Review of
Recommendations for Probabilistic Seismic Hazard Analysis

Guidance on Uncertainty and Use of Experts

NATIONAL RESEARCH COUNCIL

Review of Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts

Panel on Seismic Hazard Evaluation
Committee on Seismology
Board on Earth Sciences and Resources
Commission on Geosciences, Environment, and Resources
National Research Council

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Preface

In the 1980s two studies produced probabilistic seismic hazard estimates for nuclear power plant sites in the central and eastern United States. The first, sponsored by the U.S. Nuclear Regulatory Commission (USNRC), was conducted by Lawrence Livermore National Laboratory. The second, sponsored by utilities in the Seismicity Owners Group, was conducted by the Electric Power Research Institute (EPRI). The studies produced similar hazard curves and generally similar estimates of relative hazard. But for several sites absolute hazard levels differed by two or more orders of magnitude.

Because absolute hazard levels are important for nuclear power plant design, a new study, sponsored jointly by the USNRC, EPRI, and the U.S. Department of Energy, was undertaken by the newly formed Senior Seismic Hazard Analysis Committee (SSHAC) to determine the source of the major discrepancies in the two hazard estimates and to derive a robust probabilistic seismic hazards analysis methodology that could be used for future estimates.

At the same time, the USNRC asked the National Research Council (NRC) to review the work of the SSHAC study and evaluate the proposed methodology. This review was undertaken by the Panel on Seismic Hazard Evaluation of the NRC's Committee on Seismology which followed the work of the SSHAC study and produced the present critique of the SSHAC report.

Carl Kisslinger
Chairman

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Executive Summary

This review and commentary by the National Research Council's Panel on Seismic Hazard Evaluation presents the panel's evaluation and critique of the report titled *Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts* (U.S. Nuclear Regulatory Commission, NUREG/CR-6372, Washington, DC, 1997). The reviewed report was prepared by the Senior Seismic Hazard Analysis Committee (SSHAC), a committee created and sponsored by the U.S. Nuclear Regulatory Commission (USNRC), the U.S. Department of Energy, and the Electric Power Research Institute. The panel was appointed at the request of the USNRC to provide an independent interactive review of the results of SSHAC's efforts.

SSHAC's charge from its sponsors' perspective was to provide an up-to-date procedure for obtaining reproducible results from the application of probabilistic seismic hazard analysis (PSHA) principles established in past practice, not to advance the foundations of PSHA or develop a new methodology. This focus led to an emphasis on procedures for eliciting and aggregating data and models for performing a hazard analysis, rather than an examination of the earth science foundations of PSHA. SSHAC focused on process because previous PSHA studies have shown that different groups of experts can produce highly discrepant results. A second major theme in the SSHAC report is the treatment of uncertainties in data and models in arriving at stable estimates of seismic hazard at a selected site.

With this in mind, the panel found that the SSHAC report offers substantial contributions to the foundations and practice of PSHA. In particular, the panel commends SSHAC for emphasizing the need for critical evaluation of expert opinion. But the panel also identified some limitations in both the report and the recommended procedures, of which potential users should be aware. Only certain key points are highlighted here in the summary; the rest are included in later chapters.

MAIN FEATURES OF THE SSHAC REPORT

As stated above, the SSHAC report focuses on procedures for using experts in probabilistic seismic hazard analysis and for determining uncertainties at key stages of the analysis process. In its treatment of the use of expert opinion, SSHAC outlines four possible levels of effort and complexity. But the SSHAC report is strongly flavored by emphasis on hazard analysis for nuclear and other critical facilities, and SSHAC therefore discusses at great length its highest-level (level 4) procedure for evaluating expert opinion. And although SSHAC includes proper disclaimers the unwary reader could gain the incorrect impression that the high-level (level 4) PSHA procedure is needed for every hazard analysis.

The panel agrees that all PSHA projects should share the same basic principles and goals, but that the elaborate level 4 methodology is not required for every PSHA study. SSHAC does indeed recognize that alternate simpler methods are probably adequate for less critical facilities, but the simpler methods are not discussed in detail and the reader is not fully advised about other sources of information. Adequate disclaimers in the SSHAC report should protect the analyst who chooses to use procedures other than those recommended by SSHAC from the need to defend that decision in a regulatory setting.

THE SSHAC METHODOLOGY

SSHAC's contributions to PSHA methodology include the testing and full explication of the technical facilitator/integrator (TFI) entity, which is the essential ingredient in implementing SSHAC's high-level (level 4) analysis.[1] The TFI approach was found to be very effective in two workshops on ground motion estimation and led to an unexpected degree of agreement among the experts consulted, who began with many diverse viewpoints. The panel notes that TFI elicitation procedure is not

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[1] For a description of the TFI entity, see Chapter 2.

synonymous with PSHA methodology. Nor is the TFI approach recommended by SSHAC for every PSHA study.

In outlining its four levels of complexity, SSHAC visualizes three distinct roles that experts should play at various stages of the process. First, an expert may start out as the proponent of a particular position (data or model). Then the expert is asked to become an objective evaluator of the positions of the other experts in the group. Finally, the expert becomes an integrator and aggregates all the positions to arrive at a putative position of the whole informed scientific community. This estimation of the position of the whole informed community by integration of the positions of a sample of well-qualified experts is the primary goal of the more complex SSHAC procedure. **The panel questions whether any group of experts can truly assess the view of the whole informed scientific community on the entire range of relevant issues.**

BACKGROUND WORKSHOPS

SSHAC sponsored workshops on seismic source characterization, ground motion estimation, and earthquake magnitudes. These workshops are documented in detail in Appendixes A,B C, and H, of the SSHAC report. The workshops contributed both to the development of the procedures SSHAC recommends and to advancement of our knowledge of the earth science elements of PSHA for the eastern United States. Because SSHAC focused on procedures for PSHA rather than technical issues, some of these valuable results are presented but not highlighted. They deserve more attention.

THE TREATMENT OF UNCERTAINTY

The SSHAC report emphasizes the importance of how uncertainty is treated because the results of a PSHA can be influenced heavily by uncertainties in the data, the models, or both. SSHAC's treatment distinguishes and emphasizes the difference between two types of uncertainty: aleatory (i.e., uncertainty due to variability inherent in the phenomenon under consideration) and epistemic (uncertainty due to our limited knowledge of the phenomenon). After separation, these two components must be quantified for the model or parameter under consideration. The panel has more trouble with this element than any other in the SSHAC report.

Recognition of the two kinds of uncertainty is useful initially when eliciting and combining expert inputs. Experts need to be aware of the sources of uncertainties (e.g., limitations of available data) so that they can make informed assessments of the validity of alternative hypotheses, the accuracy of alternative models, and the value of data and then transmit those uncertainties to the TFI. However, as detailed in Chapter 3 of this report, the panel believes that the statistical analysis and uncertainty separation procedures recommended by SSHAC may in some cases be more sophisticated than is warranted by the data or the purposes for which the results are to be used.

During the planning of a PSHA, a detailed analysis of uncertainty would be helpful but typically is not available. It may be sufficient for planning purposes to conduct limited sensitivity analyses, using bounding hypotheses, and to consider the level of effort that would be required to reduce the associated uncertainty.

In addition, the value of an epistemic/aleatory separation to the ultimate user of a PSHA is doubtful. In particular, it is not clear that such a separation would be more helpful than the display of expert-to-expert variability of a mean hazard at the time of an analysis, with an explanation of the source of the differences.

The panel also notes that the SSHAC report's discussions and recommendations on uncertainty and the use of experts are quite independent of PSHA and can be applied to other types of risk analysis. The panel believes that the SSHAC report makes a solid contribution to the methodology of hazard analysis, especially in the use of expert opinion.

1

Introduction

"The future utility of PSHA in decision making depends to a large degree on our ability to implement the process in a meaningful and cost-effective way. Development of the SSHAC guidelines was planned with this goal in mind."

—from Sponsors' Perspective, SSHAC Report

This review and commentary by the National Research Council's Panel on Seismic Hazard Evaluation presents the panel's evaluation of the report *Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts* (U.S. Nuclear Regulatory Commission, NUREG/CR-6372, Washington, DC, 1997). That report was prepared by the Senior Seismic Hazard Analysis Committee (SSHAC) (not a committee of the National Research Council) with sponsorship and oversight by the U.S. Nuclear Regulatory Commission (USNRC), the U.S. Department of Energy (DOE), and the Electric Power Research Institute (EPRI).

WHAT IS SEISMIC HAZARD ANALYSIS?

Earthquakes present a threat to people and the facilities they design and build. Seismic hazard analysis (SHA) is the evaluation of potentially damaging earthquake-related phenomena to which a facility may be subjected during its useful lifetime. An SHA is done for some practical purpose, typically seismic-resistant design or retrofitting. Although strong vibratory ground motion is not the only hazardous effect of earthquakes (landslides, fault offsets, and liquefaction are others), it is the cause of much widespread damage and is the measure of earthquake hazard that has been accepted as most significant for hazard resistance planning.

The level of effort put into an SHA depends on the investment in the facility that might be lost and the consequences to society should it fail. Critical facilities are those that are deemed so important to the functioning of society or whose catastrophic failure will have such disastrous consequences that a maximum (and necessarily costly) effort to assess seismic and all other natural hazards is justified. The SSHAC project was born in the context of SHA for such critical facilities, nuclear power plants in particular. Even though SSHAC broadened its concept of the applicability of its recommended approach to SHA, its report is strongly influenced by this orientation toward very large, costly facilities for which the end goal is to prevent catastrophic failure, even at great expense.

Two general approaches to SHA have been developed and applied. The first approach uses discrete, single-valued events to arrive at scenario-like descriptions of the hazard. Typically, a seismic source location, a maximum earthquake associated with that source, and a ground motion attenuation relationship are specified. The ground motion at the site of interest implied by the chosen inputs is then calculated. The frequency of earthquake occurrence is usually not taken into account, and there is no formal and open way of treating uncertainties. This approach has been labeled deterministic seismic hazard analysis (DSHA) and has been used for many years in the design of power plants, large dams, and other critical facilities.

The other approach is probabilistic seismic hazard analysis (PSHA) and is the subject of the SSHAC effort. PSHA allows the use of multivalued or continuous events and models incorporating the effects and frequencies of all earthquakes that could impact a site. PSHA can easily incorporate model and parameter uncertainties. The results of a PSHA, including the uncertainties, can be represented as a series of curves (mean, median, or selected fractiles), showing the annual frequency of exceeding different levels of the chosen measure of ground motion. The intent of high-level PSHA is to capture and display as much as possible of the knowledge provided by existing data, theory, and computational simulations.

It should be noted that the procedures recommended by SSHAC for the elicitation and aggregation of expert opinion as input to PSHA are equally applicable for compiling the input for DSHA. The only essential difference between DSHA and PSHA is that the latter carries units of time while the former usually does not (Hanks and Cornell, 1994). In the case of a specific design situation, both DSHA and PSHA result in estimates of ground motion values or time histories that provide the basis for earthquake-resistant design. PSHA yields, in addition, the annual frequency of exceedance of that ground motion level together with attendant uncertainties. SSHAC's responsibilities did not extend to a discussion of the steps by which project engineers and sponsors use the output of a hazard assessment. One approach to this issue is presented in a recent paper by McGuire (1995).

Projection of the location, severity, and frequency of occurrence of future extreme natural events inherently involves a variety of uncertainties. Yet decisions on the siting and design of needed facilities must be made in the face of these uncertainties. No amount of statistical analysis, no matter how rigorously based and carefully done, can totally compensate for the incompleteness of available data and the defects of our evolving scientific knowledge. **A primary objective of SSHAC was to acknowledge and document uncertainties explicitly so that users of PSHA will be able to make better-informed decisions.**

BACKGROUND AND CONTEXT OF THIS REPORT

The Panel on Seismic Hazard Evaluation was created under the Committee on Seismology of the National Research Council in October 1992. The panel was formed in response to a request from the USNRC to provide an independent review and evaluation of a report on PSHA to be produced by SSHAC.

The work of the panel was influenced by several factors. First, the USNRC asked the panel to provide an “interactive review,” that is, to submit feedback to SSHAC as it worked in order to avoid the production by SSHAC of a report in which the panel might find serious flaws after it was completed. This request raised serious questions as to how the panel could meet its requirement and not become so involved in the production of the SSHAC report that the objectivity of the panel's own review would be compromised. The panel agreed with the USNRC to provide “arms-length” interaction with SSHAC and developed methods of operation to achieve that goal.

Another factor affecting the work of the panel was a change in the charge to SSHAC after it began its work. The original task assigned by the sponsors concentrated on the reconciliation of two studies done in the mid-1980s by Lawrence Livermore National Laboratory (LLNL) and EPRI of the earthquake hazard at nuclear power plant sites in the United

States east of the Rocky Mountains. These studies were prompted by advice to the USNRC from the U.S. Geological Survey, based on its reconsideration of the likelihood that a major earthquake, such as the Charleston, S.C. earthquake of 1886, could occur again in Charleston or elsewhere along the eastern seaboard. The possibility of such an earthquake could have implications for the safety of nuclear power plants in the eastern United States. A brief history of the LLNL and EPRI studies is given in the SSHAC report.

Although the two studies ranked the many sites approximately the same (from most hazardous to least hazardous in terms of the mean hazard estimates), the absolute hazard values for specific sites, in terms of the mean value of the annual probability of exceeding a specified level of ground motion, differed greatly, with the LLNL results consistently greater.

The problem is illustrated in Figure 1.1, which displays the hazard at three widely separated sites as the annual frequency of occurrence of peak ground acceleration (PGA), the ground motion parameter chosen for this evaluation. The median hazard curve from each study is shown, as well as the 85th and 15th percentile curves. In two of the three cases shown, the median hazard calculated by LLNL is well above that derived by EPRI, and the “uncertainty,” measured by the spread of the 15th and 85th percentile curves, is much greater for LLNL than EPRI. Also, the uncertainty is large, a factor of 5 or more at potentially damaging levels of ground motion (PGA greater than 200 cm/sec^2).

The mean hazard curves, not shown in the figure, differ by even greater factors in many cases. This is because the LLNL median and 85th percentile curves are above the EPRI results, and arithmetic averages spanning several orders of magnitude give greatest weight to the largest numbers. This explains the relatively high values of the mean hazard derived by LLNL but it does not get at the fundamental cause for the differences in the estimates.

The desirability of discovering the cause(s) of the discrepancies was obvious, not only for intellectual reasons (why did competent scientists working from the same or similar knowledge and data bases get vastly different answers?), but also for the practical reason that the quantitative estimate of seismic hazard is important in judging whether earthquakes represent a substantial threat, as well as the weight of earthquakes relative to other natural hazards in making design and retrofitting decisions. The USNRC funded LLNL to investigate the

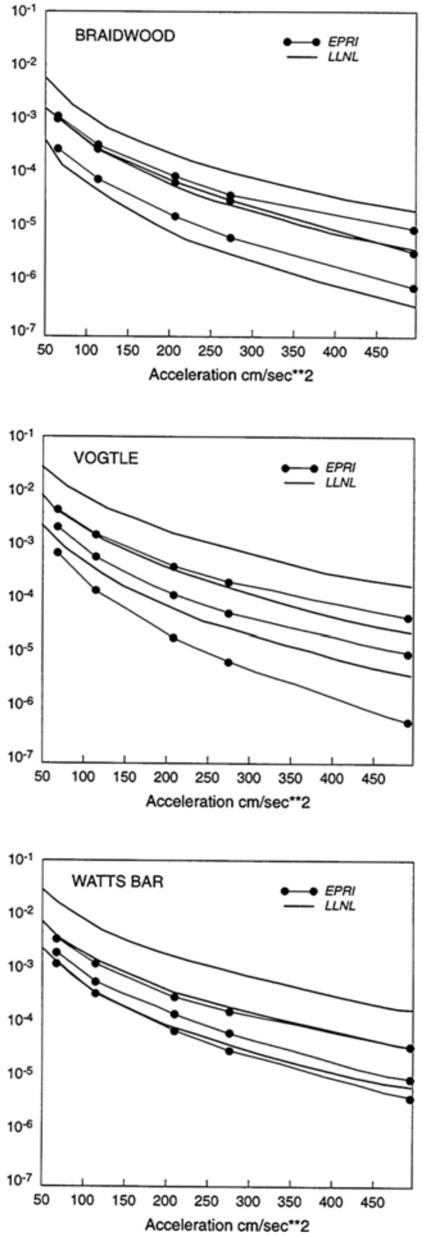

FIGURE 1.1 Median, 15th, and 85th percentile hazard curves for three representative separated sites in the eastern United States, illustrating the differences in results of the LLNL and EPRI studies. The ordinate is the estimated annual frequency of exceedance of the peak ground acceleration shown as the abscissae (adapted from Figures 2.3.1, 2.3.7, 2.3.8 in Bernreuter et al., 1987).

problem. LLNL's study (Bernreuter et al., 1987) concluded that the factors involved in the discrepancy were: (1) different values were chosen for the lower-bound earthquake when the groups were integrated over seismicity to calculate the hazard, (2) different ground motion models were used, and (3) LLNL included a correction for local site effects and EPRI did not. This explained why the two studies obtained different answers but does not explain why competent analysts arrived at significantly different inputs to the hazard calculations.

As SSHAC was being assembled, the underlying cause of the discrepancies between the two studies was identified by further study at LLNL. Researchers there concluded that the differences were due to the ways in which the inputs provided by experts had been elicited. Once this was recognized and taken into account, the differences in the outputs (mean hazard curves) were reduced from orders of magnitude to small factors that represented satisfactory agreement, given the many uncertainties in every step of the analysis. This resolution of the original problem led to changes in the SSHAC charter (1994), from which the following items are selectively cited to provide the context within which the SSHAC report was developed:

> *Objective: T*o develop implementation guidelines, including recommended methodology, suitable for the performance of PSHA for seismic regulation of nuclear power plants and other critical facilities.
>
> *Requirements and Guidelines* (for the implementation guidelines and methodology):

- Be able to provide probabilistic seismic hazard results in the form of fractile probabilities and mean values over a range of ground motion levels suitable for use in probabilistic seismic risk assessments for nuclear facilities.
- Be defined in sufficient detail that, when independently applied by different organizations, no ambiguity exists on how the PSHA is to be performed and comparable results are obtained.
- It is specifically not the objective of this program to advance PSHA methodology or to develop a new PSHA methodology. Rather, an important step in reaching the

objective of this program is expected to be the completion of evaluations of independent PSHA applications by LLNL and EPRI as well as other relevant applications.

- The outcome of this process will be the recommended methodology and implementation guidelines for PSHA in nuclear power plant licensing.

The emphasis on methodology for doing PSHA as the central theme is reflected in the title of the SSHAC report. The focus on siting nuclear facilities, though not emphasized explicitly in the report, strongly influenced its concentration on high-level PSHA.

It should be recognized that the charges to SSHAC and to the panel did not call for the defense or promotion of PSHA as a method for evaluating earthquake hazards. **SSHAC has produced a document that sets forth its conclusions and recommendations on the proper way to do a PSHA if that is the approach chosen by project developers and their analysts.** Neither the SSHAC report nor the panel evaluates the efficacy of PSHA relative to other methods, DSHA in particular. The SSHAC report does provide criteria that can be used to decide the appropriate level of effort for a specific study. Some of the issues related to alternatives to a full-blown PSHA and alternatives to SSHAC's recommended procedures are discussed elsewhere in this report.

The panel offers its appraisal of the SSHAC report, with primary emphasis on the scientific validity of the work and its conclusions, with appropriate attention to the clarity of the presentation, possible sources of misinterpretation, and the report's contributions to PSHA.

INTERACTIONS OF THE PANEL WITH SSHAC

The panel met with SSHAC three times (June 28-29, 1993; May 27-28, 1994; and December 9-10, 1994). Members of SSHAC, representatives of the three sponsoring organizations, and scientific and technical consultants to SSHAC attended the meetings. In addition, Thomas Hanks, a member of the panel, attended a number of SSHAC meetings as liaison observer.

By the nature of its charge, the panel was not able to begin its work until it received a draft product from SSHAC and could not finish its work until it had received the complete final SSHAC report. The June

1993 meeting was devoted primarily to briefings by agency representatives, SSHAC members, and scientific consultants, designed to educate the panel about the goals of SSHAC, the background of the problems being addressed, and the procedures SSHAC would follow. A spokesman for the USNRC explained that the agency wanted two products from SSHAC: (1) a set of guidelines for the process of seismic hazard assessment, and (2) a set of guidelines for the agency, using current data sets and computer codes, to reevaluate the hazards at existing sites. A SSHAC spokesman concluded that the central thrust of the project was to develop, justify, and illustrate methods for capturing both the inherent uncertainties in the parameters that go into an analysis and the disagreement among experts about the values of these parameters. At this time, the panel decided that it needed two additional members, one who could provide expertise in expert opinion analysis and decision science and one with extensive knowledge of both the deterministic and probabilistic approaches to seismic hazard assessment.

By May 1994 the focus of the SSHAC effort had changed, as noted above, from the reconciliation task to the more substantial and significant task of building on the lessons learned from prior experience in hazard assessment to develop scientifically sound procedures for doing PSHA. The SSHAC chairman explained that his committee's goal had been broadened to the development of a methodology that would be applicable not only to nuclear power plants but to other critical facilities as well. SSHAC members presented detailed technical briefings in their areas of expertise, so that the panel gained insight into the flavor of the report that SSHAC would produce. Vigorous discussions of both earth science and decision science issues provided a forum for the panel to explore details of the proposed SSHAC approaches and to convey in broad terms some concerns of the panel. Points raised in these discussions and the panel's evaluation of how SSHAC treated each are addressed elsewhere in this report.

The December 9-10, 1994, panel meeting was based on a detailed review of a draft report submitted by SSHAC. The draft was incomplete; in particular, the extensive appendixes, which on later examination proved to be essential and very valuable contributions of the SSHAC effort, were not available. But, the panel did conduct a detailed review of the main report. SSHAC members, as well as the agency representatives, were present for this review. The results of the review were submitted in the form of a formal letter report to the USNRC on March 16, 1995 (reproduced here as Appendix B). The USNRC forwarded this letter report to SSHAC as part of its oversight of the final version of the SSHAC report.

The March 1995 letter report was the principal formal feedback from the panel to SSHAC. The letter report offered the panel's general comments on the SSHAC draft, a statement of concerns and problems, with suggestions for improvement, and a summary of specific scientific and technical concerns that the panel thought should be addressed. A draft of the final SSHAC report was sent to the panel on October 6, 1995. The present report is based on the panel's review of the October 6 draft, supplemented by several figures and parts of the appendixes that were submitted later. (Although the October 6 draft needed editing the panel was informed that the work of SSHAC was completed and that no further substantive changes in the SSHAC report would be made.)

The expectations of the sponsoring organizations are expressed succinctly in the last sentence of the *Sponsors' Perspective* that opens the SSHAC report, which is quoted at the beginning of this chapter. The panel has reviewed and evaluated the SSHAC report in light of these expectations and how well the goal has been achieved.

ORGANIZATION OF THE PANEL'S REPORT

The panel determined that the SSHAC report could be reviewed under four main headings: (1) process (elicitation and aggregation) and documentation, (2) the treatment of uncertainty, (3) seismic source characterization, and (4) ground motion estimation. The first two concentrate on the decision science components of PSHA, the latter two on the earth science inputs. Following a chapter on each of these, the panel offers a summary of its findings and recommendations.

2

Process and Documentation for a Probabilistic Seismic Hazard Analysis

By its own definition, the main emphasis of the Senior Seismic Hazard Analysis Committee's (SSHAC) report is on the procedural rather than the technical aspects of probabilistic seismic hazard analysis (PSHA). SSHAC argues that many of the major potential pitfalls of PSHA are procedural and therefore goes to great efforts to outline what it views as an appropriate process. In SSHAC's view the important aspects of "process" have to do primarily with experts, their interaction, and methods for translating their views into useful input for a PSHA. Of particular significance is the role assigned to the facilitation/integration team that organizes and directs a PSHA project and its use of experts. SSHAC lays out two basic principles underlying the PSHA process and its results:

1. Regardless of the scale of a PSHA study, the goal (as stated by SSHAC) is *"to represent the center, the body, and the range of technical interpretations that the larger technical community would have if they were to conduct the study."*
2. " *It is absolutely necessary that there be a clear definition of ownership of the inputs into the PSHA, and hence ownership of the results of the PSHA.*"

The panel supports these principles as ideological guidelines for planning and executing a PSHA study, at least in the case of critical facilities. The first is, or should be, the goal of a sponsor in initiating a PSHA, the assumption being that using the collective input of the *informed* technical community would be the best, and most defensible, way of defining seismic hazard. That principle also has an enabling effect because, as discussed later, it allows experts to transcend the role of being proponents of models (the usual mode in scientific discourse) into the roles of objective evaluators and integrators. **The extent to which this goal can reasonably be pursued in a particular case should depend on the scope and importance of the project and the resources available to support the study.**

The second principle is important because it assigns to an identified entity, the "owner," clear intellectual or scientific responsibility for the conduct and results of a PSHA. This does not necessarily mean that the "owner" agrees with every particular input or result but that the owner feels confident that the PSHA has fulfilled the purpose of representing the larger technical community and can be defended in scientific and regulatory arenas, as necessary. These principles underlie the primary recommendations of the SSHAC report that deal with the PSHA process.

LEVEL OF EFFORT IN A PSHA

SSHAC recognizes that a PSHA can be carried out at different levels of effort and emphasizes that the effort expended should match the importance of the facility, the degree of controversy, uncertainty, and complexity associated with the relevant scientific issues, and external decision factors, such as regulatory concerns and the resources available. This is shown in Table 2.1, taken from Chapter 3 of the SSHAC report.

Four levels of study are defined, the first three of which rely on a single entity called the technical integrator (TI), who is responsible for all aspects of the PSHA, including specifying the input. Although experts may be involved on a consulting basis, there is no formal elicitation of their views. The highest level of study (level 4) makes use of formally elicited expert judgment. As such, a new entity called the technical facilitator/integrator (TFI) is needed. The role of the TFI is discussed below. A large part of the SSHAC report is devoted to defining what is necessary to carry out a level 4 study and explaining the function of the TFI because the ideas are new, not because this level of effort is required for every seismic hazard assessment. **It would be inappropriate to infer that all PSHAs require the considerable resources needed to carry out the level 4 PSHA described by SSHAC.**[2]

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[2] Nor does SSHAC make such a claim or inference. This statement is more a caveat to users than a criticism of SSHAC.

The Panel endorses the conceptual framework embodied in Table 2.1, recognizing that the application of PSHA to engineering and regulatory problems is varied and that the level of effort needed should also vary.

SSHAC points out that most site-specific studies make use of some type of TI approach. The TI performs analyses, accumulates information relevant to each issue, and develops a representation of the technical community's views on the relevant input models, parameters, and their uncertainties. At the lowest level of effort (level 1) the technical community's views are determined primarily by a literature search. At higher levels the TI makes use of outside technical researchers and proponents to gain insight into different data sets and models.

The panel emphasizes that a TI must still be guided by the principles of representation and ownership described above.

The importance of peer review is discussed below, but the panel stresses its particular significance when the TI mode is used. Reliance on a single entity (TI) to characterize the input of the whole technical community may be a very efficient mode of operation, but additional assurance is needed to provide confidence that the results are a reasonable representation of the community's views.

THE MULTIPLE ROLES OF EXPERTS

The TFI process views experts as acting in different roles—proponents, evaluators, and integrators. The proponent role is one in which the expert explains, and argues for, the choice of a particular model or set of parameters. The aim is to make sure that the different views in the technical community are presented and discussed by the expert panel. If necessary, individuals outside the expert panel may be brought in to argue points of view with which panel members may not be comfortable. The next role the experts are asked to assume is that of independent evaluators representing their own views of the information presented. Mean estimates of model, component, or parameter values are elicited, along with their uncertainties as appropriate. The result should be the group's composite views of the issues at hand. The experts are encouraged to evaluate their own and other models according to their own technical judgment, without regard to who originally proposed the models. In the past, most PSHAs that have relied on formally elicited expert judgment have strived to get experts to think in this manner. The hope was that the experts' composite view also represented the composite view of the technical community as a whole.

TABLE 2.1 Degrees of PSHA Issues and Levels of Study (Table 3-1 of the SSHAC Report)

Issue Degree	Decision Factors	Study Level
A **Non-controversial; and/or insignificant to hazard**		**1** **TI evaluates/weights models based on literature review and experience; estimates community distribution**
B **Significant uncertainty and diversity; controversial; and complex**	• **Regulatory concern** • **Resources available** • **Public perception**	**2** **TI interacts with proponents & resource experts to identify issues and interpretations; estimates community distribution**
C **Highly contentious; significant to hazard; and highly complex**		**3** **TI brings together proponents & resource experts for debate and interaction; TI focuses debate and evaluates alternative interpretations; estimates community distribution**
		4 **TFI organizes panel of experts to interpret and evaluate; focuses discussions; avoids inappropriate behavior on part of evaluators; draws picture of evaluators' estimate of the community's composite distribution; has ultimate responsibility for project**

To more truly represent the technical community's view, the SSHAC report recommends that the experts be specifically asked to assume the role of integrators and to characterize their perception of how the *technical community as a whole* would view the issues at hand. Thus, although the expert may view his/her assessment as being the most correct, he/she is explicitly thrust into the role of trying to fulfill the first principle of PSHA as outlined above and must be willing to do so. This mode of expert behavior may not be achievable in all issues. Also, **the**

panel is not aware of any objective way to test the assumption that a whole technical community's views can be accurately determined from the interactions of a small group of experts.

SSHAC introduces some useful concepts in its discussion of the interaction among experts. One is that in the process of eliciting, aggregating, evaluating, and integrating the opinions of experts the TFI (discussed in the next section) should create an atmosphere in which there will not be “winners” and “losers.” Another useful idea is the avoidance of unintended dissent or consensus. Apparent disagreement may arise because of lack of communication and understanding among those disagreeing; the process of “active listening,” in which a listener is asked to give back what he/she has just heard, is a step toward eliminating disagreement where it really does not exist. At the other extreme is the development of an apparent but false consensus; the TFI should strive for consensus among the experts only if it is really agreed on.

The panel views the role of expert as integrator as important and worthwhile. However, successful implementation of the integrator role of the experts should be viewed more as a goal to strive for than a uniformly and demonstrably achieved measure of success.

The SSHAC report implies four basic criteria for the identification and selection of experts: (1) technical expertise, (2) strong communication skills, (3) willingness to assume the role of independent evaluator, and (4) willingness to commit the time and effort to participate actively in the study. The choice of disciplines to be represented and the breadth of knowledge of each expert depend on the issues to be addressed and whether or not interdisciplinary subgroups of experts will be formed to provide input. SSHAC also strongly recommends a formal nomination process based on consulting the literature and asking technical societies, government organizations, and knowledgeable individuals to submit the names of potential experts. **Whatever the issue or structure of elicitation, the panel believes that the credibility and quality of an elicitation-based PSHA depend very much on the choice of experts. The panel supports the need for careful attention to the selection process and finds the criteria suggested by SSHAC to be reasonable and likely to be effective.**

TECHNICAL FACILITATOR/INTEGRATOR

One of SSHAC's main contributions to PSHA methodology is the introduction of the technical facilitator/integrator (TFI) concept. The SSHAC report describes this new function in Section 3.3.1 as follows:

> The TFI is a single entity who has the responsibility and is empowered to represent the composite state of information regarding a technical issue of the scientific community.... The TFI process is centered on the precept of thorough and well-documented expert interaction as the principal mechanism for integration.

As SSHAC acknowledges, a major stimulus for its charge was the need to resolve the differences in hazard estimates between the Lawrence Livermore National Laboratory and the Electric Power Research Institute studies. SSHAC's investigation revealed that the process of elicitation and the procedures for integration allowed room for considerable misunderstanding and potential misinterpretation. Six areas in which improvements could lead to a better outcome are detailed in Section 3.3.2.2 of the SSHAC report:

1. Overly diffused responsibility
2. Insufficient face-to-face expert interaction
3. Inflexible aggregation schemes
4. Imprecise or overly narrow objectives
5. Outlier experts
6. Insufficient feedback

The TFI concept was designed to resolve these procedural issues. This approach is described in detail in Chapters 3 through 5 and Appendix J of the SSHAC report. **The panel concurs that, in cases in which decisions about a critical facility of major complexity depend on controversial and uncertain inputs, the TFI approach offers an effective mechanism for capturing the best of what is known about the particular issues.**

The Proposed TFI Process

The seven steps proposed by SSHAC for the TFI approach (Section 3.3.4) were first suggested by Keeney and von Winterfeldt (1991), based on their experience in eliciting expert judgment for probabilistic risk assessment of nuclear power plants. The steps are:

1. Identification and selection of technical issues
2. Identification and selection of experts
3. Discussion and refinement of technical issues
4. Training for elicitation
5. Group interaction and individual elicitation
6. Analysis, aggregation, and resolution of disagreements
7. Documentation and communication

A flow chart of the process as applied to ground motion elicitation by SSHAC is reproduced here as Figure 2.1. Appendix J of the SSHAC report spells out the background, evolution, and details of the TFI process as developed by SSHAC. Appendix J must be read carefully; readers may need to consult additional references in order to fully understand some of the issues discussed, such as the weighting of individual expert inputs.

The TFI process requires careful and time-consuming setup procedures to ensure that all participants are clear on the objectives of the study, their roles in the study, and the intended results. The TFI (an individual or, perhaps, a team of two or three people) must be highly competent in the relevant subject areas, adept at elicitation and group process, and thorough. Because a strong TFI will have a major influence on the outcome of the elicitation/aggregation process, **it is essential that, if more than one TFI is assigned to work on a particular analysis project, they all be equally well qualified.**

The panel concludes that for appropriate issues the TFI process holds significant promise for PSHA. This process was developed by SSHAC as part of its effort to overcome limitations of previous PSHA studies. The panel cautions, however, that this process is expensive, time consuming, and demanding of all participants. SSHAC's criteria for identifying the issues for which the full TFI process is justified (Table 2.1) must be understood by project sponsors and their analysts.

As discussed in the next chapter, each element of a seismic hazard analysis may involve high degrees of uncertainty. Many situations arise in which competent experts may legitimately disagree in their interpretation of extant data and theory. In view of the complexity of the issues and models involved in PSHA, SSHAC concluded that an improvement in the process of elicitation would help focus attention on the technical issues by reducing previously observed problems in "consensus," unintended agreement, and unintended disagreement.

At each step of the elicitation process, the TFI strives for complete understanding by each expert of all technical issues. The goal is that all experts are "on the same page." The results of two ground motion workshops conducted by SSHAC and documented in Appendixes A and B of its report indicate that investment in the TFI process bore substantial results.

The panel is aware that the TFI process, as implemented in these workshops, has rarely been used in the earth sciences. An example of the application of the process in a related subject field is provided by a probabilistic volcanic hazards analysis (Coppersmith et al., 1995).

TREATMENT OF EXPERT INPUT

Integration of Expert Opinion

SSHAC correctly points out that in theory it is always possible to formulate the expert integration problem as a Bayesian inference problem in which the opinions rendered by the experts are viewed as "noisy observations" of the quantities of interest (e.g., parameter values, distributions). Difficulties lie in the formulation of an "observation model" tailored to each expert combination task and sometimes in implementing the Bayesian analysis to produce *a posteriori* uncertainties. A discussion of combination problems and models is given in Appendix J of the SSHAC report. SSHAC repeatedly warns against blindly using any specific model and stresses that the models described in Appendix J are only examples for illustration. The panel agrees with these warnings and adds the following comments:

- In essence, Appendix J presents two very different types of models: (1) the so-called classical models, which emphasize the "noisy observation" interpretation of expert opinion, and (2) the TFI model, which regards each expert as being potentially correct, with a probability proportional to an assigned weight. Although this interpretation of the TFI model is not given in the SSHAC report, the fact that the community distribution is defined as a weighted sum of the expert distributions is equivalent to saying that each expert is correct with a probability equal to his/her assigned weight. At the end of Appendix J, the two approaches are compared numerically and shown to produce very different results. Without an in-depth discussion of when each type of model (or neither) is applicable, Appendix J may leave the reader confused. The classical models combine distribution functions with the meaning of uncertainty on the value of an unknown parameter. Hence, in this case the object of estimation is an unknown *scalar quantity* and the distributions express uncertainty on that quantity according to different experts. The TFI model, on the other hand, combines distribution functions that express the state of uncertainty of the scientific community according to different experts. In this second case the object of estimation is the *distribution function* itself. Therefore, while the inputs to, and results from, both

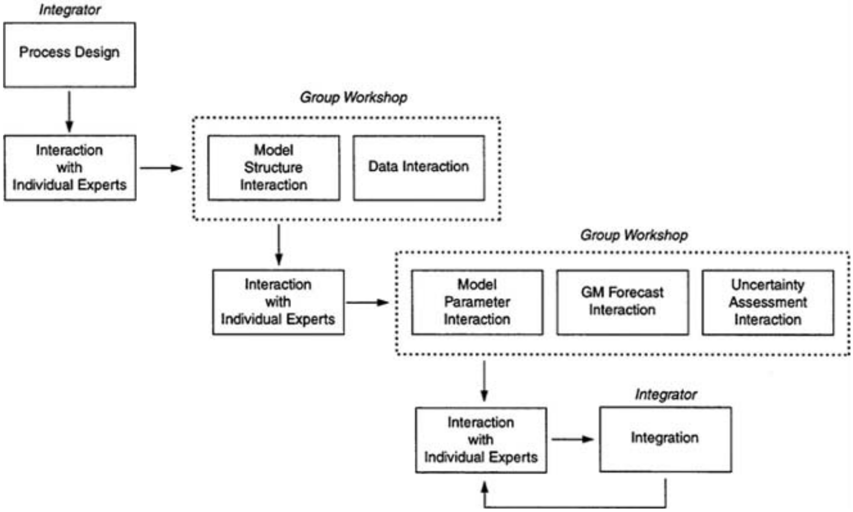

FIGURE 2.1 Roadmap of ground motion elicitation process (Figure 5-5 of the SSHAC report).

models are in the form of probability distributions, such distributions have different meanings in the two cases and should not be compared.

- The community distribution, which the TFI model estimates, is defined in Appendix J, Section 5, of the SSHAC report as “the mixture of the distributions of the individual experts if [the decision maker] believed that the experts . . . in this ‘perfect community' were effectively equally informed on the issue of interest and equally interdependent. . . .” **As the entire SSHAC procedure revolves around this distribution, the panel believes that its definition should have been given in the main report, with a detailed explanation and justification.**
- SSHAC gives expressions for the mean and variance of the community distribution after stages 1 and 2 of the TFI process. Given the approximate nature of the results for the variance and the fact that distributions, not just mean values and variances, are needed, a much simpler and basically as accurate combination rule would be to take the weighted average of the distributions provided by the experts. The statement in Appendix J that “determination of the predictive (i.e., *a posteriori*) distribution follows a straightforward but cumbersome Bayesian statistical analysis” indicates that SSHAC knows how to perform a fully nonparametric Bayesian estimation of the community distribution function. This panel could think of no straightforward procedure to do so (one would need to consider the expert distribution estimates as random processes given the true community distribution function, with serious practical and conceptual implications). Because determination of community distribution and its uncertainty is at the core of the SSHAC approach, the report should have been more explicit about such a procedure.
- SSHAC favors an equal weighting integration scheme, unless there are clear indications that different weights should be used, for example, to reduce the influence of outliers. Linear combination rules with equal (unequal if necessary) weights are applied to parameter estimates (classical models) as well as to the probability distributions that, according to the panel of experts, quantify uncertainty in the scientific community (TFI model). Conditions for “equal weights” are set forth in the report. The panel believes that there may be some confusion about linear combination with equal weights and symmetrical (but possibly nonlinear) treatment of the expert assessments. The conditions quoted in the SSHAC report apparently lead to symmetrical treatment, not necessarily to averaging. There is a brief reference to nonlinear

> combination rules in the section on nonequal weights in Appendix J, with little discussion. Analysts are advised to verify whether the conditions of linearity and normality of the observation model apply before using a linear combination rule. Contrary to what SSHAC states (e.g., Figure J-6), in some cases it would be better to combine the parameters of the distributions provided by the experts rather than the distributions themselves (combining the parameters results in a *nonlinear* combination of the distributions.) For example, if the experts agree on all distribution characteristics except for a location parameter, combining the estimated locations would be the right thing to do.

In view of these limitations and the objective difficulties in properly combining expert opinions, the panel recommends the following:

1. **Use the models in Appendix J of the SSHAC report for reference, not as prescriptive or even recommended combination procedures.**
2. **Do not accept the results of a mechanical combination rule unless they are consistent with judgment.**
3. **If a mechanical combination rule is used, a general way by which to derive that rule is to view experts as noisy observers of the quantity being estimated. This approach is always the correct one from a Bayesian viewpoint, irrespective of the problem at hand. What differs in different cases is the nature of the observation errors, which need not necessarily be normal, additive, or independent.**
4. **When combining expert opinions on distribution functions, the correct Bayesian approach requires the use of a random process formalism, unless the problem can be reduced to a discrete one through appropriate parameterization. In all but the simplest cases a formal analysis becomes prohibitive, and the panel recommends primary reliance on judgmental combination procedures.**

Weighting

One of the more problematic aspects of PSHA has always been the aggregation of input from different experts, especially when one or more expert opinions are outliers relative to the views of the rest of the participants. This problem has led to consideration of weighting of different experts' opinions based on quantitative or qualitative assessments of the degree of expertise (typically a highly subjective exercise). The extensive interactive education and elicitation process proposed by SSHAC is intended to bring all expert participants to parity. This process should make it more reasonable to use equal weighting of all the experts. Appendix B of the SSHAC report states that equal weights were used for the combination of expert opinions and concludes that the TFI “integration process is robust.”

The panel concurs that equal weighting of experts should be the clearly preferred target in a multiple-expert PSHA. To achieve this, proper choice of experts and group interactions should be emphasized, as outlined in Chapter 4 and Appendix H of the SSHAC report. In the case in which a different weighting scheme is applied, the burden of proof rests with the TFI; nevertheless, every effort should be made to obtain expert concurrence on the weights used or modification applied.

Dependency Among Experts

A related aggregation problem, dependency among experts, is, on the surface, exacerbated by the TFI process. The overall community is composed of a finite number of experts who rely on a finite number of models and methodologies. While one or more of the participating experts may not be thoroughly familiar with the entire range of such models and methodologies at the beginning of the exercise, such familiarity is an objective of the TFI process. As shown in the second SSHAC ground motion workshop, this interactive process narrowed the range of estimates as the experts increased their knowledge and understanding of issues and methods. One goal of a well-executed TFI process is that all participating experts are better able to make informed independent judgments.

Peer Review

SSHAC requires that peer review be an integral part of the PSHA process. The panel concurs. SSHAC defines two types of review: (1) participatory and (2) late stage. Participatory peer review involves “full and frequent access throughout the entire project" by the reviewers. The advantage of a participatory review is the opportunity to subject interim results and deliberations to independent feedback. This provides the PSHA team with an opportunity for adjustment and limits the possibility that a lengthy and costly effort might be found to have serious flaws in the end. SSHAC recognizes that a limitation of participatory peer review is that "peer reviewers might lose their objectivity as they interact with the project over time." The panel views a participatory peer review as equivalent to a backup group of experts who provide oversight of the work of the primary team. **Safeguards must be established to preserve the objectivity of the review process.** As explained in the introduction to this report, this panel was asked to provide participatory peer review to SSHAC, and the panel insisted on a process by which it would not become so deeply involved in the preparation of its report that its objectivity would be compromised. The panel believes that this is also a necessary precaution for peer review of any PSHA study.

The late-stage review is closer to the traditional academic review in that it occurs near the end of a project. SSHAC strongly recommends participatory peer review on the grounds that a late-stage review can be risky, especially with regard to the process aspects of a PSHA study. Table 3-2 in the SSHAC report summarizes its recommendations on how to structure the peer review process.

The panel concludes that participatory review, as part of a PSHA process, would serve to improve the quality of a study insofar as it is another step toward incorporating the views of the broad informed scientific community. Other considerations—for example, the requirements of regulatory bodies—might call for a late-stage review also.

Documentation

Chapter 7 of the SSHAC report puts much emphasis on the importance of fully documenting every PSHA study. The guidelines on documentation are intended to ensure that each step of the PSHA process is not only completely recorded but also that the records are stored in accessible formats that permit the technical community to review all operations and decisions. This documentation also greatly facilitates later reanalysis and update as new information becomes available, perhaps eliminating the necessity of redoing the entire PSHA.

The panel believes that the calculated seismic hazard derived from each individual expert's input needs to be presented. It is not clear whether this is included in SSHAC's recommendations. Regardless of how the aggregation is carried out, it is important to be able to compare results caused by each expert's input with those of the composite produced by aggregating the individual inputs. This comparison provides users with a good indicator of the diversity of input and its impact on the final calculations, as discussed in Chapter 3.

SSHAC proposes that this documentation follow a two-tiered approach that is to be applied to every element of a PSHA. Tier 1 documentation is defined as all documentation that must be published as part of the main report or its appendixes, so that it is widely accessible. Simply stated, tier 2 is everything else that constitutes background material for the analysis. SSHAC's prescription for what materials should go into the two tiers is spelled out for each of the elements of a PSHA (i.e., seismic source characterization, ground motion attenuation, and the methods used to produce the PSHA results).

The SSHAC report specifically states that the computer software used should be identified and archived. This would include any relevant programs and code that would be necessary for an independent analyst to replicate the study. Should problems be identified later with either the computer code or the input data, reanalysis is greatly facilitated. **The panel recommends that specialized computer programs needed to implement the SSHAC procedures be readily accessible to any group that wants to engage in seismic hazard evaluation as part of a research program or business venture.** The availability of these programs becomes especially important if the procedures recommended by SSHAC are so successful that they become the standard adopted by governmental regulatory bodies and the major engineering concerns of the nation.

To facilitate the accurate and timely documentation of PSHA projects, **the panel recommends that an individual or small team be designated as the Project Archivist and that a documentation plan be in place at the beginning of each project.** The thoroughness and complexity of the SSHAC approach, especially when the TFI is used, require that all participants have ready access at any time to materials generated previously. This implies a documentation process that keeps current with the rest of the project.

The panel concludes that the discussion of the documentation process in Chapter 7 of the SSHAC report provides thorough and useful guidance for numerous other applications in addition to seismic hazard assessment. **Documentation is not one of the more glamorous aspects of the scientific enterprise, but it is essential to the full realization of the benefits of the large investment in data acquisition, analysis, and interpretation that are characteristic of large projects.**

3

Treatment of Uncertainty

A fundamental aspect of the Senior Seismic Hazard Analysis Committee's (SSHAC) methodology is the distinct and separate treatment of aleatory and epistemic uncertainty. Throughout its report, SSHAC emphasizes the need to distinguish between these two types of uncertainty, the quantifications of their contributing sources, and the propagation and full display of the epistemic component to users (see, e.g., Sections 1.8 and 1.9). SSHAC deals with techniques to assess, elicit, combine, propagate, document, and display epistemic uncertainty, and it is clear that much if not most of the effort in any probabilistic seismic hazard analysis (PSHA) conducted according to SSHAC's recommendations would have to be expended in activities related to the handling of uncertainty.

The two fundamental types of uncertainty are defined by SSHAC as:

- Epistemic: the uncertainty attributable to incomplete knowledge about a phenomenon that affects our ability to model it.
- Aleatory: the uncertainty inherent in a nondeterministic (stochastic, random) phenomenon.

Epistemic uncertainty may be reduced with time as more data are collected and more research is completed. Aleatory uncertainty, on the other hand, cannot be reduced by further study, as it expresses the inherent variability of a phenomenon.

Making a rigorous separation between aleatory and epistemic uncertainty, as advocated by SSHAC, requires a level of effort and expertise much greater than that for most PSHA efforts. Therefore, the panel thinks it is appropriate to elaborate as to when and why such classification may be needed and indeed whether it is appropriate (these issues are not addressed directly by SSHAC). In this regard, it is useful to consider separately two questions:

1. Is the aleatory/epistemic classification unique and clear?
2. Why is a separate treatment of epistemic and aleatory uncertainty needed and to what degree should it be pursued in a PSHA analysis?

Embedded in the second question are issues of utilization of results in which epistemic uncertainty and aleatory uncertainty are separated (i.e., of results stated in a “probability of frequency” format), either in the process of conducting the PSHA study or in the process of decision making by the ultimate user. In this chapter the panel briefly reviews SSHAC's position on these issues and makes some recommendations.

IS THE ALEATORY/EPISTEMIC DISTINCTION UNIQUE AND CLEAR?

SSHAC correctly points out that the classification of uncertainty as epistemic or aleatory depends on the model used to represent seismicity and ground motion. For example, epistemic uncertainty would be much greater if, in the assessment of seismic hazard at an eastern U.S. site, instead of representing random seismicity through homogeneous Poisson sources one used a model with an uncertain number of faults, each with an uncertain location, orientation, extent, state of stress, distribution of asperities, and so forth. As little is known about such faults, the total uncertainty about future seismicity and the calculated mean hazard curves would be about the same, irrespective of which model is used. However, the amount of epistemic uncertainty would be markedly different; it would be much greater for the more detailed, fault-based model. Consequently, the fractile hazard curves that represent epistemic uncertainty would also differ greatly.

A reasonable interpretation of the probabilistic models used in seismic hazard analysis is that they represent not intrinsic randomness but uncertainty on the part of the analyst about the actual states and laws of nature—for example, about the number of earthquakes of magnitude 6 to 7 that will occur in the next 50 years in a given crust volume. According to this interpretation, all or most of the uncertainty in PSHA is due to ignorance. In certain cases, uncertainty due to ignorance may be expressed numerically by long-term relative frequencies. For example, with a very long record of seismicity, one could extract the long-term relative frequency with which earthquakes of magnitude 6 to 7 occur in a generic 50-year period. In the absence of other relevant information, it is reasonable to use this long-term relative frequency as a measure of epistemic uncertainty about the occurrence of the event in the next 50 years. Note that as interest in PSHA is typically in the occurrence of rare events in the near future and because the occurrence of such events depends to a large extent on the current physical conditions of the earth's crust near the site, ignorance or epistemic interpretation of the occurrence probability is more appropriate than the long-term relative frequency or aleatory interpretation. In certain parts of its report, SSHAC concedes that in reality there may be just one type of uncertainty. For example, Section 2.2.3 reads, in part:

> . . . Even though we have discussed probabilities appearing in the model of the world and the epistemic model, and we have given them different names, leading philosophers of science and uncertainty (e.g. de Finetti 1974; de Groot 1988) believe that, conceptually, there is only one kind of uncertainty; namely, that which stems from lack of knowledge.

Other statements support this position. For example, Section 2.2.6 states that “. . . the different terminology [aleatory versus epistemic] is not intended to imply that these uncertainties are of fundamentally different nature.” Similarly, Section 1.8 points out that in the context of seismic hazard analysis, “the division between the two different types of uncertainty, epistemic and aleatory, is somewhat arbitrary.” **The panel concludes that, unless one accepts that all uncertainty is fundamentally epistemic, the classification of PSHA uncertainty as aleatory or epistemic is ambiguous.**

Reference to a particular class of seismicity models (e.g., the models described in Sections 2.1 and Chapter 4 of the SSHAC report) produces some stability in the epistemic/aleatory distinction. However, if such distinction is to have any impact on the decisions, the basis for choosing any particular model type should be made clear, as alternative and equally valid choices would lead to different decisions. In view of this undesirable dependence of epistemic uncertainty on the models selected for PSHA, one may question whether the epistemic/aleatory uncertainty decomposition is actually called for in a PSHA study and the extent to which it is needed for decision making by the users. These questions are addressed in the following section.

IS THE EPISTEMIC/ALEATORY SEPARATION NEEDED?

SSHAC does not provide a clear rationale for the need to separate aleatory uncertainty from epistemic uncertainty, although the report refers to several uses of this separation. Sections 2.2.5 and 2.2.6 of the report cite facilitated communication of results, discipline on the part of the analyst, and completeness of results. A “theoretical foundation” for the aleatory/epistemic distinction is offered in Section 2.2.6 by quoting a result by de Finetti in probability theory that shows how to combine epistemic and aleatory uncertainty to quantify total uncertainty for a particular (the binomial) model. However, the same result indicates neither how to separate the two uncertainties in practice (this is acknowledged by SSHAC) nor how to make decisions considering epistemic uncertainty. Therefore, the panel finds reference to de Finetti's result not relevant to whether or why the aleatory/epistemic distinction is necessary.

Reference to the decision-making implications of the epistemic/aleatory character of the uncertainty is made at the end of SSHAC's Appendix F, where it is stated that: “because epistemic and aleatory uncertainties are treated differently in making design and retrofit decisions, and because the median hazard is sometimes the preferred central measure of hazard due to its stability, it is also important to allocate uncertainties in the proper category.” While it is true that the median curve is often preferred to the mean curve, a clear rationale for this practice or, more generally, a procedure for dealing with epistemic uncertainty in decision making is not presented in the SSHAC report. Finally, in Section 7.6 reference is made to the need for multiple hazard curves in the context of probabilistic risk assessment studies.

It is not the purpose of this discussion to analyze in detail each of the reasons for quantifying epistemic uncertainty. However, the panel observes that different uncertainty representations are appropriate for different applications. To add focus to this discussion, we consider and contrast three main uses of quantified epistemic uncertainty in PSHA:

1. In the *elicitation and experts/model combination process,* quantitative estimates of epistemic uncertainty are used to characterize the credibility of alternative hypotheses and models, to assess the statistical variability of parameters, and to communicate this information among the experts and between the experts and the TFI.
2. In the course of a properly conducted analysis, the effect of epistemic uncertainty on the final hazard is used to *assess the relative importance of different models* (e.g., of the seismicity model versus the ground motion model) *and parameters* and to guide the analyst in seeking further information (data, expert opinion, etc.) to reduce uncertainty in the most cost-effective way.
3. A project's sponsor typically accounts for uncertainty in a hazard when *making decisions* (e.g., about the design of a new facility or the retrofitting of an existing one).

For ease of reference, we label these three phases of uncertainty consideration as the elicitation/combination phase, the PSHA planning phase, and the final utilization phase. Different needs for uncertainty representation characterize these phases.

In the *elicitation/combination phase,* experts need to be aware of all pertinent sources of uncertainty, including parameter and model uncertainties and their correlations, and the limitations and errors of the available data, so that they can make an informed assessment of the validity of alternative hypotheses, the accuracy of alternative models, and the value of data and can convey such uncertainties to the TI/TFI. **The panel finds the type of epistemic uncertainty analysis recommended by SSHAC to be most useful at this stage of a PSHA study.**

In the *PSHA planning phase* (which refers to resource allocation for the purpose of maximizing the reduction of uncertainty on the final hazard results), there is no need for a detailed analysis of uncertainty. In fact, such analysis is usually not available when the PSHA effort is structured. **For this purpose it may be sufficient to conduct limited sensitivity analyses, using bounding hypotheses, and to consider the level of effort that would be required to substantially reduce each component of uncertainty.**

The final *utilization phase* is critically important and arguably the one phase that should drive the level of uncertainty analysis and mode of uncertainty representation in a properly conducted PSHA. SSHAC's position is that the final results of a study should represent the epistemic uncertainty of the informed scientific community. This is roughly defined by SSHAC as the average of the uncertainties of the experts that make up the community (possibly weighted according to their degree of expertise, their outlier status, etc.).

A fundamental problem with this way of presenting the final results is that, as previously noted, the epistemic uncertainty in the hazard depends on which among many legitimate models one uses—for example, a deterministic or stochastic model of earthquake occurrence. What changes with the model is not the mean hazard but the amount of epistemic uncertainty and, therefore, all the fractile hazard curves—including the median. Therefore, any decision that is based on the fractile curves rather than the mean curve depends on the essentially arbitrary choice of how much epistemic uncertainty is included in the seismicity and ground motion models. This well-known fact has often been taken to mean that the only admissible decision rules are those based on the mean hazard and that other decision rules are wrong and should be excluded. In fact, this is not quite correct. As the study by Veneziano (1995) quoted in the SSHAC report shows:

> 1. If the mean hazard can be assumed to remain constant over the lifetime of the project (e.g., because only a small amount of relevant new information is expected to become available in the near future), decisions should be based exclusively on the present mean hazard.
> 2. On the other hand, if the mean hazard cannot be assumed to remain constant over the lifetime of the project, decisions should depend on possible future fluctuations of the mean hazard (Veneziano, 1995, p. 121).

These results show why the common practice of using mean probabilities is appropriate in certain cases but also explain why in other cases one should act conservatively. Notice that **the distinction does not depend on the total amount of current epistemic uncertainty but on the amount of total uncertainty that might be explained in the future and thus might cause the mean hazard to fluctuate.**

This is consistent with intuition. As a classic example of the irrelevance to decision making of the aleatory/epistemic classification, the betting attitude of a rational individual on the outcome of a coin flip should not change from before flipping, when all the uncertainty is aleatory, to after flipping (but before the outcome is revealed), when the same total amount of uncertainty is epistemic. On the other hand, the importance of temporal fluctuations of a mean hazard may be illustrated by considering the retrofitting problem, which occurs when, at some time after completion of a project, the estimated mean hazard changes and exceeds a regulatory limit. The reason why future volatility of the mean hazard should in this case affect present decisions is that the utility of each decision depends in an asymmetric way on future positive and negative changes in the mean hazard: large penalties are associated with retrofitting if the mean hazard increases, whereas only modest gains may result from future reductions in the mean hazard. The decision maker should consider the potential future volatility of the mean hazard and include it in his/her deliberations.

In the future, fundamental advances in PSHA may come from adopting this time-dependent view of earthquake safety decisions. However, explicit quantification of future volatility of a mean hazard would require a level of analysis even more sophisticated than that proposed by SSHAC, and the panel does not advocate such an extension at the present time, even for critical facilities.

Short of explicitly quantifying the future variability of the mean hazard, what could be done to provide the decision maker with a useful representation of epistemic uncertainty? One possibility, but certainly not the only one, is to calculate the mean hazard according to the uncertainty of each participating expert, when that expert acts as an evaluator (not integrator) of alternative models, data sets, etc. **To the degree that the beliefs held now by different members of the scientific community reflect possible future fluctuations in the overall community mean hazard, this should be useful input to the decision maker.** For example, this information would allow the decision maker to see how the decision he/she must make would vary if different experts in the informed scientific community had to make that same decision. Notice that the hazard curves derived from each expert do not suffer from the limitations of the fractile curves observed earlier; each of them is a mean hazard curve and therefore is insensitive to the choice of model type used by the expert.

Some observations should be made on presenting the final hazard results through the community mean hazard and the interexpert variability in the mean hazard, as just described:

1. One might argue that full epistemic uncertainty quantification is needed anyway, to calculate the mean hazard of the community and the mean hazard of the individual experts. However, this is true only in theory, as it is clear that different amounts of information are needed to estimate with confidence the mean value of a random variable, as opposed to its complete distribution. For example, the use of best estimates for recurrence and ground motion models often leads to hazard values that are close to the mean hazards obtained by considering a large number of alternative models. Moreover, there is no need when calculating the mean hazard to label accurately each component of uncertainty as epistemic or aleatory, provided that the total uncertainty is accounted for. Therefore, the elaborate machinery needed to carefully separate uncertainties of different types is no longer needed.
2. Much emphasis is given in the SSHAC report to intensive interaction among experts, discussion of alternative models, and exclusion or downweighting of outliers. These are all appropriate and remain valid under the format proposed here. **In essence, what changes is that the TFI quantifies not the total uncertainty of the scientific community, as done in the SSHAC approach, but the variability of the mean hazard according to the experts that make up that community.** In so doing, weights can be applied and outliers can be removed for the same reasons and in the same way as discussed by SSHAC.
3. The multiple interpretations, models, and model parameters at the basis of the elicitation process are not “lost.” They remain part of the documentation of the PSHA study and should be made available to interested users. The panel anticipates that users will primarily be technical experts—for example, in the context of a regulatory review or an update of a PSHA study. However, that information should, for the most part, be irrelevant to the decision maker.

As observed previously, the correct way to represent epistemic uncertainty for decision making would be through the uncertain fluctuations of the mean hazard in future assessments. The expert-to-expert variability of the mean hazard at the time of the analysis is only a surrogate for this variability and is not entirely satisfactory because using it this way implies that, during the time interval of interest, new evidence and knowledge may end up “proving right” one member of the present group of experts. While this may not be a valid assumption, documentation of the expert-to-expert variability in the mean hazard may be preferable to the full display of epistemic uncertainty proposed by SSHAC.

4

Seismic Source Characterization

Chapter 4 of the Senior Seismic Hazard Analysis Committee's (SSHAC) report, entitled “Methodology for Characterizing Seismic Sources,” describes the key elements of a seismic source characterization (SSC): the seismic source requirements for a probabilistic seismic hazard analysis (PSHA), the uncertainties in seismic source characterization, and guidance on expert elicitation for seismic source description. The chapter presents a good description of the state of practice for SSC in a PSHA, as shaped chiefly by guidance on methodology from the seismic hazard programs of the Lawrence Livermore National Laboratory and the Electric Power Research Institute (EPRI), as well as from other PSHA exercises modeled on those programs, for many other critical facilities. In the panel's judgment, **practitioners of PSHA should be aware of and free to use other valid approaches to SSC.**

SCIENTIFIC VALIDITY AND CLARITY OF PRESENTATION

A primary concern of the panel is the overall scientific validity of the procedures recommended by SSHAC. The basic methodology for SSC described in the SSHAC report has been validated by extensive peer review of prior projects in which such a methodology was used. The SSHAC report correctly states that a seismic source is a construct developed for seismic hazard analysis as a means of approximating the locations of earthquake occurrences. Insofar as SSC involves a simplified representation of real-world complexity, the validity of the simplifications is always an issue. Such validity is generally tested as part of sensitivity analyses, which are an essential part of a PSHA, as correctly advocated in SSHAC's report. With regard to modeling real-world complexity, the classification of seismic source types (Section 4.2) is nonunique, and the categories described in the report are admitted to be arbitrary. Nevertheless, they provide a useful framework for discussion and guidance on methodology.

The practitioner experienced in PSHA will have no trouble understanding SSHAC's Chapter 4. However, the nonpractioner scientist may be confused by the subtleties between differing concepts of a “seismic source” presented in chapters 4 and 5. Chapter 4 describes a seismic source as a geologic structure or as a domain within which the spatial and temporal occurrences of earthquakes are approximately uniformly distributed.Chapter 5, on ground motion, describes seismic source basically as a dynamic excitation in the earth that causes ground motion at the surface.

Readers of the SSHAC report should be aware that two different terms, upper-bound and maximum magnitude, and two symbols, m_u and M_{max}, are used Section 2.1 and in Chapter 4 to denote the largest-magnitude earthquake that a particular seismic source is capable of producing. This magnitude is the upper bound of the frequency of occurrence magnitude curve used in the analysis. A value for this parameter must be specified in order to carry out the integration over all relevant magnitudes when calculating seismic hazard. The problems encountered and conventional procedures used in the selection of M_{max} (m_u) and the specification of the substantial epistemic uncertainty often associated with it are discussed in Sections 4.2.2 and 4.3.2 of the SSHAC report.

If one accepts the basic formalism of uncertainty analysis presented in Section 2.2 of the SSHAC report, the approaches for characterizing uncertainties in SSC (Section 4.3) will seem logically consistent and well established in practice. Similarly, the guidance described in Section 4.4 for the expert elicitation process follows one's acceptance of the decision science methodology laid out in Chapter 3.

A notable gap in Chapter 4 of the SSHAC report is the absence of discussion on and guidance for earthquake catalogs. In Section 4.4 the technical facilitator/integrator (TFI) or the technical integrator (TI) is given responsibility for providing a comprehensive and uniform data base to the experts for use in the PSHA. The only guidance given, under the subheading “Area Sources” in Section 4.2.3, is the recommendation that “seismicity catalogs should be reviewed for uniformity in designation of magnitudes and for completeness as a function of magnitude, location, and time. The association of older historical events with particular seismic sources should be assessed bearing in mind the location uncertainties."

Earthquake catalogs can play a major, even dominating, role in determining the outcome of a PSHA, particularly in the central and eastern United States, where information on active faults and other geologic structures is generally lacking. There are many problems hidden in earthquake catalogs that need be sought out and identified. There may be improper or mistaken entries, particularly for historic earthquakes. In many cases, locations and sizes were assigned to historic earthquakes based on inadequate or incomplete information. Unfortunately, modern earthquake catalogs often do not indicate which events have been critically reexamined and which have been carried forward without question from original catalog compilations.

Uniformity of the data with time is also variable even in times of instrumental monitoring. Changes in network configurations and sensitivity and changes in the procedures for computing event magnitudes reported in earthquake catalogs (often not documented in an easily available form) should be sought out and carefully considered in a PSHA. Tests are available for identifying time-varying systematic shifts in reported magnitudes. Declustering or decomposing earthquake catalogs into main and secondary events (foreshocks, aftershocks, swarm events) is a nontrivial procedure that also requires careful attention.

Recognizing that earthquake recurrence relationships based on seismicity depend critically on factors such as those described above, EPRI undertook major efforts to address these and other earthquake data base issues, which are still of great importance in PSHA—both in principle and in continuing practice. **Those who utilize the SSHAC procedures should be aware of these requirements for preparation of their earthquake catalog for PSHA. To the panel's knowledge, a comprehensive study of the effects of systematic changes in earthquake catalogs on the results of a PSHA has not been done.**

Most of Chapter 4 of the SSHAC report is well organized and well written, and the presentation should be easy for general readers to follow. The text refers to Appendixes H and I, each of which provides some ancillary pertinent material. Appendix H describes the results of a workshop on expert elicitation of seismic source (zone) information, while Appendix I describes effects of a nonuniform spatial distribution of seismicity in a seismic source (zone). Both of these appendixes are informative.

The table in Section 4.2.1 is important for guidance, but it is confusing. The lines beginning with “Faults” and “No faults” should be understood to be “if” statements, recognizing “fault” to mean a “Type 1 seismic source” (i.e., “If no Type 1 fault source within 50 km of a site, then . . .”).

Because the SSHAC report is intended for general PSHA guidance, the following question arises: Is the EQPARAM code (which is introduced as an important element of the methodology in Section 4.3.5) readily available or is it proprietary to EPRI? If the latter, it should have been described as such. This question illustrates the concerns of the panel about software availability expressed in the previous discussion of documentation.

CONTRIBUTIONS TO THE DEVELOPMENT OF PSHA

Because SSC is such a major component of a PSHA, the comprehensive methodology for expert elicitation presented in Section 4.4 of the SSHAC report is an important contribution. On first reading, the material in Chapter 4 may appear to be just a restatement of Chapter 3. However, SSHAC is correct in noting in Section 4.4 that the elicitation procedures and methods for SSC differ from those for ground motion characterization. Further, “lessons learned” from past SSC exercises are incorporated into major PSHA projects (Appendix H).

Another important contribution of Chapter 4 and its accompanying appendixes is the practical guidance provided for carrying out sensitivity analyses to determine “what drives the seismic hazard” and “what contributes significantly to uncertainties in hazard.” Basic discussion relevant to SSC is presented in Section 4.3.6, but important details are given in Appendix G and Section 7.8.

A third major contribution of Chapter 4 is the exposition in Section 4.3.5 (bolstered by Appendix I) of the effects of spatial variations in seismicity within a seismic source vis-à-vis the assumption of homogeneous seismicity. The analysis techniques date from the EPRI program (EPRI, 1989, as cited in the SSHAC report), but the detailed discussion and examples presented there forcefully demonstrate how the usual assumption of homogeneous seismicity for seismic sources can, under certain predictable cases, significantly affect both the mean seismic hazard and its statistical uncertainty.

THE OUTLOOK FOR EVOLUTION OF SSC

While affirming the scientific validity and practical effectiveness of the SSC methodology set forth in the SSHAC report, the panel recognizes that the scientific community will naturally strain against the confines of SSHAC's prescriptions for SSC. The panel applauds SSHAC's perspective that “[its] formulation should not be viewed as an attempt to ‘standardize' PSHA in the sense of freezing the science and technology that underlies a competent PSHA, thereby stifling innovation” (Section 1.2 of the SSHAC report). A few brief examples suffice to illustrate current trends in the scientific community that may influence the evolution of SSC. Diverse trends lead to advocacy for both greater simplification and greater complexity.

Frankel (1995) proposes a method for PSHA that uses spatially smoothed representations of historic seismicity instead of seismic source zones to directly calculate probabilistic seismic hazard. Insofar as he demonstrates the capability to produce values of mean seismic hazard similar to those from the more complicated EPRI methodology, his simple methodology offers understandable attraction. The applicability obviously pertains to cases where seismicity “drives the hazard”—either for specific regions or for definable exposure periods.

In terms of modeling earthquake occurrence with greater complexity, one example is the multidisciplinary approach (e.g., Ward, 1994), in which data from space geodesy and synthetic seismicity are added to the traditional information from geology, paleoseismology, and observational seismology. Main (1995) examines the implications if earthquake populations are really an example of a self-organized critical phenomenon. If this is correct, the *a priori* assumption of the Gutenberg-Richter frequency-magnitude distribution is no longer valid in some cases, and Main provides evidence for questioning the use of only the Poisson distribution in seismic hazard analyses, based on the accumulating evidence of local or long-range interactions of earthquakes. It should be pointed out that PSHA is not limited to the use of the Gutenberg-Richter relationship. Alternate estimates of the frequency-magnitude distribution are, and have been, used in probabilistic analyses.

Main (1995) also discusses an independent approach to the vexing problem of estimating the maximum-magnitude earthquake that is “credible” for a seismic source zone, based on his suggested distribution of moment release and the long-term slip rate on the causative fault system. Geophysicists are becoming increasingly aware of the nonstationarity of earthquake occurrence, particularly in light of observations of fault interactions leading to "triggered" or "encouraged" earthquakes. As earth scientists improve their ability to assess time-varying earthquake potential on active faults, SSC will evolve correspondingly. Indeed, "time-variable seismic hazard" is already a topic of special sessions at geophysical society meetings.

5

The Estimation of Earthquake-Generated Ground Motion

Chapter 5 of the Senior Seismic Hazard Analysis Committee's (SSHAC) report, entitled “Methodology for Estimating Ground Motions on Rock,” addresses the basic building block of a well-executed probabilistic seismic hazard analysis (PSHA) that has the surest observational and theoretical foundation. The past two decades have brought significant theoretical advances in ground motion models, as well as significant new data sets with which to test the new models. Fundamental to the stability of state-of-the-art high-frequency ($f = 1$ Hz) ground motion estimates is the essential constancy of earthquake stress drops. This allows the substantial experience developed from California and elsewhere to be transferred to the eastern United States (EUS) with little modification.

There are, to be sure, real variations in earthquake stress drops, and recent data for the EUS point to some anomalous magnitude-dependent high-frequency excitation (Atkinson, 1993). The EUS data set on the excitation and propagation of earthquake ground motion for the purposes of PSHA is still very sparse. Model predictions of EUS earthquake ground motion, whether empirical or theoretical, can vary significantly across the magnitude, distance, and frequency range of interest.

SCIENTIFIC VALIDITY AND CLARITY OF PRESENTATION

SSHAC's Chapter 5, together with the supporting Appendixes A and B (Ground Motion Workshops I and II), is an impressive synthesis of current knowledge about estimating high-frequency ground motions and their uncertainties in the EUS. The reader experienced in SHA will note that site-response issues, including nonlinear effects, are not addressed, on the grounds that they can only be incorporated on a site-specific basis.

Chapter 5 is itself a well-written primer on the essentials of ground motion estimation, valid for any region in which earthquakes occur. It begins with basic ground motion measures; provides the fundamentals of magnitude, distance, and site response; and describes the essentials of empirical and theoretical predictions of earthquake ground motion. It explicitly warns against the use of fixed spectral shapes anchored by peak ground acceleration (PGA) alone, and then progresses to a discussion of uncertainty in ground motion predictions. A fourfold decomposition of uncertainty for the Hanks and McGuire (1981) pointsource, stochastic model, the simplest physical model used in these predictive exercises, is demonstrated in this discussion. Readers should study this decomposition carefully (Table 5-1, Section 5.5.1). It is difficult, and, if this example is not well understood, similar attempts at uncertainty decomposition for more sophisticated and parametrically complicated models will be frustrating.

Section 5.7, “Specific Expert-Elicitation Guidance for Obtaining Ground Motion Values,” is based on the results of Workshops I and II, reported in detail in Appendixes A and B. Figure 5-5, reproduced as Figure 2.1 in this report, is intended to guide readers through the process. Regrettably, it is not well keyed to the description in the text.

CONTRIBUTIONS TO THE DEVELOPMENT OF PSHA: SUMMARY OF THE GROUND MOTION WORKSHOP RESULTS

The comprehensive treatment of ground motion estimation in Appendixes A and B is an important contribution to the SSHAC effort. Workshop I provided for the presentation of four basic ground motion estimation models: (1) intensity-based models presented by M. D. Trifunac, (2) empirical models presented by K. W. Campbell, (3) stochastic or random-vibration models presented by G. M. Atkinson, and (4) the empirical source-function method presented by C. Saikia. These proponents of the models were asked to evaluate the models in the company of 10 additional experts, the “invited participants” listed in Table A-1 of the SSHAC report. The principal result of Workshop I was rejection of intensity-based models for estimating ground motion in the EUS (SSHAC Table A-2). Additional information was collected on the applicability or validity of all models as a function of frequency, magnitude, and distance (SSHAC Tables A-3 and A-4). These polls of the assembled experts also show a distinct preference for the stochastic models.

Workshop II proceeded to actual ground motion numbers and their uncertainties on the basis of the "selected models" resulting from Workshop I. The threefold elicitation exercise that constituted Workshop II, described below, provided for pre-, co-, and postworkshop estimates. Prior to the workshop, the four proponents were asked to provide estimates of peak acceleration and spectral accelerations based on the ground motion models they actually use, along with the corresponding estimates of epistemic and aleatory uncertainties. The distances, frequencies, and magnitudes for which estimates were requested are listed in an unnumbered table in "Instructions for Proponents, " Appendix B. In keeping with the Workshop I preference for stochastic models, two of the four Workshop II proponents supported stochastic models (Atkinson and Silva), although there are significant differences between their models.

In advance of Workshop II these ground motion estimates were sent to three additional experts. These experts were asked to provide their own estimates of ground motion and uncertainties for the same distances, frequencies, and magnitudes, on the basis of what the proponents had provided, as well as any other information they considered relevant. Significantly, the four proponents were also asked to perform as experts; as such, their ground motion estimates were generally not the same as those they provided as proponents. These pre-Workshop II ground motion estimates and uncertainties are labeled as Expert 1 results, examples of which are shown in SSHAC Figure B-3, reproduced here as Figure 5.1a.

The second stage of the elicitation process occurred at the workshop, attended by all proponents and experts, the integration team, and several observers (SSHAC Table B-1). The principle of "active listening" was put to work, the idea being that all proponents and experts were to understand what every other proponent and expert was doing, whether or not he/she agreed with it. The panel concludes that this worked very well, revealing significantly different interpretations of key terms and procedures. It is noteworthy that Workshop II deliberations also revealed considerable misunderstandings about the differences between epistemic and aleatory uncertainties.

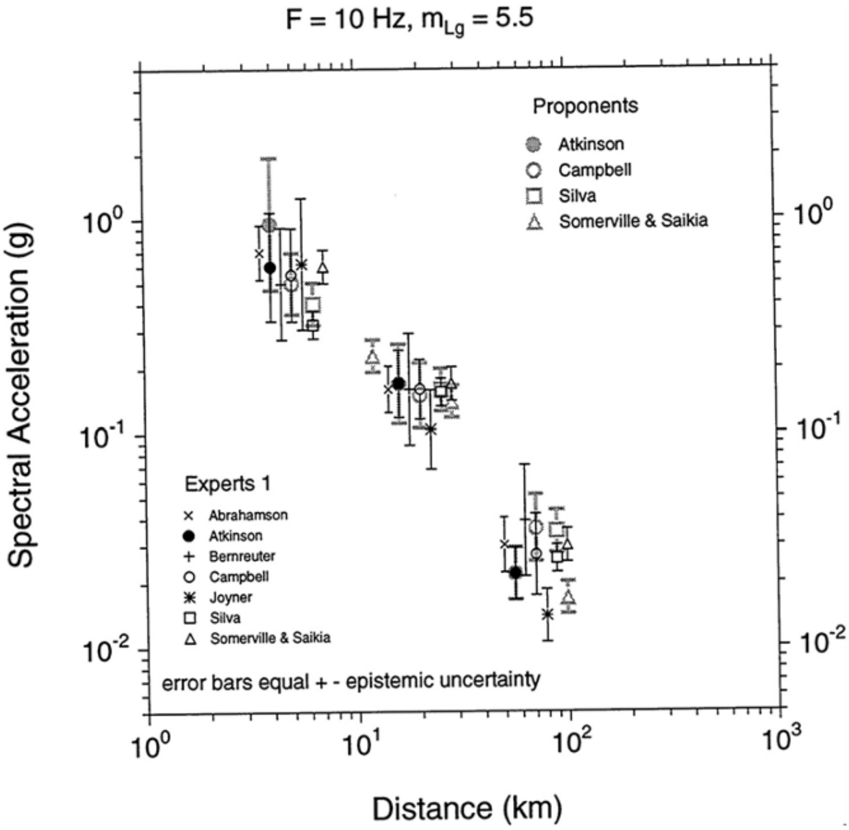

FIGURE 5.1a Comparison of proponents' estimates (gray) to Experts 1 estimates (black) of 10-Hz spectral acceleration for $m_{bLg} = 5.5$. The error bars represent $\pm \sigma_{epistemic}$ range.

Next, experts (at this stage all proponents were now experts) were asked to reconsider overnight their estimates of ground motion and uncertainties. This led to the Expert 2 results, which are compared to the Expert 1 results. An example (SSHAC Figure B-7) is reproduced here as Figure 5.1b. The differences are modest to zero at $f = 10$ Hz and somewhat greater at $f = 1$ Hz.

Two activities followed the workshop. First, all experts were invited to change their estimates one more time. Only a few did, and no one offered significant changes. An example of the integrated Expert 3 (postworkshop) results is shown here in Figure 5.1c (SSHAC Figure B-21). The second postworkshop activity was the manipulation of the Expert 3 results by the Integration Team. The results of the seven experts were weighted equally (SSHAC Table B-8, shown here as Table 5.1), and the results of the four proponents were weighted unequally (SSHAC Table B-9). The former are the preferred results, but the differences in median values and epistemic and aleatory uncertainties are slight.

IMPLICATIONS FOR FUTURE GROUND MOTION ESTIMATION

The many successes and few limitations of the Workshop II elicitation/integration process are summarized in Section B.5, "Concluding Observations and Discussion," of the SSHAC report. The panel is impressed with the success of this process in two principal ways, one of which SSHAC recognized and the other it did not.

SSHAC recognized explicitly that "the Proponents and Experts exhibited a striking amount of agreement. . . ." **Once freed from the thicket of unintentional disagreements, mutual misunderstandings, and individual egos, the group of specialists who participated found that what it knows about ground motion estimation is impressively consistent. The panel doubts that this degree of consistency and agreement could have been achieved without this highly interactive elicitation/integration process.**

There may be some who will believe that this agreement is illusory, that in some unspecified way it was cajoled or coerced. The panel finds no evidence of this. Doubters should note the workshop finding that "the estimated values of aleatory uncertainty for 10 Hz and

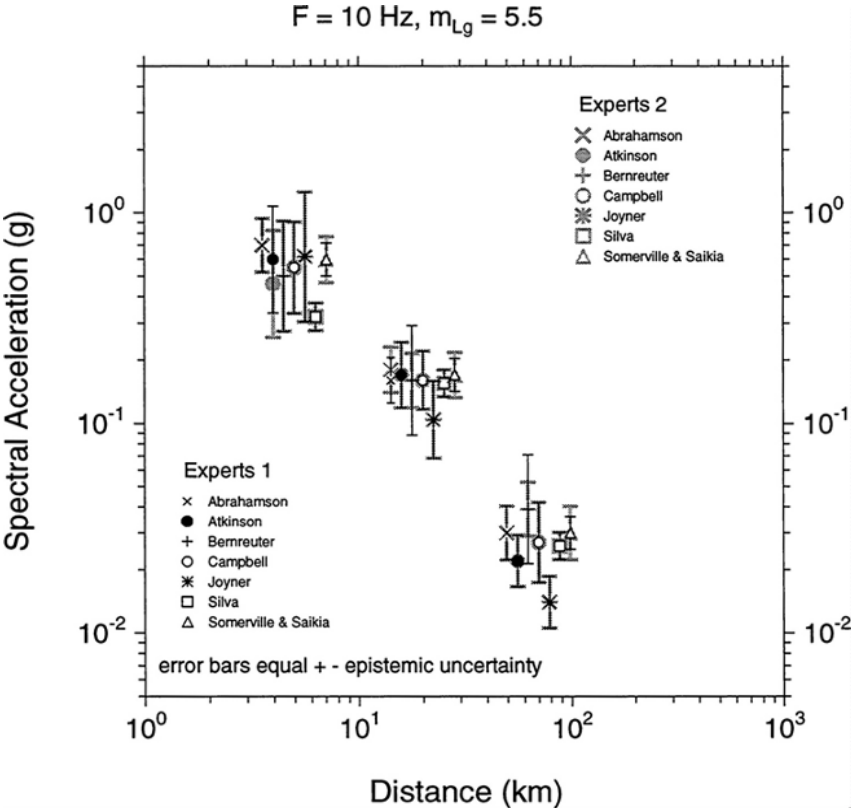

FIGURE 5.1b Comparison of Experts 2 results (gray) to Experts 1 results (black) for 10-Hz spectral acceleration at $m_{bLg} = 5.5$ as a function of distance.

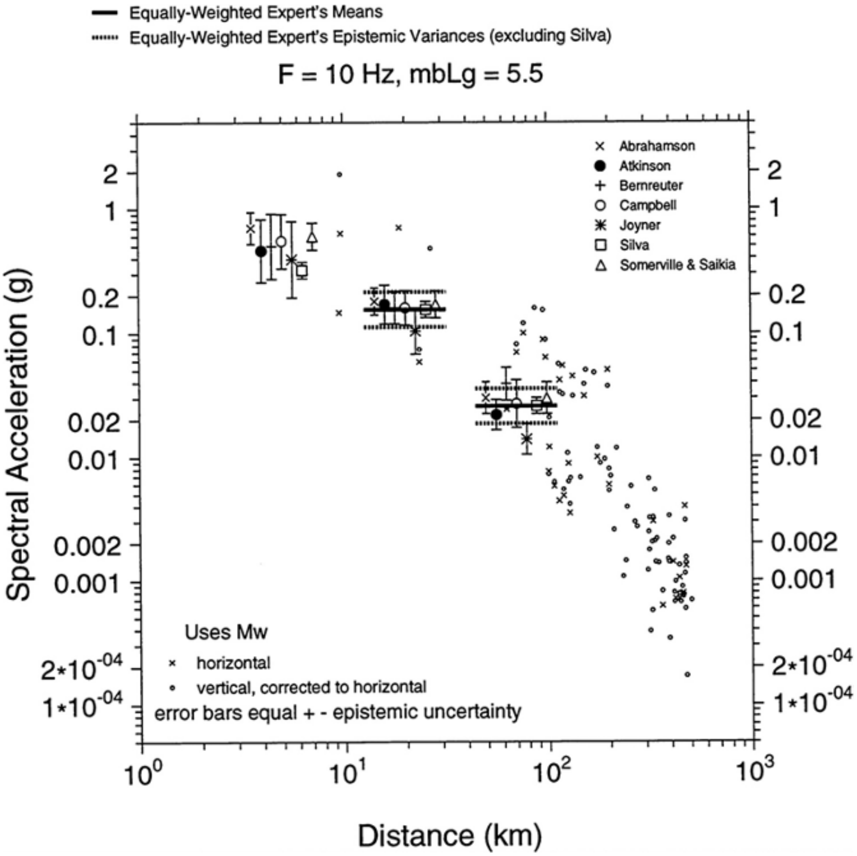

FIGURE 5.1c Experts 3 results, together with mean values and variances obtained from equally weighting the Experts 3 results for 10-Hz spectral acceleration at $m_{\mathrm{bLg}} = 5.5$ as a function of distance. Small circles and crosses represent instrumental data.

PGA are, however, significantly higher than [the] values obtained using western North America strong-motion data, especially for large magnitudes."

SSHAC did not comment on the extent to which the workshop ground motion estimates and uncertainties can actually be used in future PSHA studies, at any level. The panel recognizes that there is a certain incompleteness about Table 5.1. Considerable interpolation and some extrapolation of the results in that table will be required to cover the many distances, frequencies, and magnitudes that must be considered in even the lowest-level PSHA. Unfortunately, the elicited results for $R = 5$ km, where R is the distance between the seismic source and the affected area, are not presented by SSHAC, presumably because of problems with the interpretations of "closest distance."

TABLE 5.1 Results of Integrating Experts' Estimates with Equal Weights (Table B-8, Appendix B, SSHAC Report)

f (Hz)	m_{bLg}	R (km)	Median Amplitude (g)	Epistemic Std. Dev.	Aleatory Std. Dev.
1	5.5	20	1.09E`02	0.48	0.80
	5.5	70	2.27E`03	0.46	0.80
	5.5	200	9.36E`04	0.37	0.80
	7.0	20	1.67E`01	0.66	0.78
	7.0	70	4.50E`02	0.71	0.78
	7.0	200	1.82E`02	0.73	0.79
2.5	5.5	20	4.17E`02	0.34	0.77
	7.0	20	3.67E`01	0.53	0.73
10	5.5	20	1.55E`01	0.32	0.73
	5.5	70	2.58E`02	0.32	0.75
	7.0	20	8.45E`01	0.52	0.70
	7.0	70	1.88E`01	0.53	0.72
25	5.5	20	2.13E`01	0.34	0.73
	7.0	20	1.07E+00	0.51	0.70
PGA	5.5	70	1.28E`02	0.41	0.75
	7.0	70	9.36E`02	0.51	0.70

Even if the SSHAC ground motion results are not suitable for further use in their present form, the panel wonders how many times this information will be reelicited in the future. **The panel believes that community consensus on PSHA-type ground motion issues, at any level of PSHA, may well be close at hand, at least within the limits of the ground motion models and data sets available in 1994.** The broad agreement resulting from the two SSHAC ground motion workshops led to this opinion of the panel. With further consideration of some additional distances, frequencies, and magnitudes, together with appropriate interpolation schemes, ground motion matters of concern to PSHA could well be resolved at least for the next few years.

6

Summary and Conclusions

GENERAL APPRAISAL OF THE SSHAC REPORT

The Senior Seismic Hazard Analysis Committee's (SSHAC) report offers substantial contributions to the foundations and practice of probabilistic seismic hazard analysis. But the primary focus of the report is not on how to create an assessment from the inputs; only in Chapter 2, in an introductory fashion in Chapter 6, and in Appendix J is a methodology for calculating the hazard estimates and their uncertainties addressed.

Instead, the central theme of SSHAC is guidance on the process of eliciting and aggregating expert opinion on seismic sources, seismicity within these sources, and ground motion attenuation, as well as the associated uncertainties and final estimates of the hazard. SSHAC focused on this theme based on its conclusion that the reason for some serious discrepancies in the results of prior studies is differences in ways in which these inputs were derived, even though the work was done by competent specialists working from the same or similar data bases. **In the panel's view, SSHAC's most important message is that the quality of a PSHA using multiple experts can be enhanced by careful and wise choice of experts and skillful facilitation of expert discussion and interaction through workshops and other meetings.**

The panel believes it very important to emphasize what the SSHAC report is and what it is not. The report presents a procedure for using experts in seismic hazard evaluation and for determining the uncertainties at key stages of the hazard analysis process. Its primary domain of application is to nuclear and other critical facilities. According to SSHAC, if a project sponsor and the analysts choose to do a probabilistic hazard analysis, its procedures will yield stable results. The SSHAC report is not a defense of the probabilistic approach to hazard assessment. In particular, SSHAC explicitly excludes any discussion of the nonprobabilistic methods of seismic hazard assessment. The panel accepts this decision of SSHAC on the grounds that an evaluation of the relative effectiveness of the two approaches, or their relationship, was not in the committee's charge. The full-blown version of the SSHAC procedure, utilizing the technical facilitator/integrator (TFI) technique where needed, is costly and will almost certainly be used only for major critical facilities. The SSHAC report offers useful guidelines as to the level of effort required for various kinds of problems and for various levels of information already available to analysts. In the view of the panel, simpler methods of probabilistic hazard analysis are appropriate for application to noncritical facilities.

GENERAL SHORTCOMINGS AND LIMITATIONS OF THE SSHAC REPORT

The SSHAC report, with its appendixes, is a lengthy and complex document that requires careful reading. Many important ideas, including clarification of the limitations of the SSHAC procedures, are distributed throughout the text. A casual scanning of the document may leave readers with incorrect impressions as to what SSHAC has recommended, especially with regard to nonnuclear facilities. Most importantly, the report appears to have been written for those already quite familiar with PSHA methods, offering guidance on a preferred way to get stable results from a PSHA.

SSHAC's Executive Summary will be useful to administrators and project sponsors who are not specialists in hazard analysis methodology, but it includes nothing about the excellent earth science materials that are in the report and its appendixes.

SSHAC provides an up-to-date procedure for obtaining stable results from the application of PSHA principles that have been established in past practice. It does provide a consistent and systematic approach to elicitation and aggregation of diverse expert opinion and the uncertainties that arise therefrom, but this is not the same as the calculation of seismic hazard from the information elicited.

The SSHAC report does not make reference to nuclear reactors or other nuclear facilities, thereby lending an air of generality to its final report and the applicability of its recommended procedures. The panel believes, nevertheless, that the flavor of the report is strongly influenced by concern for applications to nuclear facilities and this generality is more apparent than real. In response to recommendations in the panel's March 1995 letter report (Appendix B) to the U.S. Nuclear Regulatory Commission, SSHAC did attempt to narrow the scope of the applications for which its recommended procedure is intended. Disclaimers are included in several places that are technically adequate to protect a practitioner who chooses not to use the SSHAC prescription against the need to defend that decision in a regulatory situation. Nevertheless, it seems clear that the report was written to support the highest, most sophisticated level of PSHA practice. Because the concept of the TFI is held by SSHAC to be one of its most important contributions to PSHA practice, a great deal of space is devoted to this topic, even though there are repeated comments that it is not needed for many of the issues that arise. The impression is given that this highest level of operation is really the key to success in general.

The panel concludes that the SSHAC contention—namely, that all PSHA projects should share the same basic principles and goals—should be taken as an overarching postulate for project design. But this contention should not be taken as implying or imposing the full elaborate and demanding methodology for application to every PSHA study. That alternate simpler methods may well be adequate for noncritical facilities is acknowledged by SSHAC, but they are not discussed nor is guidance offered as to where readers can learn about them.

In meetings and in its letter report of March 1995 (Appendix B), the panel urged SSHAC to document in adequate detail the manner in which lessons leading to the recommended SSHAC procedures were learned from the study of prior PSHA studies. Although the SSHAC report states that its conclusions are based on a thorough review of a number of such studies, the requested details are not offered and no previous PSHA analyses other than the Lawrence Livermore National Laboratory and Electric Power Research Institute studies are referenced.

The panel's evaluation of SSHAC's treatment of uncertainty is presented in detail in Chapter 3 of this report. The panel acknowledges that recognition of the two kinds of uncertainty is useful in elicitating expert opinion and in making decisions about where additional data gathering and research are likely to lead to reduced uncertainty about hazard estimates. However, as discussed in Chapter 3, the panel has reservations about how this distinction is ultimately helpful to final users, especially because the distinction between uncertainty types is sometimes ambiguous and the amount of epistemic uncertainty regarding a hazard depends on the type of models used in the analysis.

Moreover, it is the impression of the panel that the statistical analysis and uncertainty separation procedures recommended in the SSHAC report are, at times, more sophisticated than is warranted by the data on which such analysis is based or the purposes for which the results are used.

The problem of integrating the opinions of a group of experts is difficult. It is treated in greatest detail in Appendix J of the SSHAC report. The panel found that this treatment is not easy to follow and that specific aggregation models described are not exhaustive. **Therefore, the panel recommends that the quantitative methods of Appendix J be used as examples and not be regarded as prescriptive procedures.** Given the current state of the art in formal expert aggregation and the difficulties specific to the earthquake hazard problem, the panel suggests that judgmental combination rules may be at least as valid as quantitative procedures.

SOME CONTRIBUTIONS OF SSHAC TO HAZARD ASSESSMENT

The contributions that the SSHAC report makes to the hazard assessment process are discussed in detail in the preceding sections of this report. A few key items are highlighted here.

The TFI Methodology

SSHAC considers the TFI methodology to be the centerpiece of its work and developed it from lessons it learned from prior hazard analysis studies and from workshops conducted as part of its study. The panel is favorably impressed with the concept and its implementation in the two ground motion workshops (SSHAC's Appendixes A and B). Readers of the SSHAC report should keep in mind that use of a TFI is not recommended or needed for all hazard assessments and should not even be viewed as a rigid prescription for a high-level PSHA. The TFI elicitation procedure is not synonymous with PSHA methodology.

Clear Definition of Experts' Distinct Roles as Proponents, Evaluators, and Integrators

It is important that experts be educated to the significance of their distinct role as proponents of a particular position or as evaluators. The panel is not sure that experts can truly assess the view of the whole informed community on the entire range of relevant issues.

Results of SSHAC-Sponsored Workshops

SSHAC held workshops on seismic source characterization, ground motion estimation, and earthquake magnitudes. The outputs of these workshops (Appendixes A, B, C, H), especially those on ground motion, are a valuable contribution of the SSHAC effort and led to the formulation of many of the recommended procedures in the committee's report.

Considering the broad consensus on ground motion modeling that was reached at the end of Workshop II, the panel believes that a real opportunity exists now to formulate, with further work to fill in necessary details, a ground motion model that can be used as a standard in the eastern United States for PSHA until new data or future theoretical developments warrant a reevaluation. The results of this effort would eliminate the need to elicit again ground motion input for each hazard analysis and could be used as a baseline for more detailed studies as needed for specific problems.

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Appendix A

ACRONYMS

DOE	Department of Energy
DSHA	deterministic seismic hazard analysis
EPRI	Electric Power Research Institute
EUS	eastern United States
LLNL	Lawrence Livermore National Laboratory
NRC	National Research Council
PGA	peak ground acceleration
PSHA	probabilistic seismic hazard analysis
SHA	seismic hazard analysis
SSHAC	senior seismic hazard analysis committee
SSC	seismic source characterization
TI	technical integrator
TFI	technical facilitator/integrator
USNRC	United States Nuclear Regulatory Commission

Appendix B

LETTER REPORT OF THE PANEL ON SEISMIC HAZARD EVALUATION, MARCH 1995

Committee on Seismology, National Research Council
Comments on SSHAC Draft Report of 11 November 1994
Based on the Panel Meeting of December 9-10, 1994

The Panel on Seismic Hazard Evaluation of the Committee on Seismology, National Research Council (NRC), is charged with reviewing the report to be produced by the Senior Seismic Hazard Analysis Committee (SSHAC) under the sponsorship of the U.S. Nuclear Regulatory Commission (USNRC), the Department of Energy (DoE), and the Electric Power Research Institute (EPRI). The USNRC prescribed that the Panel provide feedback to SSHAC as they prepare their report, but in such a way as not to compromise the objectivity of the Panel in providing its review of the final product. SSHAC submitted for review a draft of their report in mid-November, 1994, and the Panel met, with all SSHAC members present, on December 9, 1994, for discussion of the draft.

Unfortunately the draft was not complete, missing some key appendices, some sections of text, and an executive summary. It should be understood that the Panel may have comments with regard to the missing material when it is available for the final review. The discussions of December 9 were carried out in the presence of representatives of the sponsoring organizations. The Panel met in executive session on December 10 to continue its review. The resulting comments and recommendations are submitted to the USNRC.

The suggestions made are offered as guidance to SSHAC on the issues at this stage of their work, in accord with the request of the USNRC. They should not be interpreted as a substitute for the final report to be developed by the Panel.

GENERAL COMMENTS

The Panel believes that the draft report is a basis for a useful final product that has the potential to advance the process of Probabilistic Seismic Hazard Analysis (PSHA). However, the Panel feels that the introduction to the report must be expanded to make clear the purpose and scope of the report, and specifically to state what the report is not. As it stands, the report implies that the methodology is applicable to a broader range of facilities than can be justified. The full range of alternative approaches is not discussed, let alone taken into account.

From the discussions, it appears that there may be a conflict between the expressed needs of the USNRC for a single unified, fully prescribed regulatory method of seismic hazard analysis (SHA) and the attempt by SSHAC to produce a general consensus methodology. The USNRC wants a prescribed procedure that is based on what has been learned from past PSHA experiences. The USNRC recognizes that the way in which input from experts was obtained is a main reason for the discrepencies between the analyses made by Lawrence Livermore and EPRI.

The Panel recognizes the strengths of the report and the significant contributions it offers to PSHA. As applied to nuclear regulations the SSHAC report breaks new ground in its discussion of the Technical Integrator (TI)/ Technical Facilitator Integrator (TFI) approaches. However, as discussed in detail below, the presentation of these ideas needs to be made more clear to eliminate some apparent contradictions and advise the users of the report when the full TFI treatment is called for. The TI/TFI approach has the potential to overcome some aspects of past PSHA applications that have led to objections by critics of the whole process.

Because the focus of the report is on process for PSHA, rather than on the underlying earth science, the detailed attention to the treatment of uncertainty is appropriate. However, as discussed below, the motivation for this careful treatment of uncertainty and the way in which the results will be applied are not made clear to the potential user.

Again without yet having the benefit of full discussion of the subject, the Panel feels that the recommendation that behavioral aggregation of expert input be employed is sound, because mechanical aggregation algorithms, if used as "black boxes," may lead to poor results.

CONCERNS AND PROBLEMS

Recommendations for Improvement

Some suggestions for revision and restructuring of the report were given orally to SSHAC during the Panel meeting. The most essential of these, which the Panel feels cannot be neglected during revision of the report, are repeated here for completeness of the record.

The word “Consensus” should be removed from the title, perhaps replaced by a more appropriate adjective.

An excellent executive summary is essential for the success of this report. The report is lengthy and detailed. The key findings and recommendations of SSHAC must be assembled in concise, easily understandable form if they are to be accessible to others than the experienced practioneer of PSHA.

The draft as submitted is overly repetitious. Unnecessary redundancy should be eliminated, to reduce the length substantially without loss of content.

The specific criticisms to follow all can be categorized as due to one or more of the following: inadequate *focus* of the report, absence of the *history* of evolution of the key concepts and recommendations, or lack of a presentation of the *context* within which the report was developed and is to be understood and applied.

> ***Motivation.*** The reader should be offered better motivation for adopting the procedures required or recommended in the report. In addition, the context for the procedures should be framed in such a way that the PSHA analyst who follows other procedures for any of a number of valid reasons is not put in a position of having to defend in a regulatory situation the failure to carry out the SSHAC prescription in every detail.

PSHA methodologists often have sound reasons for introducing new concepts and approaches, but have not always included in their reports the background reasoning that has led to these innovations. Where it exists in this report, this shortcoming must be overcome if the final SSHAC product is to be widely accepted and applied. In particular, the report should say how the results are to be used as motivation for the great emphasis on the distinction between aleatory and epistemic uncertainty and the need to separate the two in SHA.

Space and emphasis devoted to the TFI approach. Scattered through the text, and asserted by SSHAC members at the December 9 meeting, is the key idea that the full TFI approach is required only for some complex issues for which a review of the published literature cannot produce satisfactory input to the PSHA process. However, the great detail in which the recommended TFI approach is depicted tends to obscure this principle. The reader is left with the impression that the use of the TFI is dominant in a properly executed PSHA.

- SSHAC must carefully set out the criteria for deciding if an issue requires a TFI. What are the operational criteria for deciding if an issue is of type A, B, C?
- SSHAC must state its perception of the qualifications required of the TFI. The recommendation for use of a *strong* TFI for prescribed issues, without clearly expressed qualifications, contradicts one of the stated criteria for success: that the recommended methodology, when applied independently by different groups, should always yield comparable results.
- The Panel is concerned that the TFI is empowered to act as a “super expert,” able to overrule the diverse views of the experts from whom input is elicited. It is not prudent to generate an apparent consensus unless consensus among the experts is really achieved. It is not necessary that the TFI agree with the outcome of the process; the TFI can stand behind that outcome as the result of thorough interaction among experts.

The issue of breadth. The statement on breadth of application on page 1-7 of the draft report and other statements related to the intended breadth of application of the recommended methodology are the cause of much uneasiness among the Panel. *A clear statement of the purpose and scope of the report should be included early in the introduction.*

- It should be made clear that the recommended methodology is based on a study of the experiences with LLNL and EPRI procedures. This should be brought out in the history-context material called for above. In the appropriate places, specific references to the lessons learned by examination of previous PSHA projects should be cited. The studies from which the recommended methodology was derived should be clearly described, even though the intent of the report is not to address the reconciliation of the LLNL/EPRI studies. The reader should be made aware of the lessons learned from the evaluation of those (and other?) studies that have gone into the formulation of this report. The reader should be told explicitly that alternate PSHA approaches were not assimilated and that this report is not based on a consensus of a broad sample of practioneers.

- Some statement of costs would be in order. What a hazard evaluation can deliver is often a matter of how many dollars are available. Cost estimates may be beyond SSHAC's scope, but even this could be mentioned.
- The Panel anticipates that the full procedure recommended in this report will not be applied to the seismic regulation of all critical facilities. It is not a general methodology that will be applied step-by-step in all situations. Therefore, criteria or guidelines are needed in the report, to aid the project sponsor and the PSHA analysts in deciding when the full procedure is justified. A statement is needed about what can be delivered with different levels of PSHA, so the buyer can make an informed decision as to what will and will not be produced. As stated above, the analyst who chooses for sufficient reasons to use other procedures should not be put by this report in a position of having to defend that decision in a regulatory setting. He or she, of course, must be prepared to defend the procedures that were adopted.

SCIENTIFIC AND TECHNICAL CONCERNS

The Panel questions whether the links between SSHAC's recommended methodology and its applications are spelled out in sufficient clarity. Although SSHAC is not charged with specifying the use of hazard numbers in engineering design, a brief treatment is needed pointing to how the results can be used, and, in particular, what the knowledge of highly refined uncertainty estimates contributes to applications. A clear and unequivocal definition of aleatory and epistemic uncertainty is needed, as well as a clear and readily applied prescription for separating the two. This is needed because of the emphasis on this subject in the report.

Although not as yet the subject of full panel evaluation, the following example illustrates the need for SSHAC to be very clear on the value and the method of application of their categorization of uncertainty. “What should count for decision is not the aleatory/epistemic distinction, but the temporal variation in the total uncertainty (in the total or predictive distribution of A_T, maximum peak ground acceleration and spectral values at the site in the next T years) during the lifetime of the project.” According to this viewpoint:

- There is no need to label uncertainty as epistemic or aleatory.
- If one sees total uncertainty as being contributed by different sources (e.g., by uncertainty on model type or on various parameters), then it is reasonable to expect that the uncertainty associated with each source will evolve in its own way in time. Making a binary distinction between epistemic and aleatory uncertainty corresponds to assuming that each source will be either explained totally (epistemic components) or will remain constant over the lifetime of the system (aleatory components.)
- One can formulate rational ways to make decisions accounting for the possible temporal evolution of uncertainty. The Panel member responsible for these comments is not, on the other hand, aware of any convincing method to make decisions based on the aleatory/epistemic decomposition. The amount of conservatism displayed by decisions under time-varying uncertainty depends on the nature of the problem (essentially on the degrees of asymmetry in the rewards and penalties associated, respectively, with future possible decreases and increases in the calculated risks).

The SSHAC report will be strengthened by addressing these concerns in a straightforward way.

Intensity data from historic strong earthquakes in the central and eastern United States is not incorporated in the ground motion models. The relation between m_{bLg} and intensity in the eastern United States, first established by Nuttli, should not be ignored.

“Seismic source zones”, a key concept in the prescribed source characterization procedure, should be explicitly recognized as an artificial construct introduced to make hazard calculations tractable. They are not real physical entities.

Some issues important for applications are not touched on. For example, the value of the availability of computed full seismic waveforms, site response analysis, and the importance of non-linear soil response in hazard calculations are not mentioned. Assessment of non-linear behavior is at least as important as uncertainties in bedrock motion. So also is the relationship between hazard-consistent time series and magnitude-distance parameters. And, as we have noted above, SSHAC's recommended methodology is based on the LLNL-EPRI experience and therefore focuses properly on power plant design. It is not necessarily suited to structures that respond to longer-period motions (e.g., suspension bridges).

Though the full treatment of these and related topics is outside the scope of the SSHAC task, they should at least be mentioned to show SSHAC's awareness that seismic hazard analysis encompasses more than the issues and procedures recommended in this report and that these problems are important in the total process. This will give greater credibility to the final report. A full report on site response analysis should be prepared in a future effort. A handbook on USNRC-approved procedures for doing PSHA, presumably restricted in scope to projects in the jurisdiction of that agency, would be helpful. This handbook would be based on this SSHAC report and additional reports on the issues outside of SSHAC's responsibility. However, as stated above, such a handbook should not be used to require a specific procedure in all hazard assessments.

Mention is made of earthquake prediction in two places in the Introduction, pages 1-1 and 1-11. The comments give a misleading impression of the goals and potential benefits of a prediction methodology, if one is eventually developed. In particular, it is implied that the ability to produce accurate short-term predictions would somehow lessen the importance of reliable long-term earthquake hazard assessments, on which sound engineering decisions must be based.

The reader should be informed where the software needed to carry out the recommended procedures can be obtained.

The discussion of the effects of correlation of parameters is apparently based on lessons from experience. The whole point should be made clearer, as the draft presentation is not readily followed by a reader who has not been through the process.