Study Plan for
Study 8.3.1.17.3.6

Probabilistic Analyses of Vibratory Ground Motion and Fault Displacement at Yucca Mountain

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U. S. Geological Survey

STUDY PLAN

for

STUDY 8.3.1.17.3.6

PROBABILISTIC ANALYSES OF VIBRATORY GROUND MOTION AND FAULT DISPLACEMENT AT YUCCA MOUNTAIN

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ABSTRACT

As part of the site characterization program for the potential high-level nuclear waste repository at Yucca Mountain, Nevada, Study 8.3.1.17.3.6 is designed to quantify the probabilities of varying levels of both vibratory ground motion and fault displacement within the geologic repository operations area. The study includes (1) evaluation and characterization of seismic sources; (2) for vibratory ground motion, evaluation of the level and attenuation of vibratory shaking; (3) for fault displacement hazard, evaluation of the amount and spatial distribution of future surface faulting; and (4) probabilistic computations of vibratory ground motion and fault displacement hazards. Interpretations providing input to the probabilistic computations will be carried out by experts on the basis of geologic, seismic, geophysical, and geotechnical data collected within and around the Yucca Mountain area. The results of the study will provide input to a Seismic Design Basis Team whose responsibility is to develop a seismic hazard information base, sufficient for regulatory review and licensing, that includes deaggregation of the hazard assessment results for the determination of significant earthquake sources, faults that may affect repository design and performance, and controlling earthquakes.

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PROBABILISTIC ANALYSES OF VIBRATORY GROUND MOTION AND FAULT DISPLACEMENT AT YUCCA MOUNTAIN

INTRODUCTION

A probabilistic approach to hazards analyses for the potential nuclear waste repository at Yucca Mountain is prescribed in the Site Characterization Plan (SCP) (U.S. Department of Energy, 1988) for Study 8.3.1.17.3.6, Probabilistic Seismic Hazards Analysis, and for Study 8.3.1.17.2.1, Faulting Potential at the Repository. Both studies (1) aim to determine hazards that may affect repository seismic design and performance, (2) apply similar methodologies in their respective probabilistic analyses of vibratory ground motions and fault displacements, (3) utilize the same basic data in their analyses, and (4) anticipate the use of panels of experts to provide the properly complete technical interpretations of the available data. For these reasons, the two studies are combined in this study plan to form an integrated study for assessing the hazards of ground shaking and faulting posed to the surface and subsurface facilities important to safety (FITS).

The integration of Studies 8.3.1.17.3.6 and 8.3.1.17.2.1 necessitates changes in the SCP as follows:

1. The combined study is numbered 8.3.1.17.3.6, and titled "Probabilistic analyses of vibratory ground motion and fault displacement at Yucca Mountain."

2. Investigation 8.3.1.17.2 and Study 8.3.1.17.2.1 are deleted from the site characterization program, and incorporated in revised Investigation 8.3.1.17.3, titled "Studies to provide required information on vibratory ground motion and fault displacement that could affect repository design and performance."

3. Activities 8.3.1.17.3.6.1 and 8.3.1.17.3.6.2 are combined into Activity 8.3.1.17.3.6.1, "Evaluate ground-motion probabilities."

4. Activities 8.3.1.17.2.1.1 and 8.3.1.17.2.1.2 are combined into Activity 8.3.1.17.3.6.2, "Potential for fault displacement at the repository."

These changes do not result in altering, to any significant degree, the objectives or designated parameters assigned in the SCP to the affected studies or activities.

Study 8.3.1.17.3.6 **Probabilistic Analyses of Vibratory Ground Motion and Fault Displacement at Yucca Mountain**

The study plan presented here implements methodologies for seismic hazards determinations that are recommended and discussed in detail in a report entitled, "Methodology to assess fault displacement and vibratory ground motion hazards at Yucca Mountain" (U.S. Department of Energy, 1994). Portions of the study plan's text are borrowed freely from that document to summarize the plan of investigation for revised Study 8.3.1.17.3.6.

The work described by this study plan will be conducted in three strongly integrated, parallel tasks leading to the determination of vibratory ground motion and fault displacement levels for seismic design of the repository structures, systems and components and to full documentation of the technical bases for these determinations. The tasks to be completed are: (1) evaluation and characterization of seismic sources; (2) evaluation of vibratory ground motion attenuation relationships, including earthquake source, wave propagation path and site effects; (3) evaluation of the amount and spatial distribution of fault displacement; and (4) probabilistic seismic hazard computations, including vibratory ground motion and fault displacement.

By nature, interpretations of seismic sources, source characteristics, and ground motion propagation involve interpretations of data and the interpretations themselves involve uncertainties. For the purposes of discussion, the term *variability* will be used in a general sense to describe the two types of "uncertainty" that are inherent in these analyses. One source of variability results from the inherent randomness of stochastic, physical processes (aleatoric uncertainty), such as the event-to-event variation in stress drop or focal depth. This *randomness* is non-deterministic and cannot be reduced by the accumulation of additional data. The other component of variability arises as modeling or scientific uncertainty (epistemic uncertainty), for example, the uncertainty about the median stress drop or depth distribution of seismicity. This study plan will refer to this source of variability as simply *uncertainties*. These scientific or modeling uncertainties are deterministic and in principle can be reduced by the accumulation of additional data so as to limit the range of viable models, of divergent interpretations and of statistical variation. Refer to Section 2.1.2 or Department of Energy (1994) for additional discussion about variability and its role in the analyses.

In this study, elicitations of expert's interpretations of Yucca Mountain data will play a major role in defining scientific or modeling uncertainty. The interpretations to be completed as part of this study will be based on seismological, geological, geophysical and geotechnical data specific for Yucca Mountain and the surrounding area. Interpretations of the various data sets will be fully integrated in order to evaluate and incorporate scientific uncertainty, to quantify parametric random variability, and to minimize variability due to data uncertainty. To evaluate scientific uncertainty, it is anticipated that seismic source interpretations will be made by (1) six teams consisting of two to three individuals expert in the seismicity, tectonics, and geology of the Yucca Mountain region, and (2) six individuals expert in seismology and ground motion assessments who will provide evaluations of vibratory ground motion attenuation relationships, and effects from earthquake source, wave propagation path, and site response. Interpretations will be accomplished through a series of workshops. Each workshop will be designed to accomplish a specific step in the overall interpretation and to insure that the relevant data are being fully considered and integrated into the evaluations. This process is designed to insure that credible interpretations are considered in the vibratory ground motion and fault displacement evaluations and that the resulting variability in these hazards is appropriately considered in determining the hazard levels to be used for seismic design of the repository structures, systems and components.

The seismic hazard computational procedures developed as part of Study 8.3.1.17.3.6 will provide quantitative evaluations of seismic hazards based on input interpretations provided by the experts. For example, as part of the characterization of seismic sources, we anticipate that the expert teams will promote several alternative tectonic models for faults near Yucca Mountain. The calculations will embody all proposed tectonic models in an attempt to assess the effects of various tectonic models on the resulting hazard levels and to discriminate models that produce the greatest variability. The quantification will incorporate variability in the hazard due to uncertainty in the interpretations (scientific uncertainty) and random variability in input parameters. The computational procedure accommodates the overall goal of incorporating interpretations and variability supported by the seismic hazard informational base. It also allows the contributions from different seismic sources or interpretations to be examined as part of the process to determine and evaluate a seismic design basis within a regulatory environment.

Probabilistic assessments of vibratory ground motion and fault displacement hazards support both preclosure and post-closure issues (see Fig. 4). For preclosure, the results will be used to determine seismic design inputs, whereas for post-closure they will provide inputs to performance assessment.

1. PURPOSE AND OBJECTIVES

The primary objectives of Study 8.3.1.17.3.6 are to quantify (1) the probability for experiencing ground motions of varying degrees of severity that might result from earthquakes of varying magnitudes and distances from the potential repository site, and (2) the potential for fault displacements of varying degrees of severity to disrupt the surface facilities or the underground repository. The assessments will provide the scientific basis and the documentation for the determinations sufficient for regulatory review and license decision making. Probabilistic hazards analyses are important to design and performance issues for both the preclosure (100 yr) and postclosure (10,000 yr) periods (as discussed in Section 3). For the preclosure period, the main concerns are waste containment during handling and emplacement, worker safety in both surface and underground facilities, and maintenance of waste retrievability. For the post-closure period, concerns center on the location of the repository relative to any active faults that have the potential for producing displacements and/or ground motions that may adversely affect repository performance. Specific objectives and parameters assigned to each of the two activities in the study will be discussed in the following sections.

2. SCOPE OF WORK

2.1 Activity 8.3.1.17.3.6.1 Evaluate Ground Motion Probabilities

The objectives of this activity are to quantify probabilistically the ground motion hazard within the geologic repository operations area at Yucca Mountain and to document the basis for this determination in detail sufficient for regulatory review and licensing.

To reach these objectives, four steps are carried out (Figure 1):

(1) Identify seismic sources and evaluate activities, locations, geometries and dependencies.

(2) Characterize seismic source magnitude and recurrence distributions.

(3) Characterize ground motion attenuation.

(4) Probabilistically integrate characterizations to determine vibratory ground motion hazard.

In carrying out these steps, variability in data and interpretations is explicitly defined and incorporated. The characterizations are determined by experts, or teams of experts, based on the complete set of available data and facilitated by a series of workshops to highlight and examine possible interpretations. Normative experts provide for the appropriate elicitation of the experts' interpretations. Data available to support interpretations is compiled and analyzed in Studies:

8.3.1.17.3.1 - Relevant Earthquake Sources
8.3.1.17.3.3 - Ground Motion from Regional Earthquakes and Underground Nuclear Explosions
8.3.1.17.3.4 - Site Effects of Local Geology and in Investigation:
8.3.1.17.4 - Preclosure Tectonics Data Collection and Analysis

In this section, first the calculational procedure is briefly discussed. This is followed by a description of the four steps identified above. Next, the treatment by the analysis of uncertainties is addressed. Finally, the process to facilitate the development of interpretations by the experts is presented.

2.1.1 Calculations of Vibratory Ground Motion Hazard

The probabilistic seismic hazard analysis (PSHA) methodology is well established and is a generally accepted practice for assessing vibratory ground motion hazard (U.S. Nuclear Regulatory Commission, 1988; 1994; Bernreuter et al., 1989; Electric Power Research Institute, 1989; Risk Engineering, Inc., et al., 1989). The method developed by Cornell (1968) forms the basis for recent state-of-the-practice methodologies that have been applied to nuclear power plants and to U. S. Department of Energy facilities. The seismic hazard computation integrates over seismic sources, earthquake magnitudes, earthquake recurrence, and ground motion variability. The computational method can accept either time dependent or time independent (Poisson) earthquake occurrence models. The model appropriate for the rates of earthquake recurrence in the Yucca Mountain area will be used. For a Poisson recurrence, the probability that at a given site a ground motion parameter, Z, will exceed a specified value, z, during a specified time period, T, is given by the expression:

$$P\,(Z > z) = 1.0 - e^{-\nu(z)\cdot T} \tag{2-1}$$

in which $\nu(z)$ is the average frequency during time period T at which level of ground motion parameter Z exceeds z at the site resulting from earthquakes on all sources in the region. It should be noted that the assumption of a Poisson process for the number of events is not critical. This is because the mean number of events in time t, $\nu(z)\bullet t$, can be shown to be a close upper bound on the probability $P(Z > z)$ for small probabilities (less than 0.10) which generally are of interest for engineering application.

The frequency of exceedance, $\nu(z)$, is a function of the variability (randomness and uncertainty) in the time, size and location of future earthquakes and variability in the level of ground motions they produce at the site. It is computed by the expression:

$$\nu(z) = \sum_{n=1}^{N} \alpha_n(m^o) \int_{m=m^o}^{m^u} \int_{r=0}^{\infty} f_n(m) \bullet f_n(r|m) \bullet P(Z > z\,|\,r,m)\, dr\, dm \tag{2-2}$$

in which $\alpha_n\ (m^o)$ is the frequency of earthquakes on seismic source n above a minimum magnitude of engineering significance, m^o; $f_n(m)$ is the probability density function of event size on source n between m^o and an expected maximum earthquake magnitude for the source, m^u; $f_n(r\ |\ m)$ is the probability density function for distance to earthquake rupture on source n, which may be conditional on the earthquake size; and $P(Z>z\ |\ m,r)$ is the probability that, given a magnitude *m* earthquake at a distance *r* from the site, the expected ground motion "Z" exceeds a given level z. In practice, the double integral in Equation (2-2) is replaced by a double summation with the density functions $f_n(m)$ and $f_n(r \mid m)$ replaced by discrete representations of their corresponding cumulative functions.

The methodology for seismic hazard assessments is summarized in four basic steps as shown in Figure 2. The result is a hazard curve expressing the annual probability that various levels of ground motion will be exceeded.

2.1.1.1 Interpretations of Seismic Sources and Source Geometries (Step 1)

A seismic source represents a region of the earth's crust in which the generation of seismic waves or the capability of surface deformation or both are known to be or suspected to be different from that of the adjacent crust. Typically, these differences are described by specific probability distributions for the source's size, spatial location, probability of activity, and frequency of occurrence. Candidate seismic sources for Yucca Mountain include exposed, buried, or hidden Quaternary faults, zones of historical seismicity, and testing sites of underground nuclear explosions. Consistent with regulatory guidance (NUREG-1451, McConnell et a' , 1992), seismic sources with a potential for fault displacement and with a potential to affect Geological Repository Operations Area (GROA) design or long-term waste isolation performance assessment (for example, Type I faults in the nomenclature of NUREG-1451) will be identified, evaluated and characterized by the expert teams for input to the PSHA.

The first step in the seismic hazard assessment involves an evaluation of seismic sources. Data from areas local and regional to Yucca Mountain will be compiled (primarily in Study 8.3.1.17.3.1), and the compilations will be provided to the experts for them to scrutinize. The database for interpretation will include:

- Information on historical and instrumental seismicity
- Information on local and regional faults
- Information on local and regional crustal stresses
- Geophysical data
- Crustal deformation data
- Information on local and regional volcanic activity
- Information on alternative tectonic models

For each known or suspected seismic source, the various experts will use conventional earth science practices to assess (among other input described in the following sections) the probability of activity, spatial locations, three-dimensional geometries, and source dependencies, if any.

The activity of each known or suspected seismic source will be assessed and expressed as a probability of activity given alternative circumstances. A probability level for activity will be defined for sources that are inferred to be active but lack evidence that can be used to assess activity, such as buried or hidden sources for example. The experts will consider additional criteria for assessing fault activity including: association with observed seismicity, association with a known Quaternary structure, and orientation relative to the contemporary stress regime (appropriate for NUREG-1451, McConnell et al., 1992).

Source geometries and locations will be described as discrete, mapped faults, or areal seismic source zones (or volumes), which will be used for postulated buried and hidden faults, zones of background seismicity, and sites of nuclear explosions. The three-dimensional geometries of seismic sources will be evaluated in terms of their map location, subsurface geometry, and downdip extent within the seismogenic crust. Alternative interpretations of fault geometry will be assessed for each source, and the basis for the assessments will be documented by the expert teams. For areas where earthquake activity cannot be associated with recognized faults, experts will prescribe the boundaries of areal source zones. A complete evaluation of seismic sources is obtained when the entire region of interest is partitioned into fault-specific sources and seismic source zones.

2.1.1.2 Evaluation of Earthquake Magnitude and Recurrence (Step 2)

The rate of earthquake activity and relative temporal distribution of earthquakes of a given magnitude define the recurrence relationship for a seismic source. The expert teams will assess the recurrence relationship for each seismic source from all pertinent geologic, tectonic, seismic and paleoseismic data. The moment magnitude of maximum earthquakes will be evaluated by the experts using seismic moment calculations and various empirical magnitude-rupture parameter regressions. Uncertainties in the fault rupture parameters will be documented, in terms of the geologic basis for the best estimate alternative values, and incorporated into the seismic hazard calculations. A maximum earthquake will be assessed for each source that incorporates uncertainties in the geologic and paleoseismic data.

Each seismic source will be characterized by a recurrence relationship (Figure 2, Step 2), which expresses the expected number of earthquakes per year of a given magnitude that are greater than some minimum magnitude, m^o. The expert teams will determine m^o and the magnitude-frequency distribution from m^o to the maximum magnitude, m^u, from the geologic data, observed seismicity, and any other pertinent information. It is expected that the experts will rely mostly on geologic data to develop recurrence relationships for fault sources, whereas observed seismicity will be used to assess recurrence for areal source zones. The level of seismicity in the Yucca Mountain region is low and the historical record of seismicity is brief (about 100 years), therefore geologic data on earthquake recurrence intervals and fault slip rates will be emphasized in the recurrence assessments.

2.1.1.3 Evaluation of Ground Motion Attenuation (Step 3)

Ground motion attenuation relationships allow the ground motion to be computed at a site from a given earthquake at a given location. Inherent in these relationships are the earthquake source and path contributions to the ground motion, and their variability. Given adequate data, these relationships may be derived empirically from regression analyses of recordings of earthquakes and underground nuclear explosions from the western United States. Empirical ground motion relationships describe the dependence of a measure of ground motion (e.g., peak acceleration, peak velocity, and response spectral ordinates) on earthquake or explosion size and distance. In this project, the experts will evaluate whether separate ground motion attenuation relationships are necessary for shallow and deep sources, vertical and horizontal motions, and different styles of faulting, as well as other important issues such as variability. The experts can rely upon, but are not limited to, the input and results of investigations being conducted in Studies 8.3.1.17.3.3 (Ground motion from regional earthquakes and underground nuclear explosions) and 8.3.1.17.3.4 (Effects of local site geology on surface and subsurface ground motions).

Ground motion attenuation relationships also may be derived on the basis of the fundamental physics of earthquake sources, wave propagation through the earth, and site response. In the numerical relationships developed, the effects of faulting style, source depth, differences between footwall and hanging wall motions, and near-fault directivity may be included using the specific geometry of the faults in relation to the site.

The inherent stochastic nature of earthquake rupture (the stress parameter and slip distribution may vary over the dimensions of a source as well as from source to source) and seismic propagation (heterogeneities in the earth scatter and focus seismic waves) lead to a significant component of random variability in ground motion. The ground motion measure at a site, therefore, is a stochastic parameter. Characterization of the ground motion parameter Z is made in terms of a probability distribution of Z as a function of the dependent parameters m (magnitude) and r (the minimum distance from the earthquake source to the site) and may explicitly include other parameters (source stress parameter, depth, source dimension, site response).

Attenuation relationships will be customized for the Yucca Mountain site. They can be developed for a certain set of geological and topographical site conditions, and can include region- and site-specific effects of the travel paths and seismic wave propagation.

2.1.1.4 Seismic Hazard Results (Step 4)

The seismic hazard results, shown as Step 4 in Figure 2, are obtained by integrating over all seismic sources, recurrence rates, and ground motion attenuation relationships. For a particular seismic source interpretation and ground motion attenuation relationship, one hazard curve is calculated giving the annual probability with which various levels of ground motion are expected to be exceeded. Completing this computation over the range of source interpretations, recurrence rates, and ground motion variability results in a family of hazard curves expressing the seismic hazard at the site and its uncertainty.

2.1.2 Evaluation and Propagation of Variability

The probabilistic seismic hazard calculation integrates over the range of earthquake sizes, locations, seismic sources, and ground motion variability to present a composite picture of the hazard at the site from all events, properly weighted by their probabilities of occurrence. This is a central feature of the method. The method of calculating probabilistic seismic hazard is straightforward; therefore, the real effort in the seismic hazard study will be put into evaluating and documenting the appropriate inputs for the analysis. A range of inputs is needed to represent uncertainty in interpretations and the range of parameter values. Consequently, the major effort of this activity will be to evaluate and document interpretations of available data as inputs to the analysis in order to express scientific uncertainty.

To represent the uncertainties in seismic hazard results, the study will evaluate and properly treat the various sources of variability. The variability has two components:

> Randomness is a probabilistic variability that results from the nature of physical processes, e.g., crustal strain accumulation and release. If a fault is active, the size, location, and time of the next earthquake on that fault is a random phenomenon, and so on.
>
> Uncertainty is statistical or modeling (e.g. "scientific") variability that expresses the lack of knowledge about the "true" state of nature. In this study, uncertainty will be expressed by the interpretations provided by experts.

This distinction between sources of uncertainty is important; the hazard analysis itself integrates over randomness, and it is that property that gives a hazard curve. The uncertainty in input is propagated through the calculations and is reflected by uncertainty in the hazard curve; e.g., the range of hazard curves.

The propagation of the uncertainties will be accomplished by use of logic trees. Figure 3 shows schematically the mechanics of the method in the form of a simple logic tree. Each node in the tree represents a point of possible alternative interpretations reflecting uncertainties which are represented by the branches starting from the node. For example, one node could be the point for expressing uncertainty in the geometry of a seismic source or the dependence on a tectonic model.

Each branch of a node has an associated probability reflecting the weight of the data supporting that interpretation. For example, at a node where a ground motion uncertainty is expressed, there could be several branches representing possible ground motion attenuation relationships that are considered credible, each with its respective weight.

In this way, a complete logic tree is constructed which enumerates the combinations of the uncertain parameters supported by the data. Going from the starting point of the tree, at the left on Figure 3, and following a single path to the ending point at the right constitutes a single set of parameters as described in Steps 1 through 3 of Figure 2, that form the basis for a hazard calculation (Step 4). The weight attached to the resulting hazard curve is the product of the weights of the branches of the path. By performing a calculation for each path through the logic tree, a complete probabilistic description of the hazard is obtained from which statistics are calculated, including the mean value of the hazard, the median and other percentile values.

The probability distributions of the uncertain parameters are discretized and expressed as branches of the logic tree, even if the uncertain parameter could be described by a continuous distribution.

As an alternative, a Monte Carlo simulation may be used to propagate uncertainty. In this approach, each simulation is similar to one path of a logic tree and is determined by randomly drawing the value of a parameter from its probability distribution function. In this study, emphasis will be placed on use of logic trees to better facilitate peer and regulatory review and evaluation because both methods give the same hazard distribution results when applied to the same input interpretations.

2.1.3 Development of Interpretations

Because the inputs required to assess seismic hazards at Yucca Mountain contain uncertainty, and the site characterization data are subject to different interpretations (i.e., different experts give different weight to data sets and to underlying tectonic processes), interpretations will be obtained from multiple experts. This has become a well established procedure for quantifying and documenting scientific knowledge and bringing available knowledge into the decision-making process (Electric Power Research Institute, 1989; Bernreuter et al., 1989; U.S. Nuclear Regulatory Commission, 1994). The range of expert interpretations (which can be attributed to scientific uncertainty) can be a significant component of the total uncertainty in a seismic hazard assessment.

The steps that will be followed in this activity to implement the methodology are the following: 1) selection of the experts; 2) compilation, analysis and dissemination of data; 3) preparation and review of interpretations and evaluations in workshops; and 4) analysis and aggregation. Each of these steps is discussed below.

The process of implementing the methodology involves a series of workshops, each designed to accomplish a specific work scope and to produce a specific product. Workshops to perform seismic source and earthquake recurrence interpretations will be conducted in parallel with similar workshops to perform ground motion attenuation interpretations. The parallel track is adopted because the two activities involve essentially different scientific expertise and data sets. In parallel with these activities, a probabilistic seismic hazard computer code will be adopted and modified as needed for efficient application to Yucca Mountain.

2.1.3.1 Selection of the Experts

Individuals who are recognized by their peers as experts in their respective fields will perform the interpretations for the Yucca Mountain probabilistic assessment. The selection process will be designed to provide experts who can develop the needed evaluations for input to the PSHA, including assessments of the range of input variability. Their expertise and association with government, scientific and private organizations should cover the range of issues and technical understandings regarding the tectonic and seismic environment of the Yucca Mountain region.

The process of expert selection will first involve developing selection criteria. These will include such attributes as: strong professional reputation, experience in the Yucca Mountain region or similar tectonic environments, publication record, and willingness to participate in an open process and provide evaluations for input to seismic hazard calculations. A large pool of potential experts will first be developed and, applying the criteria and bearing in mind the need to cover scientific views and the range of discipline expertise, the experts (18 to 24) will be selected. It is anticipated that seismic source interpretations will be provided by a panel of six teams; each team having two to three individuals. Individuals within each team will be chosen to represent different disciplines and experience, mainly within three fields of expertise including earthquake geology and paleoseismology, regional geology and tectonics, and seismicity and seismic hazard assessment. At least one member of each team will have experience working on faults at Yucca Mountain or nearby in the Basin and Range Province, for example, a geologist. Another member of the same team might be a geophysicist with experience in the regional tectonics of the Basin and Range Province, and another member might be a seismologist with knowledge about the local or regional seismicity near Yucca Mountain. The panel for ground motion interpretations will consist of five to six individuals chosen to represent different approaches to ground motion attenuation and engineering seismology.

2.1.3.2 Compilation and Analysis of Data

A key step in the assessment of seismic hazard at Yucca Mountain is the identification of useful data and technical parameters relevant to the hazard analysis. Workshops will be held early in the project to identify the tectonic, seismic, and ground motion parameters that must be evaluated and the data sets and derivative data analyses required to complete the evaluations. Once the data needs are identified, the data will be compiled and any additional analyses performed. The data and the results of any analyses will be made available in common format to the experts for their use in interpretations. The data needs workshops will play an important role in allowing the experts to discuss the significance of various technical parameters and the quality of particular data sets that might address those parameters.

2.1.3.3 Preparation and Review of Interpretations

At the next workshops on interpretations, any new data or additional analyses and various interpretations of all the available data will be presented and discussed. The workshop or workshops will be followed by a process that is designed to elicit clearly and to quantify the range of technical interpretations of the available data by the selected experts. This process is aided by facilitation teams which provide technical organization and leadership to the workshops. The facilitation team will assist the normative experts in the elicitation of each expert team as a group. The elicitations may be supplemented by one-on-one interviews and informal discussions with particular individuals of a team. Elicitations will occur in separate meetings with each team, encouraging the members of each team to achieve consensus on elicitation questions. Intra-team differences will be noted by members of the facilitation team and will be used, for example, in conducting sensitivity analyses or in promoting further discussion of potentially important issues. The experts will document their interpretations and which databases they used to develop their assessments. These assessments will be presented at the next workshop as preliminary input and will be followed by feedback workshops. The purpose of these workshops is to provide immediate feedback to the experts on the assessments made by others and a vehicle to investigate and clarify the differences in interpretations in a constructive manner. Following the elicitations and feedback workshop, a workshop will be held to assess the experts' final interpretations and associated uncertainties. The seismic hazard will be calculated based on this input.

2.1.3.4 Analysis and Aggregation

An aggregation methodology is required to combine the hazard results of the multiple interpretations and evaluations. Throughout the project, extensive interaction among the experts will be encouraged and facilitated by conducting the multiple workshops. Through such interactions, hypotheses poorly supported by the data and scientifically-indefensible models may be eliminated or downweighted by the experts. This process, referred to as behavioral aggregation through interaction, will be combined by simple mechanical aggregation (assigning equal weights) to the experts' seismic hazard results. After the elicitations and before the final hazard calculations, preliminary results of the elicitations and a variety of sensitivity analyses will be prepared, provided to the experts, and discussed in a workshop format. For example, feedback to the experts will include, but are not limited to, mean and fractile hazard curves based on each team's assessments, plots of the relative contributions of each seismic source to the mean hazard, plots of the relative contributions of source characterization variability to the total variance in hazard, and sensitivity analyses showing variability in the mean hazard as a function of the expert's assessed ranges of seismicity characteristics. The analysis and aggregation will be documented by the Facilitation and Hazards Calculation teams in accordance with appropriate management procedures.

2.2 Activity 8.3.1.17.3.6.2 Assessment of Fault Displacement Hazard

The probabilistic methodology will be used to assess the fault displacement hazard, including the use of experts for data interpretation. The basic methodology is the same as that used to assess vibratory ground motion hazard except that fault displacement rather than ground motion is the hazard parameter. Because significant faulting may be accompanied by sympathetic displacements in adjacent areas, information on the relative amounts and distribution of primary and secondary displacement will be made part of the fault displacement hazard assessment. Results will be in the form of fault-specific hazard curves relating fault displacement values to probability of exceedance.

2.2.1 Calculations for Fault Displacement Hazard

A process similar to the four steps involved in assessing vibratory ground motion hazard is used to assess the hazard of fault displacement. Although repetitious to a large degree with the discussion in section 2.1, these steps are discussed below as they pertain specifically to fault displacement.

Step 1: Develop interpretations of fault-specific seismic sources that have a significant potential for displacement that could affect the repository facilities based on identified Quaternary faults and on other site characterization data. Evaluate fault geometries, probabilities of activity, and any source dependencies.

Step 2: Characterize the magnitude-recurrence distribution of seismic sources, focusing specifically on those faults within the operational area of the potential repository, faults that intersect potential facilities important to safety, and faults within the wider area that the experts may consider most relevant to fault displacement hazards (probably faults within 15 to 20 km of the site).

Step 3: Characterize the expected spatial distribution of fault displacements that could result from local and nearby surface-rupturing earthquakes, focusing especially on the along-strike and across-strike variability in the expected amounts and distribution of primary and secondary displacements as well as on other factors deemed important by the experts such as the structural and tectonic models, kinematic connectivity, and fault segmentation models of relevant faults.

Step 4: Integrate over each combination of inputs determined in Steps 1, 2 and 3 to calculate a hazard curve expressing the annual probability that a given value of fault displacement will be exceeded. Carry out the integration for all combinations of inputs to incorporate the variability of input evaluations. Express results as a distribution of fault displacement hazard curves that can be represented by a mean curve and curves for particular percentiles of the distribution.

Specific fault data to be used in Steps 1 and 2 (above) will be collected by other studies in the site characterization program, primarily Study 8.3.1.17.4.6, Quaternary faulting in the site area, and Activity 8.3.1.5.1.4.2, Surficial deposits mapping of the Yucca Mountain area (Fig. 1), in addition to the entire data base used for ground motion assessments, including the technical interpretations of the experts. For the underground facilities, additional subsurface fault information being collected in Study 8.3.1.4.2.2, Characterization of structural features in the site area, will be used. The above data are also being compiled and synthesized in Study 8.3.1.17.3.1, Relevant earthquake sources.

2.2.1.1 Evaluation of Seismic Sources Significant for Fault Displacement Hazard Assessment (Step 1)

Consistent with NUREG-1451 (McConnell et al., 1992), seismic sources significant for fault displacement hazard assessment will be based on Type I faults--those subject to displacement and with a potential to affect repository facility design or performance assessment. These seismic sources will be a subset of those evaluated to assess vibratory ground motion hazard, concentrating on local faults. The probability of activity for each seismic source and dependencies among sources will be evaluated in the same fashion as for vibratory ground motion hazard, except that the scope will focus in at a more detailed scale appropriate to address certain fault segments in the vicinity of, and at scales equivalent to the surface and subsurface facilities. The experts will consider additional criteria for assessing fault activity including: association with observed seismicity, association with a known Quaternary structure, and orientation relative to the contemporary stress regime (NUREG-1451, McConell et al., 1992). Source geometries will be evaluated in terms of their map location, subsurface geometry, and downdip extent, emphasizing fault connectivity and expected rupture patterns and displacement distributions. Experts will be asked to evaluate whether displacements will occur on otherwise unrecognized faults or fault zones in order to quantify the likelihood of new faulting and its possible displacement amount and spatial distribution.

2.2.1.2 Evaluation of Fault Slip Recurrence (Step 2)

The evaluation of fault slip recurrence to assess fault displacement is identical to that for the assessment of vibratory ground motion. For faults, recurrence is determined on the basis of fault-specific data. Variability in the evaluations is also assessed and documented. Fault-specific slip rate and recurrence interval data derived from geologic investigations are expected to be the principal data for evaluating fault slip recurrence, in addition to recurrence derived from historical and instrumental seismicity data.

2.2.1.3 Evaluation of Fault Displacement (Step 3)

The translation from earthquake occurrence to fault displacements is comparable to evaluating the ground motions due to earthquake occurrences. Earthquake magnitude is empirically related to coseismic displacement and used to determine the amount of slip on a fault, given an earthquake size. Relationships for the distribution, sense, and amount of coseismic slip at particular locations are required, and a variety of methods are available for making this evaluation. All data relevant to the behavior of faults in the Yucca Mountain vicinity will be used in the displacement hazard assessment. These data include information on the displacement history of local faults during the Tertiary and Quaternary periods, the distribution and geometric relationship of significant faults, evaluations constraining the tectonic and geometric relationships among faults, and analogies to documented cases of coseismic rupture within similar tectonic regimes. To characterize the spatial distribution of displacement, it is anticipated that the experts will rely mostly on historical observations of earthquake rupture lengths and, in particularly, along-strike and across-strike variability in the amounts and spatial distributions of displacement that have occurred from normal- and strike-slip-faulting earthquakes in the Basin and Range Province. The experts will be asked to evaluate the empirical data and its variability in order to develop relationships that can be used to predict the effects of faulting at points of interest, given the occurrence of earthquakes of certain magnitudes at given locations. One might refer to these as "displacement attenuation" relationships, and like ground motion attenuation relationships, they can be used to consider the source, path, and site effects that potentially result from various rupture lengths, fault geometries, and the failure mechanics of soil and rock in the faulted zone.

2.2.1.4 Calculation of Fault Displacement Hazard (Step 4)

The probabilistic methodology developed by Cornell (1968) forms the basis for fault displacement hazard calculations (Cornell and Toro, 1989). The mathematical formulation presented in Section 2.1.1 also applies to fault displacement when appropriate substitutions are incorporated as follows:

- In Equation 1, Z is redefined as fault displacement and the exceedance value, z, is also specified as a fault displacement.

- In Equation 2, $P(Z>z|m,r)$ is redefined as the probability that given a magnitude m earthquake at a distance r, the primary (or secondary) fault displacement exceeds a value z at the site of interest. The probability includes an evaluation of the occurrence of secondary faulting. For fault displacement, m^{o} is a minimum magnitude below which surface fault displacement is not expected.

As for vibratory ground motion, the result of the calculation is a hazard curve expressing the annual probability that various values of fault displacement will be exceeded.

2.2.2 Evaluation and Propagation of Uncertainty

Evaluation and propagation of uncertainty for fault displacement are carried out in the same manner as for vibratory ground motion (see Section 2.1.2). The logic tree approach, and if needed a Monte Carlo approach, will be employed to propagate uncertainty and randomness (U.S. Department of Energy, 1994). The final result is a distribution of fault displacement hazard curves, represented by a mean hazard curve and percentile curves.

2.3 Computer Codes

Computer codes to assess vibratory ground motion hazard are already developed and have been subjected to quality assurance evaluation (Bernreuter et al., 1989; Electric Power Research Institute, 1989; Risk Engineering, Inc., et al, 1989). One of these computer codes or a similar code will be adopted for use in Activity 8.3.1.17.3.6.1 with modifications to incorporate the necessary subroutines for fault displacement hazard assessment for use in Activity 8.3.1.17.3.6.2. The costs of revising codes and Quality Assurance documentation, validation, and verification will be considered in the final selection. Code modifications (fault displacement subroutines, Quality Assurance documentation, etc.) will be developed during the course of this study under provisions set forth in Quality Assurance Requirements and Descriptions.

3. APPLICATION OF RESULTS

The results of the probabilistic seismic hazards assessment will be used for both the seismic design of structures, systems, and components and for input to the postclosure waste containment and isolation performance of the repository. Specifically, the results of Study 8.3.1.17.3.6, through its inclusion in Investigation 8.3.1.17.3, which, in turn, is part of the Preclosure Tectonics Site Program (Program 8.3.1.17), are directly applicable to several performance and design issues (Fig. 4), including:

1. Issue 4.4 - This issue requires information that can be used to determine whether the repository can be designed, constructed, operated, and closed using reasonably available or proven technology.

2. Issue 1.12 - This issue is concerned with developing seals needed for exploratory study facilities, exploratory boreholes, and the underground repository so that they do not become pathways that compromise the geologic repository's ability to meet the performance objective for the period following permanent closure.

3. Issue 2.3 - Resolution of this issue requires the assurance that, during the preclosure period, the repository will not pose any undue radiological risk to the health and safety of the public and repository workers as a result of possible accidents.

4. Issue 2.4 - This issue is concerned with the ability to retrieve emplaced waste during the preclosure period. Accordingly, the repository must be designed, constructed, operated, and maintained to ensure that the retrieval option is not compromised.

5. Issue 2.7 - This issue is concerned with the features (i.e., characteristics and configurations) of the repository that relate to radiological safety. These features are part of the engineered systems and components that make up the repository, but also include some aspects of the natural setting of the site by accounting for the impact of these aspects on the engineered systems and components.

All of the issues listed above address one or more of the regulatory requirements for high-level nuclear waste repositories as set forth in 10 CFR Part 60.

Because the Preclosure Tectonics Site Program also contributes data for use in the Postclosure Tectonics Program (Program 8.3.1.8), the results of Study 8.3.1.17.3.6 are indirectly applicable to Issue 1.1 (Total system performance), Issue 1.8 (NRC Siting Criteria), Issue 1.9 (Higher level findings - postclosure), and Issue 1.11 (Configuration of underground facilities - postclosure).

Study 8.3.1.17.3.6 Probabilistic Analyses of Vibratory Ground Motion and Fault Displacement at Yucca Mountain

Fault displacement and vibratory ground motion loads appropriate for design will be developed as part of Study 8.3.1.17.3.5 (Ground Motion at the Site from Controlling Seismic Events). (It is anticipated that this Study will be modified to include identification of controlling earthquakes and calculation of fault displacement in addition to ground motion.) The results of Study 8.3.1.17.3.6 (Probabilistic Analyses of Vibratory Ground Motion and Fault Displacement at Yucca Mountain) will provide one of the inputs to the procedure used to identify appropriate controlling earthquakes and related ground motion and fault displacement inputs for design.

4. SCHEDULE

A tentative schedule for Study 8.3.1.17.3.6 is as follows:

FY 1994

1) Prepare and submit study plan for review

FY 1995

1) Organize expert panels, one for seismic source characterization and one for ground motion

2) Conduct workshops to identify data needs and technical issues of importance to hazard analysis

3) Compile available geologic, geophysical, historical seismicity, and paleoseismic data from pertinent studies and distribute to experts

4) Construct alternative approaches that the experts can use to assess fault displacement hazards

FY 1996

1) Acquire and begin modification, documentation, verification, and validation of computer codes

2) Conduct elicitation workshop to collect preliminary expert interpretations and evaluations

3) Aggregate preliminary elicitations and conduct feedback workshop to evaluate results

4) Conduct workshops to finalize fault displacement and ground motion data interpretations as input to the probabilistic seismic hazard analysis team (PSHA)

5) Complete reports on fault displacement and ground motion hazards

6) Calculate vibratory ground motion and fault displacement hazards by PSHA team

7) Prepare final report as input for seismic design

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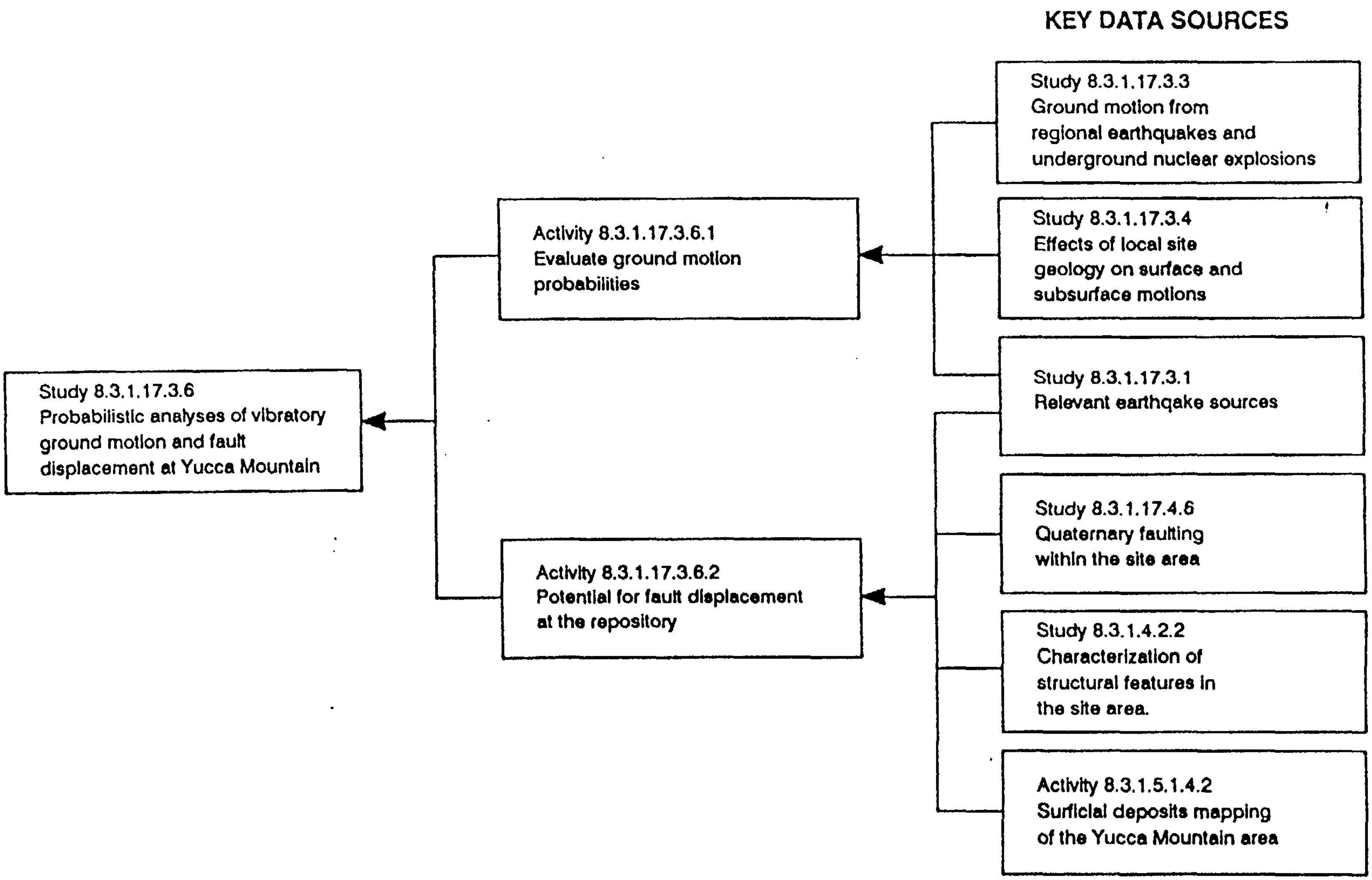

FIGURE 1. DIAGRAM SHOWING PRINCIPAL SOURCES OF DATA FOR USE IN PROBABILISTIC ANALYSES

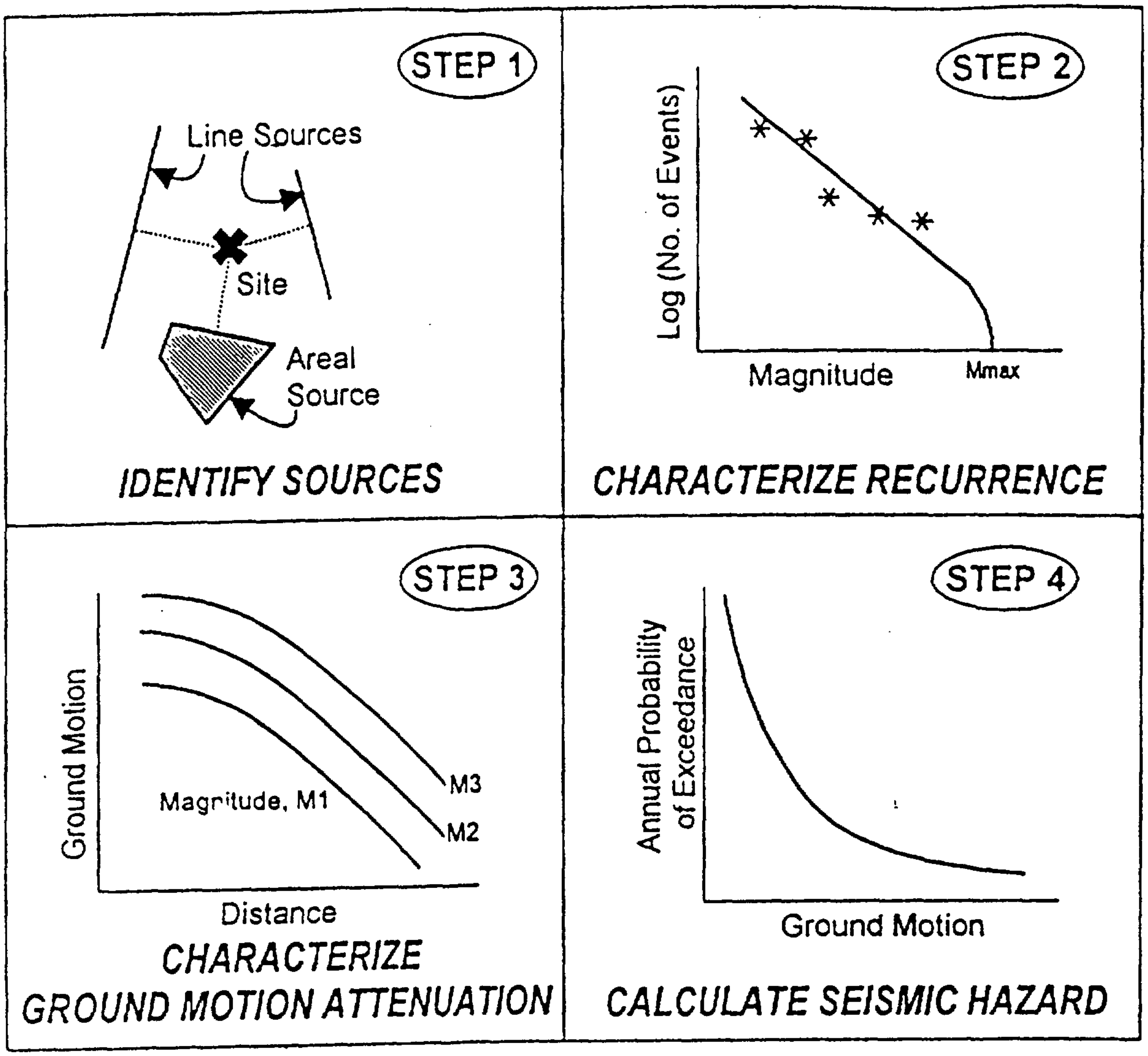

Figure 2. Basic steps of the Methodology as Applied to Vibratory Ground Motion (From U. S. Department of Energy, 1994, as modified from Reiter, 1991).

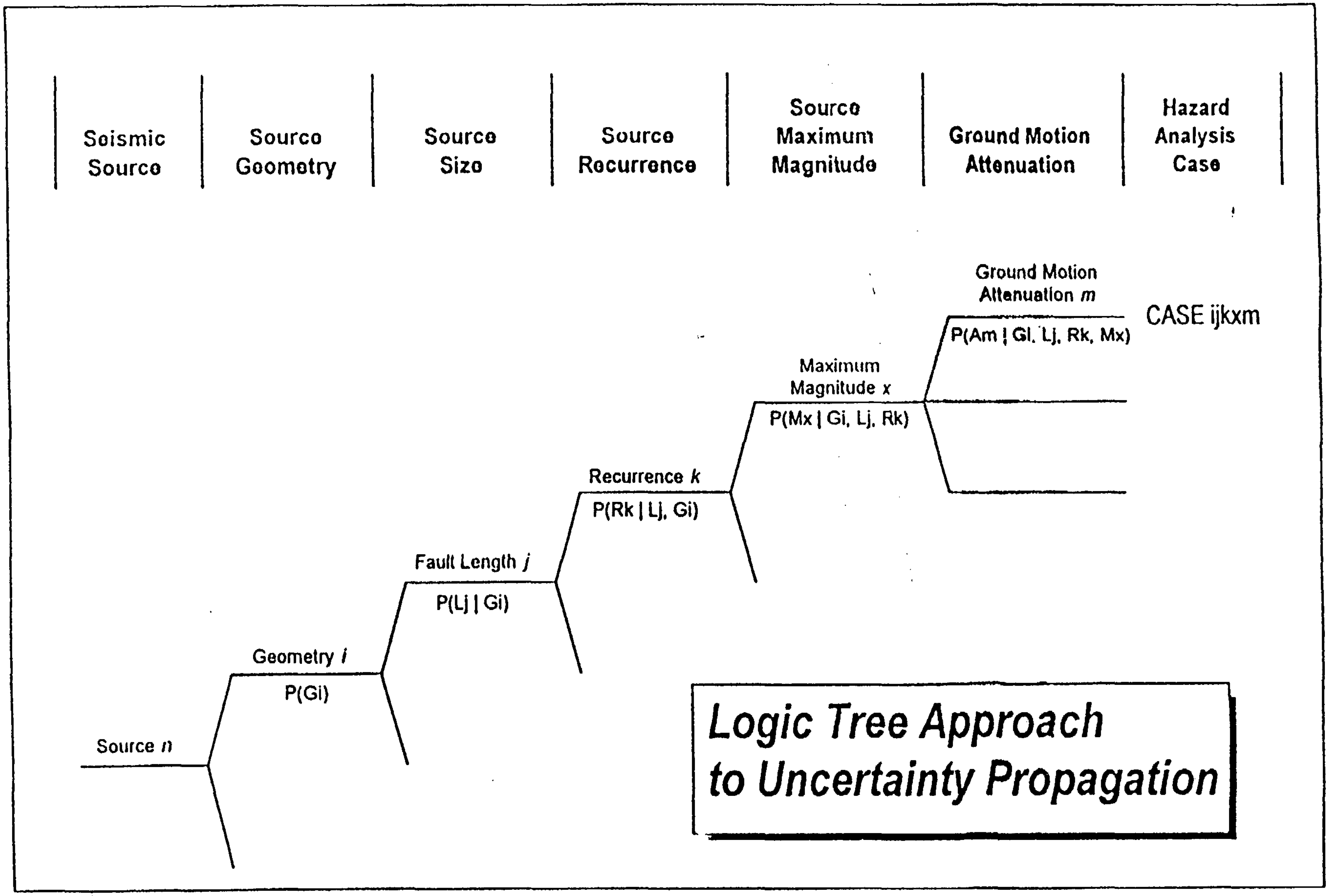

Figure 3. Example Logic Tree Showing Uncertainties in Source Geometry, Size, Recurrence, Maximum Magnitude, and Ground Motion Attenuation for A Given Source "n".

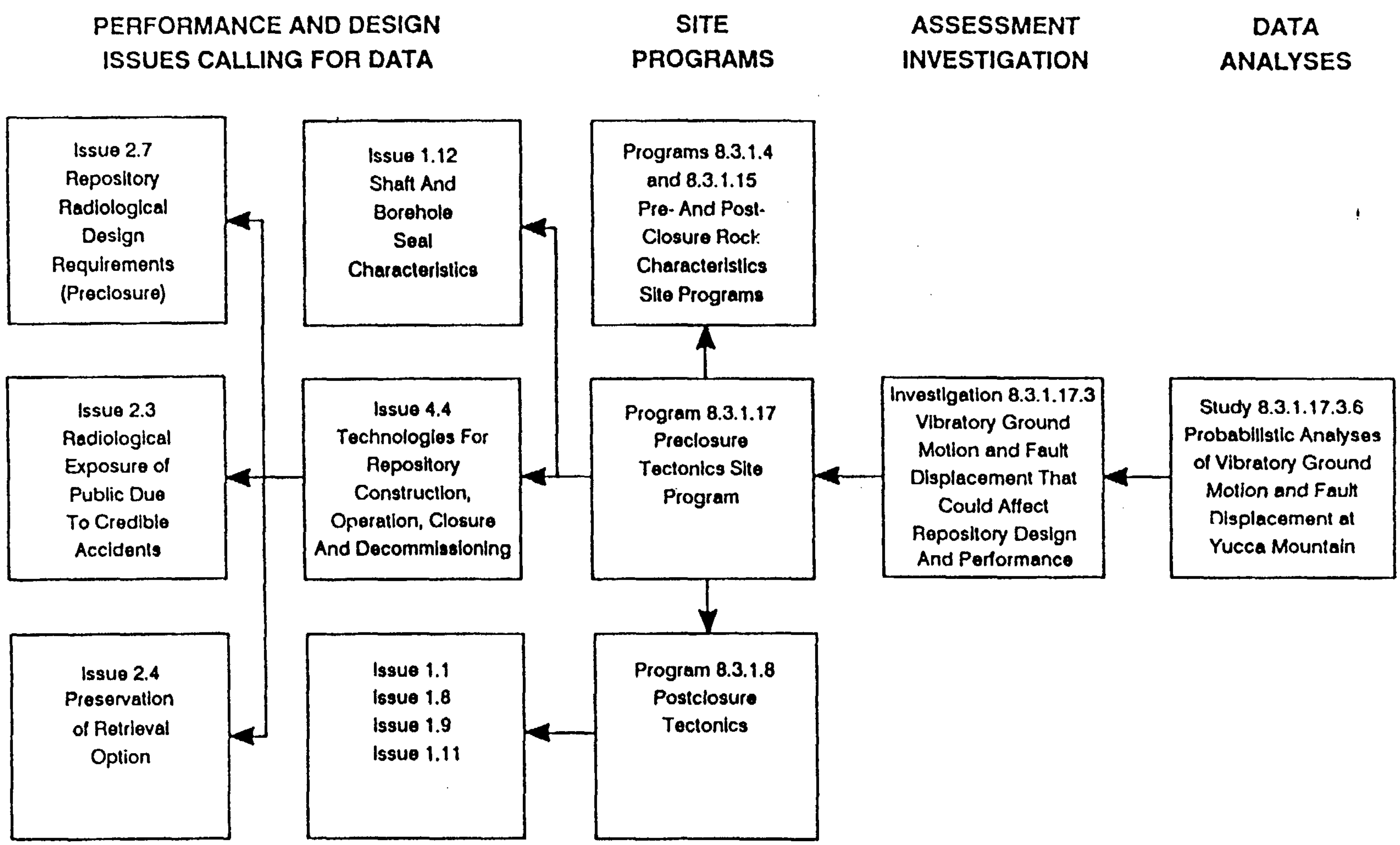

Figure 4. Logic Diagram Showing Relation of Study 8.3.1.17.3.6 to Site Programs and Performance and Design Issues.