially damaging earthquakes. A background source is modeled as always active.

4.0 Estimation of Seismicity Parameters

Among the unique capabilities of the EPRI/SOG methodology is the capacity to specify spatially varying seismicity rates within an individual seismic source. The rate of seismicity is generally described by values which characterize the exponential frequency-magnitude distribution, expressed by the relationship:

$$\log_{10} N(m_b) = a - b\, m_b$$

where N is number of earthquakes of given magnitude m_b per unit time. The a-value is indicative of the activity rate of earthquakes within a source, while the b-value is the slope of the line indicating absolute or relative frequency versus earthquake magnitude, i.e., a value which indicates the relative frequency of occurrence of earthquakes of different sizes.

The method first converts the various measures of earthquake size to a uniform measurement to simplify subsequent analysis of clustering, incompleteness, and recurrence rates. The catalog used in this study contains earthquake occurrences from 1627 to 1985. Earlier earthquakes are described by empirical measures such as epicentral intensity (Modified Mercalli Intensity, MMI) and felt area. More recent earthquakes have magnitudes specified by one or more values measured by instruments.

Main features of the EPRI/SOG procedure include:

- Uncertainty on the instrumental estimates of body-wave magnitude m_b from other size measures is specifically accounted for;
- Regressions of m_b against other size measures are not required to be linear or have constant residual variance;
- In estimating m_b for a given historical earthquake, account is taken of all the size measures reported in the catalog for that earthquake; and
- An estimator of m_b is used that does not bias the subsequent estimation of the parameters a and b of the exponential recurrence law.

Although probabilistic seismic hazard analyses assume that earthquakes occur as a Poissonian process, i.e., independent of each other in space and time, seismicity in fact often occurs as a cluster. A cluster may sometimes consist only of one event, although commonly earthquakes of a large magnitude are preceded by foreshocks of lesser size, and likewise followed by a number of aftershocks.

The cluster analysis method first orders the earthquakes according to magnitude and time of occurrence. A series of statistical tests then determines whether there is any significant clustering of events of lower or equal magnitude. Dependent events are eliminated during successive passes through the data set until no further earthquakes are eliminated.

The EPRI/SOG procedure accounts for this in the following manner:

- It is assumed that earthquakes occur in groups (clusters) and that clusters are distributed in space and time according to a nonhomogeneous but stationary Poisson process;

- In classifying earthquakes as main or secondary events, the spatial-temporal extent of the clusters are determined separately for each main earthquake, by performing statistical tests; and

- The procedure works well with spatially nonhomogeneous catalogs and with incompleteness-induced nonstationarity. Both features are very pronounced in the earthquake catalog for the central and eastern United States.

The question of completeness is addressed by dividing the central and eastern US into a series of 13 incompleteness regions based on demographics, instrumental response, and boundaries of the regional catalogs. The probability of detection within each of these regions is assumed to be spatially constant, and a function of time and magnitude.

In order to account for the incompleteness of the historical catalog the programs employs the following methods:

- Estimates of the degree to which historical earthquakes have been incompletely reported are allowed to vary not only with magnitude and time but also with geographical location. This is done by relating the probability of earthquake detection and recording to the spatial distribution of population and instruments at the time of the event; and

- The notion of "period of incompleteness" is replaced with that of "equivalent period of completeness." The latter is the period of time by which the total number of recorded events must be divided to obtain an unbiased estimate of the recurrence rate.

A numerical procedure estimates a- and b-values for each of the one-degree cells which comprise the seismic source zone, and the probability of detection for all completeness regions, magnitude classes, and time intervals.

Specifically:

- The constraint of homogeneous Poisson sources is removed, allowing a and b to vary continuously on the geographical plane;

- Seismic sources can be included in the analysis as geographical regions inside which the parameters a and b vary more smoothly; and

- Because the degree catalog incompleteness influences the estimates of the recurrence rates and conversely the recurrence relationship influences the estimates of incompleteness, incompleteness and seismicity estimation are pursued jointly as a single problem.

5.0 Estimation of Maximum Earthquake

The largest earthquake which can occur must be established for each seismic source zone to be used in the calculation of seismic hazard. This maximum magnitude is influenced by the size of tectonic features represented by that source, the character of historical seismicity, and other factors. The size of the maximum earthquake may be estimated by several methods, including:

- Physical constraints

  Properties such as fault length or rupture area, may be useful in determining a correlation with maximum magnitude in the western US, but are rarely observable in the eastern US. For the central and eastern US, physical constraints may include geophysical anomalies or tectonic features which may be assigned a maximum magnitude based on relationships developed by Nuttli (1983). The ESTs used the physical extent of defined sources in conjunction with the scaling relations of Nuttli to determine an estimate of maximum magnitude.

- Seismological methods

  This approach involves the addition of a size increment to the maximum historical event, the extrapolation of a magnitude-recurrence curve over a longer time interval, and a statistical treatment of the earthquake record to determine the likelihood of a maximum event. Because the recurrence interval for large earthquakes in intraplate regions (like the central and eastern US) is much longer than for other regions, it is likely that the historical record is not adequate in terms of duration to define the maximum earthquake for a given seismic source.

- Examination of the global database

  Because of the inadequacy of the historical database of the central and eastern US, efforts have been made to use the seismicity of other tectonically analogous parts of the world. The methodology is similar to that described in the previous paragraph, but with a database of longer duration. The examination of case studies of individual earthquakes enabled the ESTs to develop analogies with the tectonic regimes of the eastern US, and assign a maximum magnitude to different categories of tectonic features.

  (McCann 1988; McGuire 1988)

The seismic source zones used in the most recent seismic hazard assessment are listed by team in Tables 1-6 of TSD A.3.6-C. For each source zone the tables indicate the smoothing options applied to the a- and b-values (with the associated probabilities), the range of maximum magnitudes (with associated probabilities), and also the probability of activity of that source and any interdependencies between sources.

This assessment has confirmed that the Clarendon-Linden Structure, the seismic source zone closest to the site, is the dominant contributor to seismic hazard in the site vicinity.

TSD A.3.6-E describes the methods used to estimate ground motion for the tectonic province maximum earthquake.

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TABLE A.3.6-D-1

Seismic Source Zones Associated Seismicity Parameters

Seismic Source Zone Concept	Dominant Zone	Area ($10^4 km^2$)	Activity Rate (m_b4.5)	Richter b-value	$M_{b,max}$	Subjective Weight
Tectonic Lithofacies	Appalachian Basin	95.38	0.2662	0.86/1.01/1.17	6.8/6.3/58	0.10
NYSE and G (1978)	Claredon-Linden Fault Zone	0.79	0.0352	0.77/0.90/1.04	6.5/6.0/55	0.15
Niagara Mohawk Power Corp. (1983)	Claredon-Linden Fault Zone	0.79	0.0352	0.77/0.90/1.04	6.5/6.0/55	0.15
A Neotectonic Approach	C_1	20.82	0.0810	0.71/0.84/0.97	6.3/5.8/53	0.15
Hadley and Devine (1974, Plate C)	Central Stable Region	87.05	0.2319	0.82/0.97/1.11	6.8/6.3/58	0.25
Cross-Strike	-	-	-	-	-	-
Crustal Block Sources	5	3.47	0.0806	0.77/0.90/1.04	5.8/5.3/53	0.15
USGS Sources	115	0.55	0.0352	0.77/0.90/1.04	6.5/6.0/55	0.05

TECHNICAL SUPPORT DOCUMENT A.3.6-E

ESTIMATE OF GROUND MOTION

(Revision B)

SUPPLEMENT A.3.6-E

ESTIMATE OF GROUND MOTION

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Estimate of Ground Motion

1.0 Safe Shutdown Earthquake

The Safe Shutdown Earthquake (SSE) is that earthquake which produces the maximum vibratory ground motion for which certain structures, systems, and components are designed to remain functional. This level of ground motion is generally that expected from either the largest historic earthquake within the tectonic province in which the site is located, or that determined from an assessment of the maximum earthquake potential of the closest tectonic structure or capable fault. The SSE has been superseded by the Design Basis Earthquake (DBE).

The Department of Energy (DOE) and the Nuclear Regulatory Commission (NRC) are currently working to develop a consistent and unified approach for the assessment of all natural hazard phenomena, including seismic, to meet DOE safety goals. The DOE Seismic Working Group considered improvements to UCRL-15910 (Kennedy et al. 1990, the implementing reference of DOE Order 6430.1A), in conjunction with the NRC and the Electric Power Research Institute (EPRI). UCRL-15910 does not currently provide guidelines for an appropriate method for the evaluation of seismic hazard; to address this requirement a guidance document has been issued for the systematic evaluation of seismic hazard (DOE 1991). Based on the proposed enhancements to UCRL-15910, the ground motion associated with the DBE is defined using probabilistic criteria.

The hazard posed to the WVDP by earthquakes has been the subject of numerous studies. These studies are described in TSD A.3.6-C, Tectonic Provinces of the Site Region, and TSD A.3.6-D, Tectonic Province Maximum Earthquake. The estimates of ground motion resulting from these various studies are outlined below.

2.0 Dames & Moore Site Environmental Studies - Seismotectonics (1970)

This deterministic analysis suggested a 0.12 g maximum horizontal ground acceleration, based on an earthquake of MMI VII-VIII occurring about 37 km from the site near the Clarendon-Linden fault. The maximum magnitude was assumed to be equal to the largest historical event (Dames & Moore 1970).

3.0 EDAC Seismic Hazard Analysis (1975)

The methodology employed resulted in a value of peak ground acceleration that does not increase with a longer return period. EDAC obtained a value of 0.042 g for peak ground acceleration for any return period greater than or equal to 135 years (EDAC 1975).

4.0 NRC Hazard Study (1977)

The model employed was a deterministic one in which the mean rate of occurrence of an intensity greater than or equal to the site intensity was determined, then subsequently converted into peak ground acceleration with no regard for uncertainty.

The NRC determined a value of 0.10 - 0.13 g for maximum ground acceleration with a return period of 1000 years (NRC 1977, in Dames & Moore 1983).

5.0 TERA Corporation Seismic Hazard Analysis (1981)

TERA used a probabilistic methodology which explicitly considered the uncertainties associated with assessing the zonation, the selection of the maximum earthquake, and the determination of the recurrence relationship for the WVDP site. The best-estimate curve indicated a 0.07 g maximum acceleration for the site with a return period of 100 years, and a 0.14 g maximum acceleration in 1000 years (TERA 1981).

6.0 Dames & Moore Seismic Hazard Analysis (1983)

The minimum magnitude bound considered was m_b = 4.5; uncertainty in the maximum magnitude was accounted for by equally weighting three values including the best-estimate and ± 0.5 magnitude units. Two attenuation functions were employed in the determination of acceleration at the site.

A range of annual exceedance probabilities of 3×10^{-2} to 3×10^{-3} was adopted for the WVDP as a conservative representation of the seismic hazard to the site consistent with then-current analyses for a typical nuclear power plant in the eastern United States. In all, forty-two seismic hazard curves were generated in this study. Based on the subjective weight of each model, the median, 0.16 and 0.84 (± approximately one standard deviation) fractile curves were calculated.

This study yielded a peak horizontal ground acceleration of less than 0.07 g for a return period of 3×10^{-2} to 3×10^{-3} years, even at the 84 percent fractile (Dames & Moore 1983).

7.0 Dames & Moore Seismic Hazard Analysis (1992)

The hazard methodology developed by the Electric Power Research Institute (EPRI), in conjunction with the Seismicity Owners Group (SOG), was used in this study. The methodology represents a compilation of current expert opinion regarding the tectonic framework and seismicity of the central and eastern United States. Included in the code are step-by-step procedures for analyzing the historical earthquake catalog, specifying seismic source zones, designating the seismicity parameters on a cell-by-cell basis within these source zones, and then aggregating multiple alternative interpretations of site data to assess the median seismic hazard and its uncertainty. The Nuclear Regulatory Commission issued a

Safety Evaluation Report (SER) for the EQHAZARD program in September 1988, concluding that the methodology is an acceptable method for use in calculating seismic hazard in the central and eastern US.

The EPRI/SOG methodology was developed during an intensive fifteen-month research effort by EPRI/SOG and six Earth Science Teams (EST). The methodology is a structured procedure for making tectonic interpretations of regional data and fully documented definitions of seismic source zones. The development of the tectonic framework and seismic source zones is described in TSD A.3.6-C (Tectonic Provinces of the Site Region). The maximum earthquake that may affect the WVDP site is summarized in TSD A.3.6-D (Tectonic Province Maximum Earthquake).

The program uses matrices and logic trees in which explicit subjective probabilities are assigned to potential sources and to the characteristics of these sources thought to be seismogenic. All available information and expert opinion regarding the causes of earthquakes, and the uncertainties associated with this information, can be accommodated. The information is used to calculate seismic hazard by applying the total probability theorem. The uncertainty in the input data results in a degree of uncertainty in the calculated hazard, which can be represented by a family of hazard curves, or, if the number of curves is very large, by fractiles of that family. Central to this method is the axiom that uncertainty in a probabilistic assessment of seismic hazard results directly from the uncertainties associated with the input and is not a result of the hazard calculation.

Details of the conceptual basis of the EPRI/SOG seismic hazard methodology may be found in a series of volumes published by EPRI (McCann et al. 1988; McGuire et al. 1988, 1989).

The calculation of the hazard contribution of each source zone is accomplished using the following categories of input data:

- Geometry of the source zone (latitude-longitude pairs specified by each EST)
- The distribution of earthquake size and location within each source, represented by the a- and b-values calculated for each cell and by the maximum magnitude specified by the ESTs
- One or more attenuation functions that estimate ground motion at the site as a function of magnitude and distance.

The attenuation functions chosen for use in estimating the ground motion at the WVDP were those specified in the EPRI/SOG methodology for the central and eastern U.S. The functions of McGuire et al. (1988) and Nuttli (1986) are of the standard form shown below with the following weights and coefficients:

$$\ln (a) = c_1 + c_2 m_b + c_3 \ln R + c_4 R$$

where,

$\ln (a)$: mean log of the desired ground motion level

c_1- c_4 : coefficients derived by theoretical or empirical methods

m_b : earthquake magnitude

R : hypocentral distance (km)

Model	Weight	Ground Motion Measure	c_1	c_2	c_3	c_4
McGuire et al. (1988)	0.5	Acceleration	2.55	1.00	-1.00	-0.0046
Nuttli (1986), Newmark-Hall	0.25	Acceleration	1.38	1.15	-0.83	-0.0028
Boore and Atkinson (1987)*	0.25	Acceleration				

* The attenuation function of Boore and Atkinson (1987) is of a more complicated form, that is specified in that reference.

The seismic hazard curves resulting from the probabilistic assessment (1992) using the EPRI methodology have been interpreted at the 10^{-3}/year exceedance interval. These fractile hazard curves are shown on Figure A.3.6-E-1; sensitivity to ESTs at the median (0.50) fractile is shown on Figure A.3.6-E-2. The corresponding hazard curves that include the effects of the site soil column (based on correction factors supplied by EPRI) are shown on Figure A.3.6-E-3; sensitivity to ESTs is shown on Figure A.3.6-E-4. The study yielded the following values of peak horizontal ground acceleration obtained from Figures A.3.6-E-1 and A.3.6-E-3:

Without site amplification			With amplification from site soils (from factors supplied by EPRI/SOG)		
median	mean	$+\sigma$	median	mean	$+\sigma$
0.03 g	0.045 g	0.08 g	0.07 g	0.09 g	0.16 g

Both the EPRI and the Lawrence Livermore National Laboratory (LLNL) seismic hazard methodologies attempt to account for uncertainty in the values used for the input parameters by carrying this uncertainty throughout the analysis. The use of uncertainty propagation methods (a logic-tree structure in the EQHAZARD program of EPRI) may result in the abandonment of the heretofore common practice of employing the $+\sigma$ (0.84 fractile) to capture the effect of the uncertainties involved in the specification of input values.

8.0 Dames & Moore Seismic Hazard Re-Evaluation (1995)

Current DOE guidance (e.g. DOE Order 5480.28) requires a review of state-of-the-art of natural phenomena hazard (NPH) assessment methodology and of site-specific information every 10 years and a recommendation made on the need for updating the existing NPH assessments based on the identification of a significant change.

The ground motion hazard at the WVDP was evaluated (Dames & Moore 1995) based on information in publications by the Electric Power Research Institute (EPRI) and by Lawrence Livermore National Laboratory (LLNL) pertaining to seismic hazard analyses of nuclear power plant sites in the central and eastern United States. In particular, the data in these publications relevant to the seismic hazard at the closest nuclear power plant (Ginna) to the WVDP site were reviewed. Using these publications, the results of a 1992 study by Dames & Moore that applied the EPRI hazard analysis methodology, and the guidance of DOE Standard 1024, the PGA at the 1×10^{-3} and 5×10^{-4} annual probabilities were estimated to be 0.053 g and 0.078 g, respectively. By DOE guidance, the minimum PGA required is 0.10 g.

The 1×10^{-3} annual probability associated with the ground-motion hazard is required under DOE Order 6430.1A as specified in UCRL-15910 (Kennedy et al., 1990); this probability pertains to Use Categories of DOE facilities designed as "Moderate Hazard". The WVDP is categorized as a Moderate Hazard facility. The 5×10^{-4} annual probability is recommended in the recent DOE-STD-1020-94 for Performance Category 3, which corresponds to the Moderate Hazard category in UCRL-15910.

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Figure A.3.6-E-1
Peak Ground Acceleration Fractile Hazard Curves

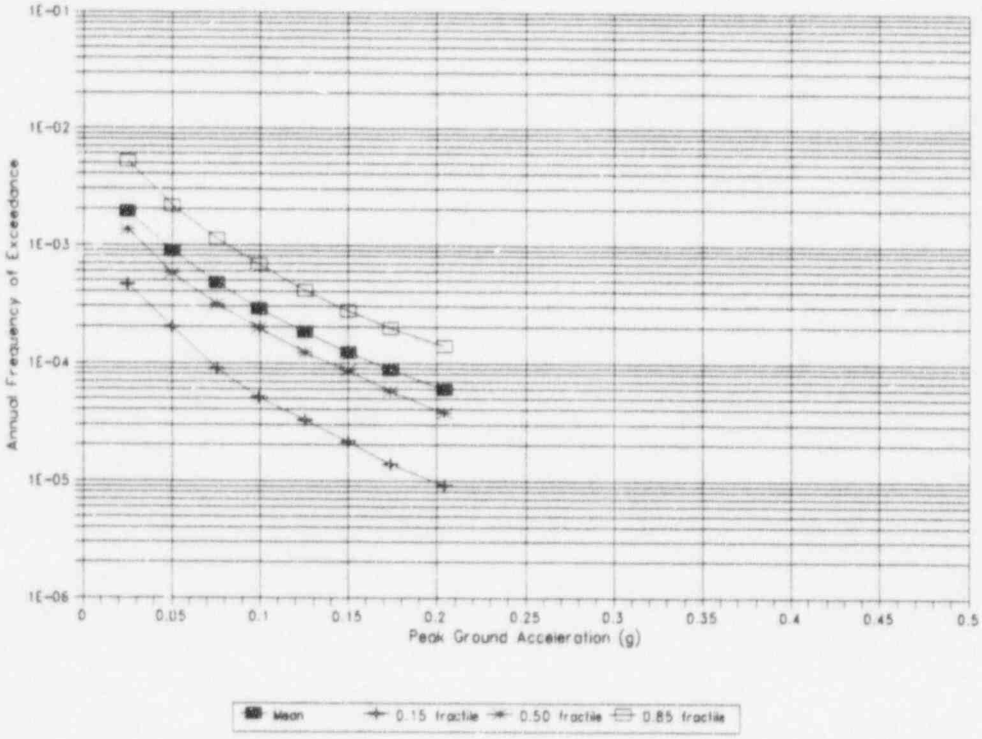


Figure A.3.6-E-2
Peak Ground Acceleration Median Fractile Hazard Curves By Team

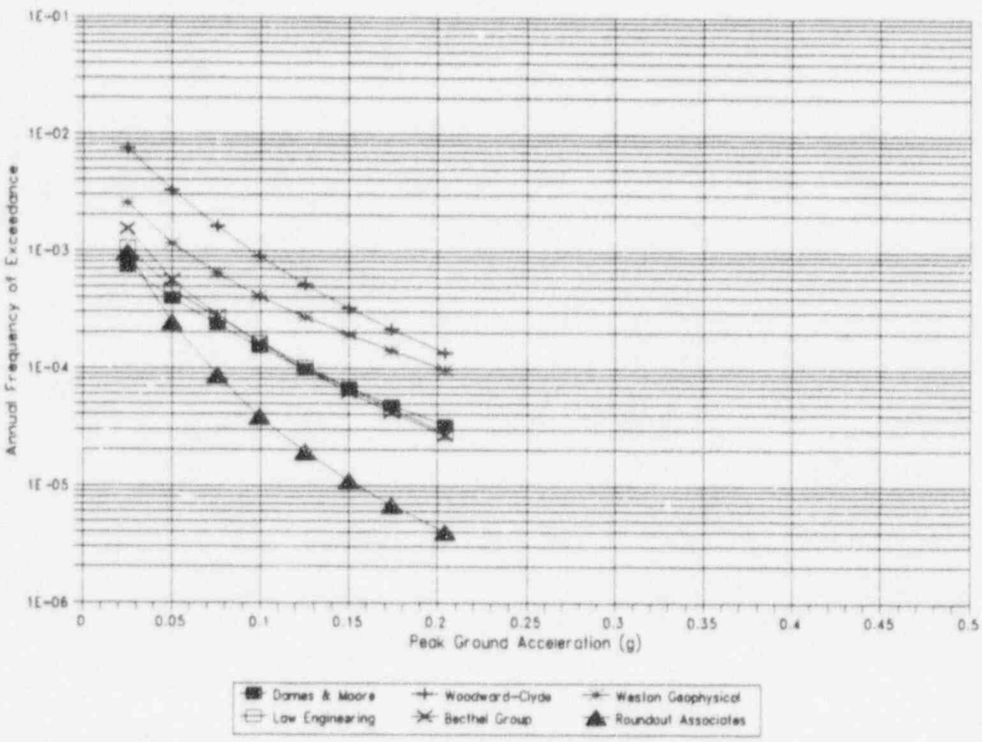


Figure A.3.6-E-3
Peak Ground Acceleration Fractile Hazard Curves with Site Amplification

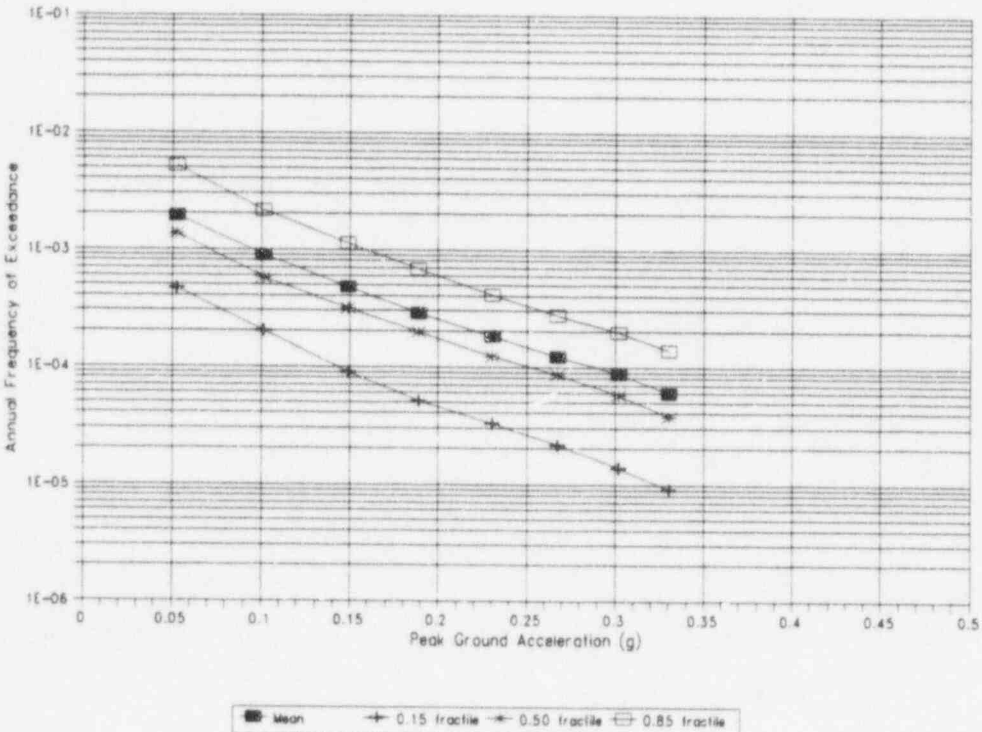
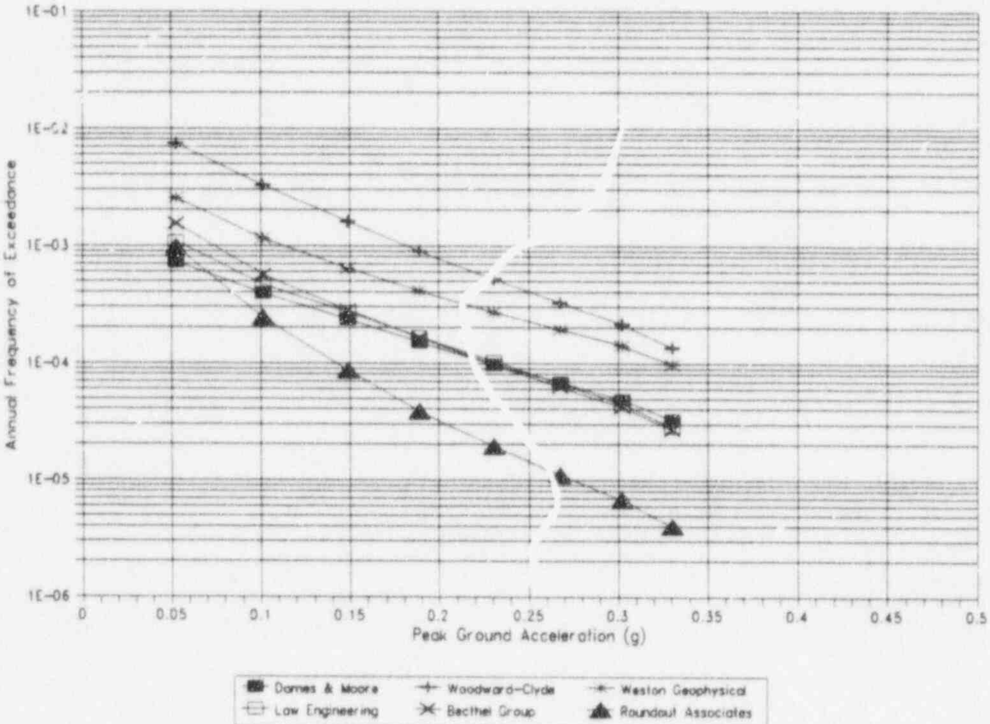


Figure A.3.6-E-4
Peak Ground Acceleration Median Fractile Hazard Curves By Team With Site Amplification



TECHNICAL SUPPORT DOCUMENT A.3.6-F

POTENTIAL FOR SOIL LIQUEFACTION

(Revision B)

TSD A.3.6-F
POTENTIAL FOR SOIL LIQUEFACTION

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Potential for Soil Liquefaction

1.0 Introduction

Earthquake-induced soil liquefaction may have potentially damaging effects on the integrity of critical facilities. In those cases where a structure itself may be able to withstand design-basis ground accelerations, it may be damaged or destroyed by failure of the underlying soils.

Soil liquefaction is the transformation of a cohesionless sediment from a solid state to a liquefied state as a result of increased pore pressure and the consequential decrease in effective stress. As the sediment is subjected to cyclic shear stress of varying magnitude, the soil tends to decrease in volume. If the deposit is undrained, no volume decrease can be accommodated, resulting in an increase in the pressure of intergranular pore water, which acts in opposition to the pressure exerted on the soil by the overlying sedimentary column.

Liquefaction typically occurs in loose, well-sorted, granular soils in combination with a high water table. Characteristically, affected sedimentary deposits include deltaic, river channel, flood plain, and eolian soils of recent geologic age.

Liquefaction produces three general types of ground failure, which are:

1) Flow failures (which occur on slopes of greater than approximately 2.5 %). In this case, undrained monotonic or cyclic loading of a loose, saturated sand results in the loss of shear resistance and the sand flows like a liquid until the acting shear stresses are equal to the reduced shear resistance.

2) Lateral spreads (occurring on slopes between 2.5 and 0.5 %). Liquefaction of an underlying layer causes lateral extension of an intact, undeformed surficial layer.

3) Bearing strength loss occurs on slopes of less than 0.5 %, where the bearing capacity of a soil is lost by the failure of an adjacent or underlying soil. (Budhu et al. 1990; Youd and Perkins 1978)

The observable evidence of liquefaction includes sand boils, tension cracks, vertical and lateral translation of buildings and foundations, and the uplifting of buried pipelines and tanks.

Criteria of liquefaction susceptibility include:

1) Depositional age and depth of burial. Increasing depositional age and depth of burial results in a greater degree of cementation, while compaction changes the void ratio of the sediment. Liquefaction is therefore generally confined to deposits younger than Late Pleistocene ag ..iose of Late Holocene are most likely to liquefy.

2) Depositional environment. Depositional environment influences the sorting and density of particles, with those sediments containing a predominance of sand-sized grains being more susceptible to liquefaction. However, silty sands and gravel may liquefy under intense cyclic loading, as clay- and silt-size particles result in a more cohesive sediment with increased shear strength. Because of depositional conditions, many fluvial and deltaic sediments are lacking in fines, which results in a loosely packed structure of grains. Such deposits are relatively susceptible to liquefaction, followed by alluvial fans, plains, beaches, terraces, and estuarine deposits. Clay-rich deposits of glacial till, common at the WVDP, are generally not easily liquefied.

3) Water table elevation. The height of the water table is a primary influence on the potential for liquefaction. Intergranular water acts to decrease the effective stress and facilitate ground failure. The most easily liquefiable soils are located where the water table is within 10 feet of the surface; the increase in soil strength with increasing depth is an associated factor.

4) Thickness. If the saturated unit is relatively thick, the dimensional changes which occur during cyclic loading will be greater, resulting in an elevated potential for damage.

5) Maximum ground acceleration. The potential for failure of soils is directly related to both the intensity and the duration of earthquake-induced acceleration.
(Budhu et al. 1989, 1990)

2.0 Methods of Estimating Liquefaction Potential

Two procedures have been developed for the estimation of liquefaction potential. The first (Youd and Perkins 1978) is based on geological criteria and compares a map of seismic activity with a map illustrating geologic age and groundwater elevatior Geologically young sediments located in an area with a relatively high water table will be more susceptible to liquefaction for a given rate and magnitude of seismic activity.

The second procedure is a qualitative method of estimating the potential for soil liquefaction using geotechnical data proposed by Seed et al. (1971, 1983). This method uses the extensive database of Standard Penetration Test (SPT) values which are collected when the soil column is sampled as a well or boring is emplaced. This method (and its derivatives, e.g., Liao et al.

1988) is the present de facto standard for estimating liquefaction potential, and was chosen for use at the WVDP site.

While soil liquefaction potential determined by field performance can be correlated with a variety of soil index parameters, the SPT is the most widely used parameter. A study by Seed et al. (1983) has established a basis for correlation between the resistance exhibited by soils to the penetration of a sampling tube and the resistance of those soils to liquefaction produced by earthquake-induced ground motion.

The method for the Standard Penetration Test is described in ASTM 1586-84, Standard Method for Penetration Test and Split-barrel Sampling of Soils. The method stipulates equipment and procedures to be followed to diminish the variability of test results. A split-spoon or split-barrel sampler is a thick-walled, steel tube that is split lengthwise. When a boring is advanced to the desired depth, the drilling tools are withdrawn and the sampler is lowered into the hole at the bottom of drill rods. A 2.0 inch OD standard-size split-spoon sampler is driven into the soil using a 140-lb hammer which is dropped 30±1 inches. The effort required to drive the sampler 24 inches into the soil is recorded at 6-inch intervals. The first six inches is required to seat the tool, the sum of the blows required to drive the sampler the subsequent twelve inches into the ground is designated the standard penetration value, or N-value.

Studies have shown that the actual energy delivered to the drill rods when performing this test may vary from between 40% and 90% of the theoretical energy developed by a free-falling hammer. This effect is primarily due to the use of different driving apparatus and methods, e.g., use of a safety hammer or drive weight, the diameter and condition of the capstan, integrity of the rope, and the number of rope turns on the capstan. Other influences include the length of the drill rods (depth of sample), and the use of a liner in the sampling tube. Variations in the diameter of the sample tube, hammer weight, and drop height may be accounted for by the relationship proposed by Lowe and Zaccheo (1975):

$$R_s = \frac{D_o^3 - D_i^3}{144WH}$$

where

R_s	=	hammer ratio
D_o	=	external diameter of sample tube
D_i	=	internal diameter of sample tube
W	=	weight of hammer (in lbs)
H	=	hammer drop height (inches)

For cohesionless soils with relative densities of less than 50% (typical of the sand and gravel of the North Plateau) the number of hammer blows required to advance the sampling tube (N), is corrected by:

$$N_e = \frac{N}{4050\ R_s^{5/7}}$$

where

N = field N-value: the number of blows required to drive the sampler from 6 to 18 inches of each advance
N_e = corrected N-value

(Budhu et al. 1987)

The corrected N-value of soil penetration resistance is normalized to an effective overburden pressure of 1 ton per square foot (N_{60}) by the relationship below. This accounts for variability in overburden pressure, lateral soil pressure, and the density of the soil, to yield a number considered to be equivalent to the use of a hammer of 60% efficiency. The value of the correction coefficient C_n has been established by Seed et al. (1983) and others, but the most commonly used relationship is that of Liao and Whitman (1986):

$$N_{60} = C_n\ N_e$$

where,

$$C_n = \sigma_o^{-1/2}$$

Cyclic Stress Ratio Model

The method developed by Seed et al. (1971, 1983) depicts the cyclic liquefaction characteristics of a horizontally bedded sand by calculating the cyclic stress ratio. This parameter is a ratio of the average cyclic shear stress (τ_h) resulting from earthquake-induced cyclic loading to the vertical effective stress (σ_o') acting on the layer before shaking. The ratio is computed from the equation below:

$$\text{Cyclic Stress Ratio (CSR)} = \frac{(\tau_h)_{ave}}{\sigma_o'} = 0.65\left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_o}{\sigma_o'}\right)(r_d)$$

where

a_{max}	=	maximum acceleration at ground surface for the design earthquake
σ_o	=	total overburden pressure
σ_o'	=	initial effective overburden pressure
r_d	=	stress reduction coefficient, which decreases linearly from a value of 1 at the ground surface to ~0.9 at a depth of 30-35 feet

The potential of cyclic mobility or liquefaction may be determined by plotting the cyclic stress ratio (corrected for earthquake magnitude) versus N_{60}, then comparing the location of the data point to empirically derived field performance curves developed by Seed et al. (1983). If the point lies above the curve which corresponds to the clay and silt content of the sample soil, there is a 50% probability that the soil will liquefy when subjected to earthquake-induced ground motion.

Probabilistic Method

Liao et al. (1988) used a regression analysis from SPT data for 278 sites of observed liquefaction to construct field performance curves similar to those of Seed et al. These curves allow the liquefaction potential to be defined in probabilistic terms with greater specificity than the curves developed by Seed.

3.0 Liquefaction Potential of WVDP North Plateau Sand and Gravel

The surficial gravel on the North Plateau is composed primarily of an alluvial fan gravel, with a smaller fraction of fluvial gravel. A grain size analysis performed by the New York State Geological Survey (NYSGS) showed the average composition of the surficial gravel to include 56% gravel, 22% sand, 13% silt, and 9% clay. A textural class plot showed alluvial and fluvial gravel to be indistinguishable on the basis of particle size (Albanese et al. 1982).

Data obtained from the installation of 28 monitoring wells were used as input for determining the liquefaction potential of the sand and gravel layer of the North Plateau. All wells were drilled as part of the 1989-1990 Resource Conservation and Recovery Act (RCRA) monitoring well program.

The thickness of the surficial gravel layer and the locations of the wells used in the calculation of the liquefaction potential are shown on Figure A.3.6-F-1.

The wells were continuously sampled using a split-barrel sampler and blow counts were recorded according to the procedures outlined in ASTM standard method D 1586-84. The thickness of the sand and gravel layer varies from 4 to 32 feet in these boreholes, which have saturated thicknesses of more than 29 feet. Table A.3.6-F-1 summarizes the input data from the wells used in the liquefaction potential calculations.

The SPT value (corrected and normalized) and cyclic stress ratio were calculated as described above and are shown in Table A.3.6-F-1. The majority of Seed's work was based on the liquefaction characteristics of soils during magnitude $m_b = 7.5$ earthquakes. The number of stress cycles induced by earthquakes of magnitudes other than $m_b = 7.5$ may be accounted for by applying a correction factor; in this case a factor of 1.5 for a magnitude $m_b = 5.25$ was taken from Seed et al (1983). A magnitude $m_b = 5.25$ event corresponds to the smallest magnitude earthquake for which the methods have been developed. (It may be that earthquakes of smaller magnitude would not provide the cyclic character necessary to elevate pore pressures to values to cause liquefaction). A magnitude $m_b = 5.25$ event at the site corresponds to a peak horizontal ground acceleration of 0.15 g - an unlikely event at the WVDP site.

4.0 <u>Results</u>

Calculated magnitude normalized cyclic stress ratios (CSR) and corrected and normalized SPT values are plotted in relation to the field performance curves of Seed in Figure A.3.6-F-2. The three curves represent the boundary condition for a 50% probability of liquefaction for a given percentage of fines (<5, 15, and 35 percent). The location of the data point for well R86-13C indicates a potential for liquefaction, assuming the soil from R86-13C is similar to the samples analyzed by the NYSGS, which contained approximately 22% fines.

The resulting values are plotted against the field performance curves of Liao (1988) in Figure A.3.6-F-3. The R86-13C sample would be subject to a 30% chance of liquefaction in the event of a magnitude $m_b = 5.25$ earthquake. The soil sample from well 104 has a 20% probability of liquefaction when subjected to an earthquake of a similar magnitude. The other samples are subject to a correspondingly lesser probability of liquefaction, with the sample from well 704 having less than a 1% chance of liquefaction in the stress regime generated by the $m_b = 5.25$ earthquake.

Liao (1988) established arbitrary categories of liquefaction potential based on field performance curves.

>50%	High (H)
10-50%	Medium (M)
<10%	Low (L)

When categorized according to the method of Liao et al. (1988), none of the WVDP samples would be classified as having a high potential for liquefaction. Seven samples would be moderately likely to liquefy; the remainder would have a low probability of liquefaction.

5.0 Conclusions

The calculated values were obtained using averaged pre-existing values of bulk unit weight and grain-size distribution. Laboratory analysis of individual samples from each of the wells used in this study may yield different values for these properties, which would affect calculations and interpretation. The curves developed by Seed et al. and Liao et al. are appropriate for sandy soils that have a more homogeneous grain size content than those which are found on the North Plateau of the WVDP. The surficial gravel of the North Plateau is a relatively more heterogeneous mixture of gravel, sand, silt, and clay, which tends to reduce the potential for liquefaction. The direct assessment of soil properties and behavior may be accomplished by the use of laboratory tests such as an undrained cyclic triaxial test, or the use of a shaking table apparatus, and may be useful as an adjunct to future studies.

Groundwater elevations used to determine the height of the saturated soil column and resultant stresses were recorded during early January 1991. Higher groundwater levels would exacerbate liquefaction hazard in cohesionless sediments.

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2	Per ECN #10300		09/30/96
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