Civilian Radioactive Waste Management System
Management & Operating Contractor

Summary of Seismic Source Characterization Feedback Workshop

SSC Workshop 5

Salt Lake City, Utah
April 14-16, 1997

Prepared for:

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INTRODUCTION

The U.S. Geological Survey (USGS) is carrying out a probabilistic seismic hazards analysis (PSHA) for Yucca Mountain, Nevada as part of the Department of Energy's (DOE) project to characterize this site as a potential geologic repository for high-level radioactive waste. This study was initiated in April 1995 and resumed in June 1996. The aim of the analysis is to provide the annual frequency with which various levels of vibratory ground motion and fault displacement will be exceeded at the site. These results will be used as a basis for developing seismic design inputs and in assessing the waste isolation and containment performance of the site.

The PSHA involves development by two panels of experts of input interpretations and assessments of uncertainties required by the hazards calculations. One panel (consisting of six teams of three experts) addresses characterization of seismic sources and fault displacement, while the other (consisting of seven individual experts) deals with vibratory ground motion. Development of interpretations is being facilitated through a series of structured workshops to evaluate available data, to explore the range of interpretations allowed by the data, to examine critically the interpretations proposed by the experts, and to provide feedback on the implications of various interpretations for the seismic hazard at the site. This report summarizes the fifth workshop in the characterization of seismic sources and fault displacement: the Seismic Source Characterization (SSC) Feedback Workshop.

The primary goals of the workshop were to: (1) provide an opportunity for the expert teams to discuss the first round of their interpretations; (2) allow each team to understand and ask questions about the interpretations made by other teams; (3) provide information on the derivative products of their first-round assessments (i.e., seismic source characteristics); and (4) provide sensitivity analyses that show the relative impact of various assessments on the calculated results. To accomplish these goals, a series of presentations and group discussion sessions were conducted, with emphasis on interaction among the SSC experts and feedback from the Facilitation and Calculation Teams. For each of six key issues, two or three teams presented their interpretations with all of the teams subsequently discussing the issue and their interpretations. These six key issues, identified by the Facilitation Team from the preliminary results, included: (1) characterization of areal seismic source zones; (2) geometry of local faults; (3) synchronous ruptures of local faults; (4) maximum magnitudes and recurrence on local faults; (5) characterization of other seismic sources, such as buried strike-slip shear zones, detachments, volcanic zones and other buried or postulated structures; and (6) methodologies for evaluating fault displacement. The focus of the presentations and discussion was on understanding the interpretations of others, their technical bases, consistency with data, and expression of uncertainty. Preliminary results and sensitivity analyses were presented for five of the teams, highlighting the most significant sources and parameters to the analyses. Assumptions and simplifications of the teams' assessments that were made for the analyses were clarified and discussed. As interpretations will be finalized shortly after this workshop, emphasis was on the experts gaining a common understanding of each other's interpretations and clarification of any outstanding questions regarding their own assessments.

The workshop agenda is included as Attachment 1. Copies of overhead transparencies shown by presenters and additional material distributed during the workshop are included as Attachment 2. Table 1 is a list of participants and their affiliations.

MONDAY, APRIL 14, 1997

Kevin Coppersmith opened the workshop with an introduction, describing the purpose and approach, and outlining the workshop agenda. He highlighted significant aspects of the key issues to be addressed, encouraged technical challenge and debate during the workshop, and emphasized that the experts need to have been exposed to and consider all of the various proponent views. He also stressed that preliminary seismic hazard results are provided only for sensitivity and information on relative importance, and are not intended as hazard results for any other purpose. He reviewed three issues relevant to the seismic source characterization for Yucca Mountain which were raised in the Nuclear Regulatory Commission's 1996 Annual Progress Report (Chapter 3 of NUREG/CR-6513, No. 1). These include questions regarding: (1) adequate consideration and incorporation of alternative tectonic models in the SSC team interpretations; (2) adequate consideration by the teams of all 52 Type I faults, identified by the NRC, as potential seismic sources that may affect repository design or performance; and (3) possible explanations for the apparent anomalous lengths of certain faults (Bare Mountain, Windy Wash, and Ghost Dance) as suggested by scaling relations between fault length and cumulative throw.

The rest of the afternoon was devoted to covering the issues of characterizing areal seismic source zones and the geometry of local faults. Al Rogers made the first presentation on his team's (Rogers, Yount, Anderson - [RYA]) interpretations of seismic source zones. They defined three zones primarily based on structural domain considerations (Yucca Mountain-Bare Mountain, Basin and Range, Death Valley-Furnace Creek), all with the same maximum moment magnitude (M_{max}) of 6.3 ± 0.3 for background earthquakes (they referred to as background faults). Recurrence rates for background faults were calculated for each zone using declustered versions of the historical seismicity catalog and uncertainties in a- and b-values were included, particularly those resulting from assessing catalog completeness. Discussions followed about observations by Walter Arabasz of an apparent systematic bias of lower magnitudes (and resulting higher b-values) for the catalog than previous M_L-based catalogs for the Basin and Range province. Also discussed were issues relating to smoothing and systematic differences in b-values from east to west within 100 km of Yucca Mountain, observed by Diane Doser.

Robert Smith made the next presentation on his team's (Smith, dePolo, O'Leary- [SDO]) interpretations of areal seismic source zones. He explained that their interpretations were not as complete as others due to changes resulting from replacing one of their team members (Christopher Menges was replaced because of health problems by Dennis O'Leary). Dr. Smith said they had defined 5 source zones, including: a host zone (Yucca Mountain-Crater Flat); the Goldfield-Spring Mountain section of Walker Lane; the Death Valley section of Walker Lane; the central Basin and Range; and a zone defined by seismicity associated with the 1992 Little Skull Mountain earthquake. Seismogenic depths of 14, 17, and 19 km were respectively weighted 0.2, 0.6, and 0.2, primarily based on maximum focal depths for earthquakes within 100 km. These large seismogenic depths stimulated lots of discussion among the experts due to resulting effects on M_{max} and moment rates. Based on historical analog earthquakes in the Basin and Range province, the SDO Team developed a probability density function of M_{max} for background earthquakes occurring in each of the zones within 100 km of Yucca Mountain (M_w 6.2, 6.4, and 6.6 for the 3rd, 50th, and 97th percentiles, respectively). Finally, he discussed their methods for processing the seismicity catalog (including declustering, completeness assessments, magnitude conversions and uncertainties, and smoothing), and estimating recurrence rates for each source zone.

Dr. Coppersmith subsequently summarized general characteristics of all of the teams' assessments of areal source zones and asked Dr. Doser to discuss her team's characterization. She explained that even though they originally defined their zones primarily based on geologic and tectonic considerations, they observed systematic seismological differences between zones (such as shallower focal depths and a greater lateral component of slip from east to west), giving them further confidence in their definition of zones. Other teams then discussed their various bases for defining zones, particularly why some of them did or did not define a "host" or local zone, and their various approaches to characterizing this zone.

After the break, Christopher Fridrich gave a presentation on his team's (Doser, Fridrich, Swan- [DFS]) interpretations of the geometry of local faults. Dr. Fridrich described their approach to developing subsurface geometric models of local faults and characterizing uncertainties in fault length, dip, and downdip extent. He showed a series of cross-sections and structure contour maps, highlighting differences between interpretations for their two basic tectonic models (domino and detachment), and for variations within the domino tectonic model (with from one to three groups of coalescing faults). He discussed their rules of assessing downdip extent, summarized what their preferred interpretations were, and highlighted some geometries that the cross-sections either preclude or suggest are less likely (e.g., coalescence of the Windy Wash, Solitario Canyon and Paintbrush Canyon into one fault). Discussion then followed about how they handled uncertainties in fault dips and calculated slip rates for the various models.

Peter Knuepfer gave the last presentation of the day, discussing his team's (K. Smith, Bruhn, Knuepfer - [SBK]) interpretations of local fault geometry. As their characterization of fault geometry is dependent on their tectonic models, he began with an overview of their models and the resulting influences or constraints on local fault dips, downdip extent, and lengths. He presented many arguments in favor of steeply to moderately dipping planar faults, including geophysical data, seismicity data, and arguments from stress-drop considerations and slip-length scaling relations. Based on the latter considerations and relations, and the Mammoth Lakes earthquake sequence as an analog for "the ash event" (Scenario U of Pezzopane, 1996), they favor interpreting the ash event as a sequence of multiple event ruptures that were not actually synchronous from a ground-motion viewpoint, but were separate events, on individual faults, that were tightly clustered in time. The expert panel discussed the uncertainties with this interpretation. Next, Dr. Knuepfer explained how his team characterized uncertainties in downdip extent and fault length. Except for the Bare Mountain fault, they interpreted the maximum southern extent of Yucca Mountain faults to be around Lathrop Wells.

This stimulated discussion about how other teams interpreted the southern termination of local faults, given the observed increase of total slip and slip rates to the south. Some had interpreted the Highway 95 (or Carrara) fault as truncating local faults, whereas others had terminated faults at the southern end of the Crater Flat basin structural domain. The panel also discussed implications for uncertainty in some fault lengths (i.e., Bare Mountain, Ghost Dance and Windy Wash faults) from scaling relations between length and total throw. Finally, discussion followed about the evidence both for and against listric fault geometries, and how fault segmentation was variously considered in the analyses.

Dr. Coppersmith asked for comments from observers and Clarence Allen asked for clarification about how the teams had considered the Ghost Dance fault in their assessments. Dr. Coppersmith explained that all teams had included the Ghost Dance fault as a possible source for secondary fault slip in their preliminary fault displacement analyses, but none, so far, had included it as a seismogenic source (an independent generator of earthquakes) in their characterizations for the vibratory ground motion analysis. Leon Reiter asked for clarification on the time frame being considered by the experts. Some had considered both long (10,000 years) and short (100 years) periods in developing their assessments, some had not thought about it, and others were still trying to resolve how to address possible non-stationarity of seismicity in both time and space. Ralston Barnard clarified that results from this project will be used for performance assessments that consider periods as long as 10,000 years and longer. Carl Stepp suggested that the experts consider two questions: (1) how to best represent long-term behavior with the available data?; and (2) what type of long-term changes (if any) can be expected for earthquake and fault slip behavior in the region? Dr. Coppersmith further encouraged the teams to think about how considering a longer time period (10,000 or 100,000 years) might change their assessment.

TUESDAY, APRIL 15, 1997

The workshop continued with a series of presentations and discussion on the remaining key issues: synchronous ruptures on local faults, M_{max} and recurrence on local faults, other types of seismic sources, and methodologies for fault displacement. Alan Ramelli gave the first presentation on his team's (Arabasz, E. Anderson, Ramelli - [AAR]) interpretations of synchronous ruptures for local faults. He described their reasons for considering synchronous ruptures, their approach to developing 11 structural model categories, and how their interpretation of local fault behavior and geometry was dependent on these model categories. They distinguished linked faults (along-strike fault connections) from coalesced faults (downdip fault connections) and defined four different models for coalescence of local faults. Thus, they considered linked, independent, and coalesced behavior for possibly linked faults (e.g., Paintbrush Canyon and Solitario Canyon faults) and only coalesced and independent behavior for other local faults (e.g., Bare Mountain fault which can either rupture independently or together with many other local faults, comprising a single coalesced system). He described their bases for: favoring independent behavior of the Bare Mountain fault, fault length distributions, and preferred dips of 60°. He said they had previously favored some degree of coalesced behavior but would be reconsidering their weights given the insights provided by Dr. Fridrich's structural analysis presented on Monday. Finally, the panel discussed the distribution of moment release during synchronous ruptures and the questions that might be raised to the Ground Motion Experts regarding information that they might require in this regard for their models.

Jon Ake gave the next presentation on his team's (Ake, Slemmons, McCalpin - [ASM]) interpretations of synchronous ruptures on local faults. He prefaced his presentation with the comment that they would be revisiting some important aspects of their assessment given some of the insights they had gained during the workshop. He said they based their models of synchronous fault rupture on both temporal and geometrical considerations. He clarified that their definition of synchronous (or simultaneous) earthquake rupture was two or more faults rupturing within 10 seconds of each other. He presented the general structure of their logic tree for local faults, gave examples of simultaneous ruptures considered, and discussed their original basis for assigning a low weight to simultaneous ruptures, although they may re-evaluate this based on geometrical considerations. This stimulated discussion among the panel about the geometries, settings, and characteristics of possible analog earthquakes that have exhibited distributive rupture on multiple faults. Examples discussed included both simultaneous rupture (according to the ASM team definition) and non-simultaneous rupture. Discussion also followed about: considering buried dike systems as a possible source, considering the Yucca Mountain faults as aseismic and dependent on the Bare Mountain fault, expanding uncertainties for synchronous rupture models and the need to clarify how teams are defining terms (such as synchronous rupture, distributive rupture, linked faults, etc.).

Craig dePolo gave the first presentation on M_{max} and recurrence on local faults, representing the SDO Team. His team's approach to characterizing M_{max} included using many different regression relations to scale earthquake size from multiple fault parameters such as length, area, maximum surface displacement, slip rate and seismic moment. He clarified how they would determine certain parameters for different scenarios in their assessment, what relations they would use, and how they would be combined. He reported some preliminary values which ranged greater than M_w 7 for certain scenarios with extreme geometries (e.g., 45° dip and 19 km depth). In terms of earthquake recurrence, he said they were considering using geodetic data, in addition to paleoseismic data, to estimate moment rates. They would also use a recurrence interval approach and he discussed how they were using the available paleoseismic data to determine average recurrence intervals for different rupture scenarios in their assessment.

Walter Arabasz gave the next presentation on M_{max} and recurrence on local faults, representing the AAR Team. He began by pointing out they had considered seismogenic depths in two different ways in their assessment because they were considering depths for Yucca Mountain that were generally larger than the depths included in the development of the empirical relations they were using to estimate M_{max} (Wells and Coppersmith, 1994). Thus, they used seismogenic depths to constrain their physical models (D_{max2}) that did not necessarily equal the seismogenic depths used to estimate M_{max} (D_{max1}), indeed D_{max2} was often greater than D_{max1}. He said they considered flexural rigidity to be a better indicator of seismogenic depth than heat flow and presented their rules for constraining downdip fault widths for their various tectonic models and structural categories. He presented the four empirical relations they had used, how they were weighted and the basis for the weights. Next, he discussed their approaches to estimating recurrence, which included both slip rate (weighted 0.6) and recurrence interval (weighted 0.4) methods, whenever data for the latter were available. They used both characteristic (weighted 0.7) and truncated exponential (weighted 0.3) models. He discussed their estimated b-values, reiterating his previous comment that 50th percentiles were surprisingly higher for Yucca Mountain than for previous Basin and Range catalogs he had analyzed. Discussion followed about their maximum magnitude distributions and how broad their uncertainties were due to the large variety of geometries considered in their various tectonic models and structural categories. The general dependence of the slip-rate method on M_{max} and geometry was also discussed. Dr. Coppersmith then summarized all of the teams approaches to estimating M_{max} and recurrence on local faults, pointing out similarities and differences. He explained the importance of choosing recurrence models and adequately incorporating uncertainty in M_{max} and recurrence parameters. He told the teams that they would each be getting their M_{max} distributions and recurrence curves shortly after the workshop.

After lunch, there was continued discussion about recurrence, particularly about declustering the catalog, other methods of processing the catalog, and the resulting effects on recurrence curves. Jim Yount then gave the first presentation on other seismic sources that his team (RYA) had considered in their assessment. He started with a buried detachment fault, explaining why they assigned a zero probability to it being an independent seismogenic source even though it may exist. He also discussed a potential volcanic source zone that they had included. To this buried source, they assigned: a seismogenic probability of 0.7, an M_{max} of 5.5 ± 0.5 based on historical analogs for basaltic events elsewhere, and a return period of 200,000 to 1.9 million years based on the PVHA report for Yucca Mountain. He also discussed their reasons for considering a buried vertical shear zone as a source that may be decoupled from local surface faults. Their assigned probability to this buried zone being an independent seismic source was model dependent, ranging from 0.05 to 0.1. Finally, Dr. Yount described their characterization of the geometry, M_{max}, and recurrence parameters for this source, also providing the bases for their assessment.

Ernie Anderson gave the next presentation on other types of seismic sources, representing the AAR Team. He started with an overview of their four tectonic models and their influence on the inclusion of various types of seismic sources. He discussed their reasons for considering any detachment faults that may exist as accommodation zones and not as independent seismic sources. He also explained that although they believe that volcanic sources may also exist, that the expected M_{max} for these sources (M_w 5-5½) is well below that for their areal source zones and any volcanic-related earthquakes are accounted for within these zones. Finally, he discussed two types of buried sources they had included for some of their structural models: cross-basin and basin-bounding faults, and a large strike-slip shear zone. The former are assumed to exist as part of a pull-apart basin model suggested by small-scale laboratory deformation experiments conducted by the Center for Nuclear Waste Regulatory Analyses. The latter is suggested by the work of Richard Schweickert and his colleagues. Dr. Anderson discussed how they characterized these buried sources, the bases, and the uncertainties.

Silvio Pezzopane mentioned that their cross-basin faults may be geomorphically expressed as the down-to-the-east faults of Ramelli and Bell (1996). Discussion followed about the geomorphic and paleomagnetic evidence for possible basin-bounding and cross-basin faults.

As part of this discussion, Burt Slemmons then gave an overview of geomorphic and geophysical evidence supporting a fault origin for the Carrara or Highway 95 scarp. He showed slides from his aerial reconnaissance and explained that the fault could not only be important as another potential seismic source but it could truncate the Bare Mountain and Yucca Mountain faults (as for example the AAR Team had interpreted in their pull-apart basin model).

Next, Dr. Coppersmith asked the teams why they had not included either the Ghost Dance or Sundance faults as independent seismic sources. Reasons given included no definitive evidence for Quaternary displacement, too short of length (events would be small and fall into "background" or areal seismic zones), and rates of activity are too low. Craig dePolo said that they may include a low-weighted scenario where the Abandoned Wash and Ghost Dance faults are linked and seismogenic, particularly to account for the uncertainty in possible early Quaternary shearing at Whaleback Ridge. Finally, the issue of why vertical slip rates on the Bare Mountain fault are apparently much lower than total vertical slip rates for Yucca Mountain faults, and what significance this may have to tectonic models, was discussed.

After the break, Frank (Bert) Swan gave a presentation on his team's (DFS) fault displacement methodology. He reviewed their general logic tree, describing their overall approach for faults, and fractures/intact rock. Their methodology uses slip rate, displacement per event, recurrence intervals (wherever available), and an event-to-event displacement variability function to characterize the displacement hazard at a location. They use Quaternary slip rates (weighted 0.7) wherever possible and also use Tertiary slip rates with three different models for behavior. These models include: a uniform slip rate since 12.7 Ma, a uniform slip rate since 11.6 Ma with only 20% of the post-Tiva Canyon slip having occurred since 11.6 Ma, and a decreasing rate such that the Quaternary rate is between 0.3 and 3.9% of the late Miocene rate. He discussed how reduction factors and resulting rates were determined for this last model. He presented the bases for all the models and all the resulting slip rates for each of the structures at the nine specified test locations. Next, he discussed their displacement per event and recurrence estimates. He then explained how they used paleoseismic data to develop a relationship between average and maximum displacement at a point along a fault to characterize expected event-to-event variability in displacement. Finally, he explained how they characterized the probability of displacement along fractures and in intact rock using three deformation models analogous to their Tertiary slip rate models.

James McCalpin gave the next presentation on fault displacement methodology, representing the ASM Team. Their approach separates primary fault displacement on seismogenic (block-bounding) faults from distributed faulting on secondary, non-seismogenic faults. First, he discussed various ways of using paleoseismic data to predict displacement per event at a point along a primary fault, given the along-strike-variability in slip, the event-to-event variability in slip, and the likely greater variability of slip in unconsolidated sediments than in bedrock. Given the displacement distributions on primary faults, the potential displacement on secondary faults is estimated based on their distance from the primary fault and using a bending beam model. He described this model, constrained by geodetic data from the 1983 Borah Peak earthquake, and highlighted some of the uncertainties in applying it to Yucca Mountain faults. He also described an alternative ratio approach to estimating secondary displacement and gave an example comparison for the two methods.

Ronald Bruhn gave the last presentation on fault displacement methodology, representing the SBK Team. He prefaced by saying that their approach was similar in many respects to the approach of the DFS Team. Their methodology is broken into two main parts: estimating slip per event at a point along the fault, and estimating recurrence of that event. He explained how they were using scaling relations between fault size and displacement to estimate displacement per event. He discussed the various relations and their uncertainties. He also presented results from a fractal analysis to characterize along-strike-variability in slip, but he said they may also use the approach developed by the ASM Team. He then discussed how they would use slip rates and recurrence intervals (wherever possible) to constrain the probability of displacement events.

Considerable discussion followed about the methodologies presented. Dr. Coppersmith encouraged the experts to be sure to capture uncertainty in the input parameters. Dr. Pezzopane discussed his progress on developing separate hanging wall and footwall probability density functions for secondary faulting during historical Basin and Range earthquakes. Concerns were raised about whether an elastic bending beam model was appropriate and that care should be taken in all of the assessments not to violate observations of the total slip on any of the faults, particularly where slip on secondary faults is predicated based on slip on primary faults. Dr. Coppersmith urged experts to be sure fault assessments were internally consistent, and consistent with their source characterizations for the ground motion evaluations.

Finally, Dr. Coppersmith asked for comments from observers. Dr. Allen mentioned evidence from historical earthquakes in California supporting characteristic behavior along faults. Dr. Schwartz added that evidence along the Borah Peak earthquake rupture also supported characteristic behavior. Bakr Ibrahim asked how focal depth distributions were being incorporated into fault displacement assessments and Dr. Coppersmith clarified that these were only relevant for principal faults and were included in the ground motion evaluation. Dr. Reiter urged experts to appropriately match the level of complexity of their models to the available data as simplified models that encompass the data are most defensible. He also encouraged them to consider using multiple methodologies in evaluating fault displacement. Discussion then followed as to whether the present schedule afforded the time necessary for adequate consideration of multiple methodologies.

WEDNESDAY, APRIL 16, 1997

Dr. Coppersmith opened the discussion to miscellaneous issues that had been raised over the past two days. Dr. Brune pointed out many issues related to using a quasi-static fault mechanics approach to evaluating the displacement hazard at Yucca Mountain. These included uncertainties in: the absolute deviatoric stresses in and below the repository, pore pressures at seismogenic depths and how these affect the earthquake cycle, the heat flow paradox, and partial versus total stress drops and the large differences in general between the quasi-static models considered and the actual dynamic conditions of the earthquake rupture process. Speaking as a proponent, he believed that fault displacement methods based on total slip or the more traditional earthquake approach, coupled with empirical relations to characterize distributive faulting, were more credible than any fault mechanics approach that can be developed given our current state-of-knowledge. Next, the difference between the probability of seismogenic slip versus non-seismogenic slip on the Ghost Dance fault was discussed.

Next, Gabriel Toro presented the preliminary results for the probabilistic seismic hazard analysis (PSHA). He prefaced his talk with some assumptions made in the modeling of the site and source geometries. Starting with the AAR Team, he gave an overview of their input (in the form of logic trees and maps), presented preliminary hazard curves for 5 and 20 Hz (without many regional fault sources), and discussed some implications from the analysis of variance for the most significant sources. He also presented the ground motion curves used, explaining the significance of the uncertainties in the curves and generally how they were combined with the SSC input to calculate the hazard curves. Following this same format of input, results, and sensitivity analyses, Dr. Toro presented feedback for each team except the SDO Team because he had just received their input. Throughout his presentation, various questions were discussed by the teams, Dr. Toro, and Bob Youngs; clarifying how some of the finer complexities of the teams' characterizations were modeled in the assessment and resolving questions about some inconsistencies and gaps. Dr. Toro concluded by summarizing that: (1) both areal source zones and local faults are important at high frequencies; (2) the Death Valley and Furnace Creek faults are the dominant contributor to hazard at lower frequencies; (3) the modeling of synchronous rupture scenarios for local faults is important; and (4) overall uncertainty is in the. typical expected range for the analyses.

Next, Dr. Coppersmith reviewed the significant aspects of the key issues discussed during the workshop including: (1) the areal source zone for Yucca Mountain (the host zone); (2) M_{max} on local faults; (3) slip rate and recurrence on local faults; (4) synchronous rupture models for local faults; and (5) M_{max} and recurrence on the Death Valley-Furnace Creek fault system. He reminded the teams that they needed to provide guidance to the Calculations Team on focal depth distributions.

After the break, Dr. Youngs presented preliminary results for four of the teams' fault displacement evaluations. He grouped the methodologies into two types: point estimate methods (including the DFS and RYA Teams), and principal-distributed faulting models (including the ASM & AAR Teams). For each team, he reviewed the input, presented hazard curves for test points 2 and 8a, and discussed the results. During his presentation, assumptions about the models were clarified and questions about various aspects of the input were resolved. Of particular concern was the assumption in some cases that, given an event on a seismogenic fault, the probability of triggered slip was assumed to be 1, which can yield too high of slip rates and total slip on secondary features. Dr. Fridrich also pointed out why he believes much of secondary faulting occurred between 12.7 and 11.6 Ma, when the primary faults first formed and had the greatest amount of movement. There was also discussion about how slip rate may be dependent on fault size, changing and perhaps decreasing with time as faults grow in size and can store more strain energy.

After lunch, Dr. Coppersmith asked for discussion about whether the team's assessments would vary if they were used for a 100-year versus a 10,000-year time frame. Possible changes included using time-dependent models, increasing uncertainties, and increasing smoothing of historical seismicity in areal source zones. Dr. Barnard then provided an overview of how the PSHA results may be used in the upcoming Total System Performance Assessment being conducted by DOE. He explained that scenarios for both volcanism and tectonism were required to analyze the impact on canisters and the consequences in terms of radionuclide release from: (1) earthquake ground motions and fault displacements; (2) the combination of seismic and volcanic events; and (3) the changes in hydrology and groundwater flow resulting from seismic and volcanic events. The performance assessors will be using results from the PSHA to judge the probability of occurrence of such scenarios over 10,000-year, to 100,000-year, to multiple-100,0000 year periods.

Next, Carl Stepp gave the experts guidance, from a regulatory perspective, on the documentation required in their elicitation summaries so that their assessments will be complete. He also discussed the revised schedule, which would allow more time for the experts to develop their fault displacement methodologies and evaluate the methodologies used by others. He said to provide more feedback and interaction on fault displacement methodologies, another one-day workshop would be scheduled for early June. The date would depend on the availability of the experts, and additional funds would be provided for associated travel costs and time.

After the break, Dr. Coppersmith and Norm Abrahamson initiated the joint session between the Ground Motion and SSC Experts. For the benefit of the Ground Motion Panel, Dr. Coppersmith reviewed the SSC issues that were covered over the last three days, emphasizing questions particularly relevant to the ground motion issues. Dr. Abrahamson prefaced his overview with the caveat that much of the SSC models are generalized by the ground motion experts to develop their source models. He then reviewed key aspects of the ground motion characterization, including: types of faults considered, magnitudes and distances that calculations were done for, the ground motion parameters calculated, and how the special cases of detachment faults and synchronous (multiple) rupture of local faults were modeled. Discussion among the panel members centered around what, if any, additional parameters the SSC experts might need to provide (such as directivity of rupture, sense of slip, and primary versus secondary rupture planes for multiple fault ruptures), and if model simplifications made by the ground motion experts were reasonable and most appropriate given the actual geologic conditions at Yucca Mountain. In regard to the latter, the geometries of detachments and synchronous ruptures of multiple local faults were of particular interest. Some discrepancies between the panels' characterizations were also highlighted, such as ground-motions models only extended to a depth of 14 km, but many SSC characterizations included deeper seismogenic depths (as deep as 22 km).

Finally, Dr. Coppersmith asked for comments from observers. Dr. Reiter commented that it would be useful to learn from experts what might occur down the road (new data or event) that would cause them to change their assessment. Responses included: (1) the occurrence of a large earthquake on a low-angle detachment anywhere worldwide; (2) occurrence of observable non-tectonic slip on local faults; (3) occurrence of a Cedar Mountain-type earthquake at Yucca Mountain; (4) obtaining additional along-strike slip data for the Solitario and/or Paintbrush Canyon faults; and (5) obtaining definitive data on deep, downdip fault geometry. Dr. Ibrahim asked how much weight was given to each of the two seismic line interpretations and how it affected their analyses. The consensus response was that the differences between the interpretations did not impact the analyses, generally because more recent markers were used to characterize rates of activity on the Ghost Dance fault. Finally, Art McGarr provided an overview of how to calculate static stress drop and insights about triggered slip from studies of mines in South Africa. Dr. Coppersmith adjourned the workshop at about 4:30 pm.

TABLE 1. YUCCA MOUNTAIN SEISMIC SOURCE CHARACTERIZATION

WORKSHOP #5 - FEEDBACK

April 14-16, 1997

Attendance List

Name	**Affiliation**
1. Ake, Jon	U.S. Bureau of Reclamation (USBR)
2. Allen, Clarence	Nuclear Waste Technical Review Board (NWTRB)
3. Anderson, Ernie	U.S. Geological Survey (USGS)
4. Anderson, Larry	USBR
5. Arabasz, Walter	University of Utah (UU)
6. Barnard, Ralston	Sandia National Laboratory
7. Bruhn, Ron	UU
8. Brune, James	UNR
9. Coppersmith, Kevin	Geomatrix Consultants
10. Cornell, Allin	Consultant
11. dePolo, Craig	University of Nevada, Reno (UNR)
12. Doser, Diane	University of Texas, El Paso
13. Fridrich, Chris	USGS
14. Golos, Joyce	USGS
15. Hanks, Tom	USGS
16. Harrington, Charles	Los Alamos National Laboratory
17. Hinze, William	Advisory Committee on Nuclear Waste
18. Ibrahim, Bakr	U.S. Nuclear Regulatory Commission (NRC)
19. Justus, Phil	NRC
20. King, Jerry	M&O/SAIC
21. Knuepfer, Peter	State University of New York at Binghamton
22. Lui, Christiana	NRC
23. McCalpin, Jim	GEO-HAZ Consulting, Inc.
24. McGuire, Robin	Risk Engineering
25. O'Leary, Dennis	USGS
26. Olig, Susan	Woodward-Clyde Federal Services (WCFS)
27. Parks, Bruce	USGS
28. Penn, Sue	WCFS
29. Perman, Roseanne	Geomatrix Consultants
30. Pezzopane, Silvio	USGS
31. Pomeroy, Paul	Advisory Committee on Nuclear Waste

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April 14-16, 1997

Attendance List

Name	Affiliation
32. Quittmeyer, Richard	WCFS
33. Ramelli, Alan	UNR
34. Reiter, Leon	NWTRB
35. Rogers, Al	GeoRisk Associates, Inc.
36. Savino, John	Golder Associates
37. Savy, Jean	Lawrence Livermore National Laboratory
38. Schwartz, David	USGS
39. Sheaffer, Patricia	USGS
40. Slemmons, Burt	WCFS
41. Smith, Ken	UNR
42. Smith, Robert	UU
43. Soeder, Daniel	USGS
44. Stamatakos, John	Center for Nuclear Waste Regulatory Analyses
45. Stepp, Carl	WCFS
46. Stuckless, John	USGS
47. Sullivan, Tim	DOE
48. Swan, Bert	Geomatrix Consultants
49. Toro, Gabe	Risk Engineering
50. Whitney, John	USGS
51. Wong, Ivan	WCFS
52. Youngs, Robert	Geomatrix Consultants
53. Yount, Jim	UNR
54. Zurflueh, Ernest	NRC

Civilian Radioactive Waste Management System
Management & Operating Contractor

Summary of Seismic Source Characterization Fault Displacement Workshop

SSC Workshop 6

Salt Lake City, Utah
June 3, 1997

Prepared for:

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INTRODUCTION

The U.S. Geological Survey (USGS) is carrying out a probabilistic seismic hazards analysis (PSHA) for Yucca Mountain, Nevada as part of the Department of Energy's (DOE) project to characterize this site as a potential geologic repository for high-level radioactive waste. This study was initiated in April 1995 and resumed in June 1996. The aim of the analysis is to provide the annual frequency with which various levels of vibratory ground motion and fault displacement will be exceeded at the site. These results will be used as a basis for developing seismic design inputs and in assessing the waste isolation and containment performance of the site.

The PSHA involves development by two panels of experts of input interpretations and assessments of uncertainties required by the hazards calculations. One panel (consisting of six teams of three experts) addresses characterization of seismic sources and fault displacement, while the other (consisting of seven individual experts) deals with vibratory ground motion. Development of interpretations is being facilitated through a series of structured workshops to evaluate available data, to explore the range of interpretations allowed by the data, to examine critically the interpretations proposed by the experts, and to provide feedback on the implications of various interpretations for the seismic hazard at the site. This report summarizes the sixth workshop in the characterization of seismic sources and fault displacement: the Seismic Source Characterization (SSC) Fault Displacement Workshop.

This workshop addressed the various fault displacement evaluation approaches of the SSC experts' teams. The purpose of the workshop was threefold: (1) to review and discuss alternative methods and models for assessing fault displacement; (2) to discuss uncertainties in parameter values and models; and (3) to facilitate the expert teams' discussion of the pros and cons of alternative approaches, models and submodels. Prior to the workshop, a working paper summarizing the fault displacement evaluation approaches developed by the SSC teams was distributed to the SSC experts. During the workshop, the alternative approaches taken by each team to evaluate displacement at the nine demonstration points were reviewed in more detail. This was followed by extensive open discussion and technical challenge about the strengths and weaknesses of all of the alternative approaches, data required to apply them, and uncertainties in model parameters.

The workshop agenda is included as Attachment 1. Copies of overhead transparencies shown by presenters and additional material distributed during the workshop are included as Attachment 2. Table 1 is a list of participants and their affiliations.

TUESDAY, JUNE 3, 1997

Kevin Coppersmith opened the workshop with an introduction, describing the purpose and approach for the one-day meeting. He reviewed the workshop ground rules and the key characteristics of the nine demonstration points chosen for analysis of the fault displacement hazard.

Next, Robert Youngs explained the purpose of the fault displacement working paper that was sent out for review before the workshop, and he distributed revised copies of the paper with some minor corrections (see Attachment 2). He emphasized that, as a summary of the alternative approaches being used by the expert teams, the paper was intended to provide the teams with a common understanding of the approaches. He also emphasized that the teams needed to consider and evaluate all the available tools in developing their final fault displacement assessments. He reiterated the input needed, the basic hazard formulation, what the final hazard curves portray, and definitions for various terms. This initiated extensive discussion about the meaning and use of "triggered" slip; it was generally agreed that this term may be problematic for describing distributed slip that occurs on secondary faults associated with (geologically coeval to) principal faulting (where principal faulting is seismogenic slip on the fault with the primary moment-release during an earthquake).

Dr. Youngs then discussed each component of the various approaches in more detail, elaborating with specific examples from the team's assessments and making comparisons between various models and submodels. Throughout his presentation, there was extensive discussion, and experts often contributed responses, explanations, and comments about their individual assessments. Of particular interest were the methods used for estimating displacement event frequency and average displacement per event at locations where faults or fractures are present in Tertiary rocks, but Quaternary paleoseismic data is lacking. Frank (Bert) Swan described how his team estimated recurrence intervals when fault-specific paleoseismic data was lacking and Ronald Bruhn explained how his team used data from the Exploratory Studies Facility (ESF) to constrain curves relating fault length and cumulative displacement. Extensive discussion also focused on the use of data from historical surface-faulting events to develop relations for the likelihood of distributive faulting.

After a break, Dr. Youngs continued his presentation, describing two approaches to estimating the probability of a displacement exceeding a given value, given that a displacement event had occurred. He emphasized that variability in fault slip has two components: along-strike, and event to event variations. Dr. Swan, Alan Ramelli, and James Yount all discussed how they had used displacement data to characterize both types of variations for Yucca Mountain faults. James McCalpin described his fault displacement curves, derived from averaging slip along five normal surface-faulting events in the western

U.S. Dr. Bruhn described how he simulated generic displacement profiles using fault roughness characterized by the fractal dimension of the fault. Using typical earthquake recurrence models, such as characteristic and truncated exponential distributions, to characterize variability between displacement events was also discussed. Throughout the discussion, the strengths and weaknesses of each approach were explored by the expert teams, particularly in regard to applying the approaches to site-specific conditions at Yucca Mountain.

Next, Dr. Youngs described how one team had used geodetic data from the 1983 Borah Peak earthquake to estimate the potential for distributive faulting at a given distance from a principal fault at Yucca Mountain. Next, Robert Smith described a somewhat similar approach his team was considering that assumes that the distribution of distributive faulting is related to the strain energy, which is proportional to the second derivative of the strain measured from geodetic data. James Brune pointed out that this model assumes that secondary strains trigger secondary faulting, whereas ground shaking may actually be the cause of secondary faulting. John Stuckless asked how differences in lithologies and mechanical behavior were being considered. Dr. McCalpin responded that this was difficult to address with the available data and Dr. Coppersmith suggested that uncertainties should be used to incorporate possible lithologic effects.

After lunch, Dr. Coppersmith initiated discussion about application of the various fault displacement tools to evaluate the hazard at specific points in the Controlled Area of Yucca Mountain. Point #2 on the Solitario Canyon fault, representing a point along a principal block-bounding fault, was the first discussed (for point locations see Attachment 2, Figure 2 in "Summary of Fault Displacement Hazard Methodologies Developed for the Yucca Mountain Site"). The experts discussed what approaches were available for estimating the frequency and amount of displacement given the conditions and available data for the Solitario Canyon fault. They also talked about the weightings they would assign to these approaches and why. Preference was generally voiced for using methods based on Quaternary paleoseismic data that was as site-specific as possible whenever it was available. Dr. Swan commented how the variability in displacement along strike of the Stage Coach Road and Paintbrush Canyon faults was similar to the variability in displacement among events for all the faults. Finally, the treatment of uncertainties was discussed, and Dr. Youngs clarified that experts needed to include the probability that a rupture of a certain magnitude reaches the surface in their assessment.

The next group of demonstration points discussed were those on various intrablock faults, including points #3 through #6. These points are on Tertiary bedrock faults where Quaternary paleoseismic data is generally lacking and so available evaluation methods are more limited and indirect. Methods for estimating displacement frequency were evaluated and discussed, such as how teams addressed the problems in applying the slip-rate approach when the parameters may have significantly changed as the fault and tectonic regime have evolved through time. The weighting of potential activity was also discussed, including consideration of the slip-tendency of faults in the present stress regime. The advantages and disadvantages of using distributive fault models were also discussed. Dr. Bruhn then described one model his team is considering in which the probability of damage and displacement is assumed to be a function of peak particle velocity at a point. He discussed general constraints on displacement probability provided by observations in underground mining studies. Dr. Brune then urged the experts to consider that the recent stress differences determined from hydrofracture tests implied that appropriately-oriented normal faults at Yucca Mountain may be on the verge of slipping.

Characterizing the frequency and amount of displacement on fractures with no measurable displacement was discussed next. Some experts commented that defendably estimating displacements on such small features is at or beyond the limit of resolution of available data and knowledge, considering the likely small size of the displacement events. Other experts commented that if a fracture showed no measurable offset in 12 million-year-old rock, the probability it would slip in the future was so low as to be negligible in the analysis. Different properties and likely behavior of different types of fractures (such as cooling, tension, shear, open, and sealed) were discussed, along with approaches used to constrain upper bounds of frequency and amounts of slip.

Next, Tim Sullivan provided an update on the ESF excavation. He stated that the tunnel boring machine reached the south portal on April 25, 1997 and provided preliminary cross-sections showing the stratigraphy and larger faults in the last part of the tunnel. Next, John Whitney showed a video of the exposure of the Ghost Dance fault at Alcove #6 in the ESF. He also distributed a one-page summary on the exposure. The exposure revealed a 0.6- to 1.0-m-wide breccia zone with isotropic fabric. There was no apparent mineralization, marker horizons, shear fabric, slickensides or other kinematric indicators. Fracture density did increase significantly within 4 m of the zone, especially in the hanging wall. The west edge of the zone appeared more open and less coherent; otherwise, there was no other evidence of repeated or different age movements. Dr. Whitney pointed out that despite the paleoseismic evidence for three to four late-Quaternary surface-faulting events on nearby faults, there is no evidence for associated secondary slip on the Ghost Dance fault. After the video, Mr. Sullivan explained that DOE plans to excavate another drift next year that will trend southeast from the ESF, intersecting the Solitario Canyon fault. The purpose of the drift is to get a better sample of the repository block to confirm constructability and investigate hydrologic parameters.

Dr. Coppersmith then gave a wrap-up presentation, discussing the process of integrating assessments, documentation requirements, and the upcoming schedule. He then reviewed the importance of the expert's elicitation summaries and described how these reports need to be complete and clearly present the logic used in developing their assessments. He discussed the key components of the summaries in detail and answered questions about the summaries and schedule.

Next, Tim Sullivan thanked the experts for their hard work on the project and assured them that results would be put to full use in upcoming performance assessments and facility design. Dr. Coppersmith added his thanks to the experts, Review Panel, and Management Team. He then asked for comments from observers. Richard Parizek urged the Management Team to get information on the project and results out into the technical community quickly. Leon Reiter asked how may experts changed their views on detachment faults as a result of discussions during the SSC workshops; the general response was interpretations had not changed significantly. The workshop was adjourned at 4:45 pm.

TABLE 1. YUCCA MOUNTAIN SEISMIC SOURCE CHARACTERIZATION

WORKSHOP #6 - FAULT DISPLACEMENT

June 3, 1997

Attendance List

Name	Affiliation
1. Ake, Jon	U.S. Bureau of Reclamation (USBR)
2. Allen, Clarence	Nuclear Waste Technical Review Board (NWTRB)
3. Anderson, Ernie	U.S. Geological Survey (USGS)
4. Anderson, Larry	USBR
5. Arabasz, Walter	University of Utah (UU)
6. Bruhn, Ron	UU
7. Brune, James	University of Nevada, Reno (UNR)
8. Coppersmith, Kevin	Geomatrix Consultants
9. dePolo, Craig	UNR
10. Doser, Diane	University of Texas, El Paso
11. Harrington, Charles	Los Alamos National Laboratory
12. Hinze, William	Advisory Committee on Nuclear Waste
13. Justus, Phil	U.S. Nuclear Regulatory Commission
14. King, Jerry	M&O/SAIC
15. Knuepfer, Peter	State University of New York at Binghamton
16. McCalpin, Jim	GEO-HAZ Consulting, Inc.
17. Nelson, Priscilla	NWTRB
18. O'Leary, Dennis	USGS
19. Olig, Susan	Woodward-Clyde Federal Services (WCFS)
20. Parizek, Richard	NWTRB
21. Parks, Bruce	USGS
22. Penn, Sue	WCFS
23. Perman, Roseanne	Geomatrix Consultants
24. Pezzopane, Silvio	USGS
25. Quittmeyer, Richard	WCFS
26. Ramelli, Alan	UNR
27. Reiter, Leon	NWTRB
28. Rogers, Al	GeoRisk Associates, Inc.
29. Savy, Jean	Lawrence Livermore National Laboratory
30. Schwartz, David	USGS
31. Slemmons, Burt	WCFS
32. Smith, Ken	UNR

TABLE 1. YUCCA MOUNTAIN SEISMIC SOURCE CHARACTERIZATION

WORKSHOP #6 - FAULT DISPLACEMENT

June 3, 1997

Attendance List

Name	Affiliation
33. Smith, Robert	UU
34. Soeder, Daniel	USGS
35. Stamatakos, John	Center for Nuclear Waste Regulatory Analyses
36. Stepp, Carl	WCFS
37. Stuckless, John	USGS
38. Sullivan, Tim	DOE
39. Swan, Bert	Geomatrix Consultants
40. Toro, Gabe	Risk Engineering
41. Whitney, John	USGS
42. Wong, Ivan	WCFS
43. Youngs, Robert	Geomatrix Consultants
44. Yount, Jim	UNR

Civilian Radioactive Waste Management System
Management & Operating Contractor

Probabilistic Seismic Hazard Analyses
Final Results Meeting

Las Vegas, Nevada
April 6, 1998

Prepared for:

U.S. Geological Survey
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April 27, 1998

INTRODUCTION

The U.S. Geological Survey (USGS) recently completed a probabilistic seismic hazard analysis (PSHA) for Yucca Mountain, Nevada, as part of the Department of Energy's (DOE's) project to characterize this site as a potential geologic repository for high-level radioactive waste. The aim of the analysis is to provide the annual frequency with which various levels of vibratory ground motion and fault displacement will be exceeded at the site. These results will be used as a basis for developing seismic design inputs and for assessing the waste isolation and containment performance of the site.

This summary describes the last meeting of project team members and observers, at which the final results of the project were presented. Members of the project management team outlined the PSHA project and described the major results in seven presentations. Three additional presentations described how the results of the PSHA are being used for seismic design inputs and are being incorporated into the total system performance assessment (TSPA) for the Yucca Mountain project. The two panels of experts who provided interpretations and assessments of uncertainties for the PSHA (the seismic source and fault displacement [SSFD] panel and the ground motion panel) attended the meeting, as did the four-member Review Panel.

The workshop agenda is included as Attachment 1. Copies of overhead transparencies shown by presenters and material distributed at the workshop are included as Attachment 2. Table 1 is a list of participants and their affiliations.

MONDAY, APRIL 6, 1998

Tim Sullivan opened the meeting by welcoming participants. He noted that members of the two expert panels were interspersed in the audience (in contrast to previous meetings, where the focus of the meeting was on the panel members seated at the front of the room). He also noted that the audience included representatives of the Nuclear Regulatory Commission (NRC), Nuclear Waste Technical Review Board, and the Affected Units of Government. He stated that the objective of the meeting was to review the results of the PSHA study.

Carl Stepp reviewed the agenda for the meeting. He described the overall PSHA project objective to assess probabilistic hazards of ground shaking and fault displacement for determining design bases for preclosure ground shaking and fault displacement, and for assessing post-closure waste isolation and containment. He described the process followed in the study, including the formal selection of experts and the formal process for developing expert evaluations, including workshops, facilitation meetings, and feedback to all expert panel members. He discussed the guidance documents followed for the study, including NRC regulation 10CFR60, NRC staff technical positions, and the Senior Seismic Hazard Analysis Committee (SSHAC) guidance. He noted that the project emphasized equal weighting of the expert interpretations both in the expert selection and in implementation of the elicitation process.

In the second presentation, John Whitney gave a project history of the Yucca Mountain site studies and an overview of the activities performed for the USGS tectonics program and the publications produced. The USGS will place all USGS reports referred to in the PSHA in an open-file, digital format that will be available to the general public. It is anticipated that the PSHA will have USGS Director's approval for publication by this summer, and will be available for distribution as a CD ROM late in 1998. Dr. Whitney closed his presentation by thanking the many individuals who participated in the PSHA project, noting that the project was a good example of how government agencies, academic institutions, and other organizations can work together.

Kevin Coppersmith, the technical leader for the seismic source characterization and fault displacement (SSFD) activities, summarized the seismic source models developed by the six SSFD expert teams to assess vibratory ground motion and fault displacement hazards at the site. He briefly described the tectonic models considered by all of the teams, the types of seismic sources included, and the characterization of the source parameters for the various types of sources considered. He emphasized that each team considered the range of seismic sources that have been postulated (e.g., seismogenic detachment faults, volcanic sources, regional and buried strike-slip faults, and various structural and behavioral models for local fault sources). In this overview, he highlighted the similarities as well as differences in the way alternative models were treated by the various teams and showed comparison recurrence curves for the different types of sources and for all sources across the various teams.

Norm Abrahamson, the technical leader for ground motion characterization, followed with a summary of the methods, models, and estimates developed by the ground motion characterization panel members. Dr. Abrahamson reviewed key aspects of the ground motion characterization, including: types of seismic sources considered (magnitudes and distances used in calculations, and how the special cases of detachment faults and synchronous (multiple) rupture of local faults were modeled); site conditions (including the estimate for kappa and location of reference rock outcrop at the repository elevation with the top 300 m stripped off); and the expert estimates for median, aleatory variability, epistemic uncertainty in the median, and epistemic uncertainty in aleatory variability. He noted that there generally was more variability in the epistemic uncertainty than the aleatory uncertainty expressed by the panel member's estimates. He noted that the Facilitation Team conducted the calculations of attenuation relations to enable the experts to focus on the weights for different models and results. He presented evaluations for epistemic uncertainty (sigma -mu) as a function of rupture distance; examples of median attenuation of horizontal peak ground acceleration (PGA) and T=1.0 sec spectral acceleration that showed the greatest variability at close distances; and examples of aleatory variability in PGA and epistemic uncertainty in median horizontal and vertical PGA. He also showed a viewgraph for approximate scale factors (not presented in the PSHA report) to estimate ground motions at a point on the ground surface 300 m above the proposed repository elevation, that could be constructed from data in the PSHA report.

Gabriel Toro then summarized the hazard results for ground motion related to the following topics: methodology, the integrated results for all SSFD teams, de-aggregation of hazard, comparisons across SSFD teams, sensitivity results for each SSFD team, and sensitivity results for ground-motion experts. The de-aggregation of hazard by magnitude-distance-epsilon shows that the most important contributors to hazard for high-frequency motions (e.g., 10 Hz) are the Paintbrush Canyon and Solitario Canyon faults (or coalesced systems containing one or both of these faults) and the host area source. For longer-period motion (1 to 2Hz), the Death Valley/Furnace Creek fault source also is important. The results of the mean hazard show that although there was great variety in the models developed by the different teams, there was not a large difference in the mean PGA (horizontal). In general the sensitivity results by the SSFD team showed that recurrence parameters (slip rate, recurrence interval, and recurrence model) were the most significant contributors to uncertainty, and that detachments and buried strike-slip faults contributed little to total hazard.

Robert Youngs summarized the models and approaches used to characterize fault displacement hazard at the site, noting the large effort required because of the relatively undeveloped state of fault displacement hazard analysis. He started by defining displacement hazard terminology and describing the basic hazard formulation, then showed an example of a fault displacement hazard curve. Next he described the two approaches to faulting hazard used by the teams for both principal faulting and distributed faulting: the displacement approach and the earthquake approach. He discussed in more detail each component of the two approaches, elaborating with examples from the team's assessments and comparing various models and submodels. The presentation ended with a discussion of the application of the team's models to nine demonstration points selected to represent the range of conditions that may be encountered. Dr. Youngs noted that more complete descriptions of the team's assessments were provided in tables distributed in the handout package.

After a lunch break, Gabriel Toro gave the first presentation of the afternoon with a discussion of results of the fault displacement analyses. He started with a general description of the methodology and demonstration sites. He then presented integrated results from all sites, comparisons across SSFD teams for all sites, and selected sensitivity results. He noted that the mean hazard results for sites 1 and 2, which lie on recognized faults, were fairly consistent among the teams. There is considerably wider scatter in the results for sites 3 through 9, none of which are located along principal faults. This difference is expected given the greater uncertainty in evaluating the likely small size of such distributed surface rupture events. At the end of Dr. Toro's presentation there was discussion about the sites included in the demonstration points; Buck Ibrahim commented on the large difference between the median and mean results for some demonstration points and questioned the implications for the hazard results; and Peter Kneupfer noted that information regarding Quaternary displacement and activity had significant impact on the assessments.

Robin McGuire next presented an overview of the development of seismic design inputs. He began by presenting flow charts that showed: (1) the steps in preparing seismic design inputs and the appropriate reference documents that define procedures and/or input data (i.e., Topical Reports and the PSHA report); and (2) the roles of the expert panels in preparing input for seismic hazard analysis. He showed a schematic diagram of the repository vicinity, indicating points at which ground motions are calculated. He noted that the ground motions calculated for free field rock conditions at the repository elevation (Point A) should not change, but ground motions at Points B and C can be revised as new data and information on the properties of rocks in the 300 m above the repository become available. He presented results of uniform hazard spectra (UHS) for horizontal and vertical motions at the reference rock outcrop (Point A). Based on the results of the PSHA vibratory ground motion assessment for a 10^{-4}-year exceedance frequency, two design events were determined—a M6.3 at a distance of 5 km, and a M7.7 at a distance of 52 km. Dr. McGuire then discussed the sensitivity of the ground motion results to the velocity models for the upper 300 m of tuff overburden, and showed results for the horizontal design spectra for the repository interface (Point B) and at the top of the tuff overburden (Point C) for both design events for 10^{-4}- and 10^{-3}-year exceedance frequencies. His summary of the fault displacement hazard results for design consideration focussed on two sites (2 and 7a) that are most significant to the site. He noted that the finite displacement hazard at 1E-05 at site 2 on the Solitario Canyon fault would have to be considered in design. In contrast, the results for site 7a indicate that fault displacement hazard will not have to be considered in design. He concluded with a table summarizing the calculated displacements for identified faults for 10^{-4}- and 10^{-5}-year exceedance frequencies. Following Dr. McGuire's presentation was a discussion of the procedures followed to obtain the seismic design inputs and how they will be used.

Rick Nolting provided an overview of the use of the seismic design inputs in both subsurface and surface design. Design data from the PSHA included vibratory ground motions, fault displacement hazard curves, and dynamic strain assessments. He presented revised values for ground motion inputs currently being used in design. Both quasi-static and dynamic analyses are being used. For fault displacement hazard, the primary approach will be to avoid faults. Where this cannot be reasonably achieved, structures are being designed based on hazard values that are an order of magnitude more conservative than for vibratory ground motions. Some types of structures that will cross the Bow Ridge and Solitario Canyon faults (e.g., the North Ramp) should be designed to accommodate displacements of 12 cm and 30 cm, respectively; other structures will not need to be designed for fault displacement. Where faults are crossed, contingency requirements will be employed for maintenance and repair. Dr. Nolting next discussed dynamic strain, noting that dynamic strains and curvatures are given as a function of depth. In his discussion of the use of seismic data for surface design, he listed structural design inputs that include soil/rock foundation investigations, ground/structure interaction dynamic analysis, FEM static and dynamic analyses, and combined load cases. As an example, for the Waste Handling Building (the most important surface facility at the site), the structural flexibility, roof slab design, and equipment design (e.g., overhead crane and equipment anchorages) are being analyzed. Dr. Nolting answered questions from observers on design values and how they would be used for specific facilities.

Next Ralston Barnard summarized the seismic disturbance calculations being conducted for the TSPA-VA. He noted that the PSHA results were being used to model rockfall, faulting (both inside and outside the repository), alterations of groundwater flow near the repository, and seismically induced transient rises in water-table. He focussed on the rockfall analysis, which includes thermo-mechanical as well as seismic triggering events. He noted that modeling being conducted by John Kemeny updates an Electric Power Research Institute model with current site data and PSHA results. Faulting hazard is not expected to have any direct PA impact on waste-package disruption if backfill is used. Potential alterations in groundwater flow path and head structure resulting from faulting outside the repository block are being considered. Questions from observers led to further discussion of disturbed events scenarios, such as the rock fall analysis, and their use in the TSPA.

Carl Stepp then summarized the project's plan for evaluating new data in accordance with regulatory requirements for the various phases of repository design, licensing, construction, and emplacement of the waste. He requested that PSHA project participants send new information that may be relevant to Ivan Wong, the designated responsible PSHA project person. He noted that when new data are determined to be potentially relevant, sensitivity analysis will be performed to assess the impact on the PSHA results, and the results of these analyses will be made part of the annual reporting. Also, the PSHA documentation will be updated as required by regulations to provide complete information for various license applications. He then summarized uses of the PSHA results, which include development of values for preclosure seismic design bases ground shaking and fault displacement; input to waste isolation and containment performance assessment; and input to the Safety Analysis Report supporting the application for a construction license.

Carl Stepp then opened the meeting to comments from the audience and to general discussion. Clarence Allen requested comments on the recent *Science* article by B. Wernicke *et al.* (Vol. 279, March 27, 1998). Dr. Stepp noted that there are several lines of evidence for strain rates in the Great Basin and that new interpretations must be considered in that context. John Whitney summarized the primary results of the study, which suggest that a strain rate of ~1 mm/yr, an order of magnitude greater than geologic slip rates. He noted that the USGS (through Jim Savage and his group) is preparing a formal written response to this paper that notes issues relating to: the small number of monuments, the dependence of the results on a single monument, monument stability, Jim Brune's calculated moment from the Little Skull Mountain earthquake and the need to examine aseismic aftereffects of this earthquake, recent work that shows increased strain rates across the Wasatch fault zone in Utah, basic research questions about what this strain means, and evidence of high velocity material under Crater Flat. He noted that the USGS is considering plans to rerun the Global Positioning System (GPS) network (which will include a station on Bear Mountain), rerun a vertical levelling line, conduct a Synthetic Aperature Radar Interferometry analysis, and/or install laser strain monuments.

Jim Brune noted that the historical seismicity strain rate based on summing the moments of historical seismicity is minimal. Tests should be designed to see whether this is a transient effect related to the Little Skull Mountain earthquake. He also noted that Wernicke *et al.* (1998) did not mention evidence for high velocity under Crater Flat as recently reported by G. Bias.

Frank Perry stated that the postulated order-of-magnitude increase in the volcanic hazard as implied by the article was simplistic. He noted that Lathrop Wells, the most recent event in the region, occurred 80 ka ago, and that the tectonic setting of the region to the south was more active than the repository site. Tom Hanks noted that the expert teams heard about Wernicke's preliminary data at an earlier PSHA project workshop. At that time, the movement was largely confined to one station, with little movement indicated by the other stations.

The NRC was asked about their view of the Wernicke *et al.* paper. Phil Justus replied that in light of the investigations John Whitney mentioned the USGS is considering, new data that may be obtained will be to the benefit of the project. The NRC agrees that the Wernicke *et al.* observations may be explained by the hypothesis presented in their paper. He noted that any scientific paper that presents anomalous data will receive attention. He was gratified by the ability of the PSHA to address new data and hypotheses, stating that this project is unique in that it has pioneered a process to deal with such situations. He offered congratulations on the completion of the PSHA Final Report and stated that the NRC will independently evaluate and scrutinize the data. Dr. Justus noted that there is a high likelihood of questions, comments, and future interactions. He questioned how disruption event scenarios and insights from these analyses will be included in the TSPA-VA. During the rest of this fiscal year, the NRC will use the PSHA to resolve as many issues as possible, although many issues may not be resolved this year. Next fiscal year they will prepare written responses to seismic issues. He noted that a guidance document for PSHA (CFR Part 60) will be revised.

Leon Reiter commented that he hoped the final report for the PSHA will be clear and readable enough to be suitable to a range of audiences. He presented the following questions/comments to the audience: (1) it would be useful to receive comments on the Wernicke article from expert panel members, as well as from the CNWRA who reviewed it prior to publication; (2) he would like to hear from Review Panel members regarding their views of the PSHA process; (3) he questioned why peak ground motion values developed by Ivan Wong and others for an early study for the Exploratory Studies Facility (ESF) were lower than the values derived during the PSHA project; and (4) he questioned Carl Stepp's earlier statement that expert panel members hold sole ownership of their results, which is inconsistent with the position of the Senior Seismic Hazard Analysis Committee (SSHAC) that ownership should be shared with the technical facilitator/integrator (TFI) for the project.

In response to the fourth question, Carl Stepp stated that there had been considerable discussion of this issue at the beginning of the project; it had been decided that sole ownership by the experts was needed to sustain the integrity of the interpretations for NRC licensing purposes. Kevin Coppersmith noted that the TFIs maintain ownership in the process/procedures, but the expert panel members independently own their interpretations. Bob Budnitz stated that the SSHAC process considers ownership to reside in two places: the experts own their own interpretations, and the aggregate results are owned by the individuals who developed the algorithms for the analysis. Dr. Coppersmith stated that the goal throughout the project was to apply equal weights to all experts, and that he was prepared to defend this process.

In response to Dr. Reiter's first question, Bob Smith discussed the differences between the data and results for geodetic strain measured across the Wasatch Fault in Utah (many instruments were installed throughout a large area) and the data for the Yucca Mountain region presented in the Wernicke *et al.* article. He noted that although the Utah results also show strain rates higher than the seismologic- or geologic-based rates, the data are based on two independent determinations (GPS as well as triangulation and trilateration data). He noted that the results are a measure of an integrated effect with depth and that the question remains whether to distribute that strain aseismically or to assign it to faults. Such data provide a new source of information for areas having low strain rates, but the networks must be monitored for longer periods to obtain sufficient data to verify the anomalous rates, particularly in such a low-slip environment. Dr. Reiter asked whether the experts would have modified their models if the Wernicke *et al.* article had been published earlier. Dr. Smith responded that the data are so sparse that they probably would not make much difference, but without performing an analysis he could not say how the data would affect loading.

In response to Dr. Reiter's third comment, Ivan Wong noted that a very simple model was used to characterize local faults in the ESF study. The principal difference in ground motion values for the ESF study and the PSHA is that the kappa for the ESF study was based on empirical data from California. If the value of kappa used in the PSHA was applied in the ESF study, ground motion values would increase by approximately 40 percent, consistent with the values obtained from the PSHA. Norm Abrahamson noted that the derivation of kappa for the PSHA included information from the Little Skull Mountain earthquake.

Next John Stamatakos summarized the CNWRA review of the Wernicke *et al.* paper. He noted that Dr. Wernicke's research had been supported in part by the CNWRA, but that it was considered an independent study. The CNWRA had two GPS reviewers look at the data and calculations of errors; they were not asked to comment on the hypotheses themselves. Wernicke and others responded to the comments made by these reviewers, as well as the reviewers for *Science*. The CNWRA staff have since looked in more detail at the hypotheses presented in the published paper, and plan to submit a written response to *Science*. Dr.

Stamatakos reiterated the point made by Phil Justus that it is important that new hypotheses are put forth and challenged.

As a member of the Review Panel, David Schwartz made the following statements. He noted that the process of completing the PSHA project was interesting, but that more time was needed. He stated that seismic source characterization was relatively straightforward, and that there is a robust history to that part of the analysis. The fault displacement analysis, however, was a large and difficult undertaking that required venturing into new territory. He noted the site's complexity in the low degree of fault activity, small displacements, and complex rupture patterns. Given the data and time available, he believes the experts provided a good "first cut" at characterizing fault displacement potential for hazard assessment. He also addressed the readability of the report, stating that it could be improved so that the document would be more useful to the general public.

Allin Cornell commented that he believed the probabilistic analyses went well. He sees the fault displacement analysis as ground-breaking work that was conducted in a credible manner, with results that reflect broad uncertainty but low values. He noted that the process followed the SSHAC methodology, emphasizing the importance of experts adopting an evaluator role, and that the team approach smoothed out the edges of individual expertise and provided more robust results. He commended the TFIs (Kevin Coppersmith and Norm Abrahamson) for their efforts and noted that they were willing to address potential difficulties (such as significant outlier positions) that might have arisen. Fortunately, such problems did not arise, and equal weighting was appropriate. Dr. Stepp commented that he agreed with Drs. Coppersmith and Budnitz about ownership of the process and defense of the equal weights assigned to team assessments, but stressed again the importance of the expert's ownership of their evaluations. Dr. Abrahamson added that the process of feedback and technical challenge eliminated significant outlying positions and contributed to the success of the project.

Tom Hanks noted that staggering quantities of data were brought to the attention of the experts and that these data were successfully incorporated into manageable and coherent results. He noted that available data were generally well understood, and that new data and interpretations (e.g., inputs to kappa; the Wernicke *et al.* paper) would be dealt with by the project as they become available. He also noted that the results of the PSHA can be constructed from the information contained in the final report, having confirmed for himself that it is not necessary to use a computer to verify the results of the study.

In his summary statements, Jim Brune, expressed agreement with the general comments of the three other Review Panel members. He stated that because he and the other reviewers were involved in the entire PSHA process, they likely would find the final report more readable than would an outsider. He added that he had looked at the expert's interpretations of fault physics and concluded that they are reasonable. However, he believes that some of the final results are too conservative when projected to the surface, based primarily on his analysis of unstable rocks in the region.

Carl Stepp closed the meeting by acknowledging the tremendous work of all the project participants, specifically noting the contributions of Ivan Wong in managing the project schedule and Sue Penn in organizing workshops and maintaining project communication. Tim Sullivan added his thanks to all, and expressed his enthusiasm that the project was complete. The meeting was adjourned by Carl Stepp.

ATTACHMENT 1

YUCCA MOUNTAIN PSHA FINAL RESULTS MEETING
Monday, April 6, 1998, AmeriSuites Hotel, Las Vegas

Final Agenda

Times	Topic	Speaker
from 6:00 am	Continental Breakfast (free to overnight guests; $6/person otherwise)	
8:30 to 8:35	Introduction	Tim Sullivan
8:35 to 8:50	Project Overview (Process and Roles, Structure of this Meeting)	Carl Stepp
8:50 to 9:00	Project Reports	John Whitney
9:00 to 9:30	Seismic Source Characterization	Kevin Coppersmith
9:30 to 10:00	Ground Motion Characterization	Norm Abrahamson
10:00 to 10:15	Break	
10:15 to 11:15	Ground Motion Hazard Results	Gabe Toro
11:15 to 11:45	Fault Displacement Characterization	Bob Youngs
11:45 - 1:00	Lunch	
1:00 to 2:00	Fault Displacement Hazard Results	Gabe Toro
2:00 to 2:30	Overview of Seismic Design Inputs Development	Robin McGuire
2:30 to 3:00	Use of Seismic Inputs in Design	Rick Nolting
3:00 to 3:15	Break	
3:15 to 3:45	Use of Seismic Hazard Results in PA	Ralston Barnard/George Barr
3:45 to 4:15	Where Do We Go From Here (New data issue, Seismic Topical Report #3)	Carl Stepp
4:15 to 5:00	Comments from Observers	
5:00	Closing Remarks	Tim Sullivan/Carl Stepp

TABLE 1. YUCCA MOUNTAIN PROBABILISTIC SEISMIC HAZARDS ANALYSES FINAL RESULTS MEETING

April 6, 1998

Attendance List

Name	Affiliation
1. Abrahamson, Norm	Consultant
2. Ake, Jon	U.S. Bureau of Reclamation (USBR)
3. Allen, Clarence	California Institute of Technology
4. Anderson, Ernie	U.S. Geological Survey (USGS)
5. Anderson, John	University of Nevada, Reno (UNR)
6. Anderson, Larry	USBR
7. Arabasz, Walter	University of Utah (UU)
8. Barnard, Ralston	Sandia National Laboratory (SNL)
9. Becker, Ann	Woodward-Clyde Federal Services (WCFS)
10. Bruhn, Ron	UU
11. Brune, James	UNR
12. Burnitz, Roby	--
13. Campbell, Ken	EQE International
14. Chen, Rui	Southwest Research Institute
15. Coppersmith, Kevin	Geomatrix
16. Cornell, Allin	Consultant
17. dePolo, Craig	UNR
18. Duan, Fei	Morrison-Knudsen
19. Dunn, Tom	Morrison-Knudsen
20. Echols, Stan	Winston & Strawn
21. Firth, Jim	U.S. Nuclear Regulatory Commission (NRC)
22. Fridrich, Chris	USGS
23. Frishman, Steve	State of Nevada
24. Gamble, Bob	Booz, Allen & Hamilton
25. Gil, April	U.S. Department of Energy (DOE)
26. Glenn, Chad	NRC
27. Greenberg, Harris	MTS/S&W
28. Gregor, Nick	Consultant
29. Hanks, Tom	USGS
30. Hanson, Kathryn	Geomatrix Consultants

TABLE 1. YUCCA MOUNTAIN PROBABILISTIC SEISMIC HAZARDS ANALYSES FINAL RESULTS MEETING

April 6, 1998

Attendance List

Name	Affiliation
31. Hawe, Tim	DOE
32. Ibrahim, Bakr	NRC
33. Justus, Phil	NRC
34. Knuepfer, Peter	State University of New York at Binghamton
35. McCalpin, Jim	GEO-HAZ Consulting, Inc.
36. McGuire, Robin	Risk Engineering
37. McKague, Larry	Center for Nuclear Waste Regulatory Analyses (CNWRA)
38. Menges, Chris	USGS
39. Nataraja, Mysore	NRC
40. Nolting, Rick	Morrison-Knudsen
41. O'Leary, Dennis	USGS
42. Orvis, Doug	Morrison-Knudsen
43. Parks, Bruce	USGS
44. Penn, Sue	WCFS
45. Perman, Roseanne	Geomatrix
46. Pezzopane, Silvio	USGS
47. Quittmeyer, Richard	WCFS
48. Ramelli, Alan	UNR
49. Reiter, Leon	Nuclear Waste Technical Review Board
50. Rogers, Al	EQE International
51. Savy, Jean	Lawrence Livermore National Laboratory
52. Schwartz, David	USGS
53. Seddon, Bill	DOE
54. Sheaffer, Patricia	Pacific Western Technologies
55. Slemmons, Burt	WCFS
56. Smith, Ken	UNR
57. Smith, Robert	UU
58. Somerville, Paul	WCFS
59. Stamatakos, John	CNWRA
60. Stellavato, Nick	Nye County, NV
61. Stepp, Carl	WCFS

TABLE 1. YUCCA MOUNTAIN PROBABILISTIC SEISMIC HAZARDS ANALYSES
FINAL RESULTS MEETING
April 6, 1998
Attendance List

Name	**Affiliation**
62. Sullivan, Tim	DOE
63. Swan, Bert	Geomatrix
64. Toro, Gabe	Risk Engineering
65. Tynan, Mark	State of Nevada
66. von Tiesenhausen, Engelbrecht	Clark County Nuclear Waste Division
67. Walck, Marianne	Sandia National Laboratory
68. Whitney, John	USGS
69. Wong, Ivan	WCFS
70. Yount, Jim	Geomatrix
71. Yount, Jim	USGS

APPENDIX D

SUMMARIES OF GROUND MOTION WORKSHOPS

SUMMARIES OF GROUND MOTION WORKSHOPS

Civilian Radioactive Waste Management System
Management & Operating Contractor

Summary of Data Needs Workshop on Ground Motion at Yucca Mountain

Salt Lake City, UT
April 20 and 21, 1995

May 25, 1995

Prepared for

U. S. Geological Survey
Box 25046, MS-425
Denver Federal Center
Denver, CO 80225

Prepared by

Woodward-Clyde Federal Services of
Civilian Radioactive Waste Management System
Management & Operating Contractor
101 Convention Center Drive
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Under Contract Number
DE-AC01-91RW00134

INTRODUCTION

The United States Geological Survey (USGS) is carrying out a probabilistic seismic hazards analysis (PSHA) Yucca Mountain, Nevada as part of the Department of Energy's (DOE) project to characterize this site as a potential geologic repository for high-level radioactive waste. The aim of this study is to provide the annual probability with which various levels of vibratory ground motion and fault displacement will be exceeded at the site. These results will be used as a basis for developing seismic design inputs and in assessing the performance of the site.

The PSHA process involves development by two panels of experts of input interpretations and assessments of uncertainties required by the hazards calculations. One panel addresses characterization of seismic sources and fault displacement, while the other deals with vibratory ground motion. Development of interpretations is being facilitated through a series of structured workshops to evaluate available data, to explore the range of interpretations allowed by the data, to examine critically the interpretations proposed by the experts, and to provide feedback on the implications of various interpretations for the seismic hazard at the site. The goal of this process is to have differences in experts' interpretations be the results of true differences in judgment and not differences in access to data, differences in definition, or differences resulting from a lack of understanding each others' interpretations. This report summarizes the first in the series of structured workshops for characterization of ground motion: the Data Needs Workshop.

The Workshop began with introductory comments including an overview of the DOE's Yucca Mountain project and specifically the PSHA project. Team experts were next briefed on several issues of relevance to the ground motion characterization and existing data bases. This information provided the grounds for a discussion by the experts of additional data required to perform a comprehensive assessment of ground motion attenuation at Yucca Mountain. Each speaker has provided a brief summary of his presentation. These summaries and copies of overhead transparencies are included as an Attachment to this Summary.

The Workshop was attended by a representative of the DOE, Tim Sullivan, and the Project Management Team, John Whitney, Carl Stepp, Ivan Wong, and Jean Savy All Ground Motion Team experts were present: John Anderson, David Boore, Kenneth Campbell, Art McGarr, Walter Silva, Paul Somerville, and Marianne Walck. Members of the Ground Motion Facilitation Team in attendance were Norman Abrahamson, Ann Becker, and John Schneider. Several members of other Teams organized for the PSHA project were also present: James Brune, Allin Cornell, and Tom Hanks (Project Oversight Panel), Robin McGuire and Richard Quittmeyer (Seismic Design Basis Team), Gabriel Toro (PSHA Calculations Team), and Mary-Margaret Coates (Data Management).

THURSDAY, APRIL 20, 1995

Introductory comments were made by Tim Sullivan, Carl Stepp, and Norman Abrahamson. The DOE Yucca Mountain Project (YMP), its objectives and background, the proposed facilities, and the project regulatory framework were summarized by Tim Sullivan. The PSHA study will consider surface ground motions on a hypothetical rock outcrop and surface ground motions on the alluvium in Midway Valley. Ground motions at the repository depth will not be considered in this study. Results of the study will be described in a report that will form part of the last in a series of three Topical Reports regarding the seismic assessment of Yucca Mountain. The Topical Report is scheduled for release in FY 1997. The findings are primarily to address the preclosure period (100 yrs), but will also be used to evaluate the postclosure (10,000 yrs) performance of the site. As outlined by Carl Stepp, the primary goal of the PSHA study is to provide input to development of seismic design parameters. The project objectives necessarily include documenting the process for regulatory review. An essential technical element is the incorporation of scientific uncertainty. This will be accomplished by considering the interpretations of a group of individual experts who will themselves incorporate uncertainty in their individual hypotheses. Norman Abrahamson, the Ground Motion Facilitation Team Leader, detailed the criteria for selection of the ground motion experts and the criteria for participation in the project. The experts must be "evaluators" of the various ground motion models. He emphasized that failure to act in a manner consistent with the criteria, particularly the endorsement of any single ground motion model without due consideration of other models would be unacceptable to the required role of evaluator expert. Dr. Abrahamson also itemized the ground motion estimates which are required for the analysis (see attached statement) and summarized the results of a preliminary assessment of the Exploratory Studies Facility as a point of reference to the PSHA project.

Because the experts must incorporate uncertainty in their ground motion predictions, the means by which uncertainty is characterized were discussed (Gabriel Toro). Total variability is composed of uncertainty and randomness, each of which can be partitioned into parametric or modeling variability. Several examples of the partitioning were cited and explained. The practical implications of large and small uncertainties were also presented and the tradeoffs inherent in categorizing uncertainty.

The elicitation process and experts' roles within the process were laid out (Jean Savy). Consensus among the experts is <u>not</u> the aim of the process. Although each expert must ultimately act as an evaluator of all models, each may also be asked to function as a proponent of a particular model in subsequent Workshops for the benefit of the other experts. Each is responsible for forming, defending, and documenting his final ground motion estimates. The project schedule was presented and the formal elicitations are planned for February and March of 1996.

The remaining briefings on the first day covered various technical issues and available seismologic data. Silvio Pezzopane discussed the tectonic and seismologic setting. He shoed known and suspected Quaternary faults and provided a comprehensive table summarizing their characteristics. A second table listed a preliminary evaluation of "relevant" (DOE specification) and Type I (U. S. Nuclear Regulatory Commission specification) faults. Data on source parameters, crustal structure (velocity profiles) and attenuation (Q), and site effects were summarized by John Schneider. Variations in stress drop and Q were noted in the results of various studies. Within 5 to 10 km of the planned repository, a variety of geophysical data are available and two current studies will provide information local to the site. The DOE is measuring velocities in several bore holes in the immediate vicinity to depths of 1500 ft and the USGS is evaluating shallow and deep crustal profiles from a seismic refraction and reflection survey. Walter Silva summarized the effect of site conditions on spectra using empirical and theoretical data. The latter were also used to illustrate the potential influence of the uncertainty in the site properties as compared to the potential influence of variability of source properties in terms of the resulting variability of the ground motion.

A key set of seismological data near Yucca Mountain was recorded in the 29 June 1992 Little Skull Mountain main shock (m_b 5.6) and aftershock sequence (Kenneth Smith). The data shown include focal mechanisms and depth sections of aftershocks. Main shock accelerograms were recorded at an array maintained by URS/John A. Blume & Associates for the DOE with epicentral distances of 15 km to 232 km from the main shock. Records are also available from portable arrays of instruments deployed by the USGS and the University of Nevada-Reno (UNR) for the aftershock sequence. A second data set was obtained from the 1993 Rock Valley sequence and an event in Rock Valley triggered by the Little Skull Mountain (LSM) earthquake. This set includes focal mechanisms, event locations, and seismograms. Site response in Midway Valley and Yucca Mountain was assessed by UNR (John Anderson) using a number of earthquakes. Kappa and relative site amplification (as a function of frequency) were estimated at 12 stations from the LSM main shock and various other earthquakes.

Site response effects were also examined by Marianne Walck using underground nuclear explosion (UNE) data. The UNE data indicate strong azimuthal dependence on amplification. The more relevant data were recorded at various sites since 1977. These data have been evaluated for 2-dimensional crustal structure to explain the amplification and transfer functions have been developed for three uphole/downhole station pairs within about 3 m of the perimeter of the planned repository.

The special case of near fault ground motions was presented by Paul Somerville. Few earthquake data are available within about 5 to 10 km a fault rupture. Empirical and synthetic data show a levelling off of ground motion in these distances. Other issues summarized include the effects of rupture directivity, the difference between vertical and horizontal spectra shapes, and the effect of the style of faulting.

The final presentation was a quality assurance (QA) training by Martha Mustard. The experts were briefed on the project QA requirements for which the overriding philosophy is that the level of QA detail must ensure the reproducibility of the results. The expert elicitation process is currently being incorporated into a QA procedure.

FRIDAY, APRIL 21, 1995

There are two current USGS projects with direct relevance to the ground motion methodology activities. The first activity, described by Paul Spudich, is to evaluate empirical ground shaking models for extensional tectonic regimes. Currently the USGS is assembling a worldwide data set from normal and strike-slip faulting in these regions. The goal is to first evaluate several empirical attenuation relationships and, if they do not adequately describe the data, to develop correction factors for the relationships or alternatively produce a new relationship based on the extensional data. The evaluation of existing relationships should be completed by October, 1995. The second activity is the ground motion modeling of scenario earthquakes at Yucca Mountain. John Schneider outlined the project which is aimed at estimating ground motion (response spectra and time histories) with uncertainty for six realistic earthquake faulting scenarios. Six different modeling methods will be used. These procedures will first be calibrated against the Little Skull Mountain records.

The existing ground motion estimation methods were then reviewed by Norman Abrahamson. They comprise empirical (earthquake and underground nuclear blast data), numerical, and hybrid empirical-numerical schemes. The input required by each model was summarized and it was noted that some additional work is needed to determine the appropriate source parameters for the different models (particularly, the numerical simulation models).

DATA NEEDS

Throughout the Workshop, the Team discussed various technical issues which must be resolved and data which are required for a thorough assessment of the ground motion estimates. Following the last formal presentation, Dr. Abrahamson led a discussion summarizing the issues which must be resolved. Six principle issues were identified for further study and were prioritized as to importance by the experts. Most of the Issues are self-explanatory and arise from a lack of detailed information or from a need to further evaluate an available data set. The issues are:

Issue 1: What are the site response characteristics specific to Yucca Mountain?

Issue 2: What is the range of values of source parameters for earthquakes in this region of the Basin and Range? (These are model dependent.)

Issue 3: What is the explanation for the apparent aseismic slip in the uppermost few kilometers of crust for earthquakes with rupture that reaches the surface?

Issue 4: What is the Yucca Mountain specific ground motion attenuation predicted by various numerical ground motion simulations?

Issue 5: What is the basis for apparent discrepancies in the literature regarding regional attenuation (combined effect of Q and geometrical spreading)?

Issue 6: What is the explanation for the reported large amplification of motions at Yucca Mountain compared to other NTS sites?

Issues 1, 2, and 6 will be satisfied by obtaining new data or evaluating existing data. Issue 3 arises from Workshop discussions regarding numerical modeling procedures. Numerical models are typically implemented with no slip assigned to the uppermost few kilometers of the rupture surface. This assumption is attributed to two possible physical constraints which the Team believes must be investigated: either low shear modulus characterizes materials in this zone or a long source rise time. Numerical simulations specific to the proposed repository conditions (Issue 4) will be used by the experts to evaluate ground motion predictions by the various models and methods. An investigation into regional attenuation (Issue 5) is required to resolve conflicting research results on geometrical spreading and Q.

During their deliberation, the experts identified data or analyses required to resolve these issues. These specific Data Needs are discussed in detail below and are summarized in Table D-1.

Site Response

To evaluate the site response requires the shear wave velocity profile on rock and alluvium (Midway Valley). Ideally, this profile should extend to 1500' depth, but shallower profiles will also be useful.

In addition to the low strain velocity profiles, standard geotechnical information, in terms of strain dependence of the shear modulus and damping, are also needed for both rock and alluvium.

Action:
Summarize the existing velocity profile and high strain data and identify additional data collection and/or analyses that are needed. These data needs will be addressed by the DOE through their existing program.

Source Parameters

The main source parameter required for numerical simulation models is the stress-drop. The "stress-drop", however, has different meanings for the different models. For example, the stochastic needs the "high frequency stress-parameter" whereas the composite source model needs the sub-event stress-drop.

A key event is the Little Skull Mountain earthquake because it was located close to Yucca Mountain. Because these data are so important, they require special attention including a site visit to determine the geologic site conditions.

Action:
Estimate the distribution (mean and standard deviation) of the stress-drop appropriate for each model appropriate for the Basin and Range using the USGS extensional data stet as well as the aftershocks of the Little Skull Mountain and Rock Valley earthquakes. Some of this work will be done as part of the ground motion scenario earthquake exercise being run by the USGS or as part of the ground motion studies by UNR. the stress-drop for the stochastic point source model will not be addressed by these other studies and needs to be developed as part of the PSHA study.

Aseismic Shallow Slip

The faulting at Yucca Mountain clearly shows that the fault ruptures to the surface, however, if large surface slip is used with the current numerical models, they drastically overpredict the high frequency ground motion near the fault as well as produce large long period surface waves. Because these effects have not been observed in empirical recordings close to faults with shallow slip, users of the models have interpreted the shallow slip to be aseismic. By not modeling the observed shallow slip, the numerical simulation models appear to be deficient. The models have not considered using long rise-times for shallow slip which may help resolve this apparent deficiency. The impact of the shallow rupture has been partially considered in the recent Southern California Earthquake Consortium (SCEC) study. These results will be summarized in a SCEC report in June 1995. Additional insight can be gained by a detailed study of the few earthquakes that have had significant shallow slip as well as nearby recordings on rock. Two events that meet these criteria are the 1987 superstition Hills and 1992 Landers earthquakes.

Action:
Perform a sensitivity study to determine the range of rise-times for shallow slip that can be used and still give reasonable agreement with the recorded data. This will provide a means for including the shallow slip without generating unrealistic ground motions. This work may be performed as part of the scenario ground motion study.

Numerical simulations

Because there is little strong motion data in the Basin and Range, and in particular at Yucca Mountain, numerical simulations will be used to provide the experts with region- and site-specific estimates of the ground motion attenuation.

The stochastic point source should be run at all magnitudes and distances for which the experts will be asked to predict the ground motion. The stochastic point source will serve as a reference model and is selected for this purpose because it is simple and well understood by the experts.

Because the site is located close to the faults, finite-source models should also be used to estimate the ground motion for the larger magnitudes (M 6-7). The following models should be considered:

Stochastic finite-fault model
Composite source model
Empirical source function model
Hybrid empirical model

All of these models except for the hybrid empirical are being used as part of the scenario ground motion study to predict the ground motion for magnitude 6.4 normal faulting events and magnitude 7.0 strike-slip faults. this study will not consider magnitude 7.0 normal faulting events.

Action:
Compare ground motions for the following cases:

Stochastic point source model for magnitudes 5 to 7 for distances of 1 to 100 km
Finite-fault model for a magnitude 7 normal faulting event for distances less than 10 km

Regional Attenuation

Different studies have come to apparently inconsistent conclusions about Q (inelastic attenuation) in the Basin and Range. Some structures have found lower attenuation than in California whereas other studies have found similar attenuation as in California. some of this discrepancy may be due to different assumptions about the geometrical spreading. Because the net attenuation of ground motion depends on both the Q and the geometrical spreading, there is a trade-off between these two parameters.

Action
Compare the net attenuation (combined effect of Q and geometrical spreading) for the different studies to determine if the results are really inconsistent.

Yucca Mountain Site Amplification

Previous studies by Sandia have found anomalously large site amplification at Yucca Mountain from UNE data. However, this anomalous amplification may result only from shallow sources (such as explosions) and may not be applicable to ground motions from earthquakes that tend to be from much greater depths. UNR has recorded several aftershocks of the Little Skull Mountain and Rock Valley earthquakes that can be used to estimate the site response for earthquakes. UNR is already developing site-response estimates for this data set.

<u>Action</u>
Evaluate the Sandia study (Philips) and determine if the results are applicable to the earthquake ground motions at Yucca Mountain.

Identify the geologic site conditions for the strong motion stations that recorded the Little Skull Mountain earthquake. This task will be addressed by the DOE/USGS.

TABLE D-1
GROUND MOTION ESTIMATION DATA NEEDS

ISSUE 1: SITE RESPONSE CHARACTERISTICS

Data Needed:
Site profile information
Shear velocity of rock and soil (geophysical)
Geotechnical properties (soil and rock)

ISSUE 2: SOURCE PARAMETERS

Data Needed:
Evaluate distribution of stress drop (for each model)
Main shocks and significant aftershocks (USGS data)
Aftershocks (Little Skull Mountain and rock Valley earthquakes)
(Site conditions for Little Skull Mountain main shock recordings)

ISSUE 3: NON-SEISMOGENIC SHALLOW SLIP

Data Needed:
Evaluate research related to effects of shallow slip
SCEC summary
Detailed study of Superstition Hills and Landers (Lucerne records) earthquakes

ISSUE 4: NUMERICAL SIMULATIONS

Data Needed:
Perform numerical simulations
Stochastic point source model (set as reference; run for all distance-magnitude pairs)
Stochastic finite fault model (run for distances less than 10 km at magnitude 7)
Composite source model (run for distances less than 10 km at magnitude 7)
Empirical source function model (run for distances less than 10 km at magnitude 7)
Hybrid empirical model (run for distances less than 10 km at magnitudes 6.4 ant)

ISSUE 5: REGIONAL ATTENUATION

Data Needed:
Investigate regional attenuation (existing studies and new data)
Methodological differences in studies on geometrical attenuation and Q?
Investigate Little Skull Mountain data (require instrument site conditions, kappa, processing)

ISSUE 6: YUCCA MOUNTAIN AMPLIFICATION

Data Needed:
Compare additional data with previous study
Summary of amplitude variation with distance for blast data and earthquakes (M>3) from
Upgraded UNR network data
Summary of Little Skull Mountain amplitude variation with distance
Evaluate Sandia study (Phillips) for applicability

Civilian Radioactive Waste Management System
Management & Operating Contractor

Summary of Methods, Models, and Preliminary Interpretations Workshop on Ground Motion at Yucca Mountain

Salt Lake City, UT
January 9 and 10, 1997

Prepared for

U. S. Geological Survey
Box 25046, MS-425
Denver Federal Center
Denver, CO 80225

Prepared by

Woodward-Clyde Federal Services of
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101 Convention Center Drive
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Las Vegas, NV 89109

February 4, 1997

INTRODUCTION

The United States Geological Survey (USGS) is currently performing a probabilistic seismic hazards analysis (PSHA) of the proposed high-level radioactive waste repository at Yucca Mountain, Nevada. The study is an element of the Department of Energy's (DOE) site characterization activities. The PSHA will result in the annual probability of exceedance of various levels of vibratory ground motion and fault displacement.

Input to the PSHA is being developed by two panels of experts: one characterizes seismic sources and fault displacement and the second estimates vibratory ground motion. Their interpretations are being facilitated in a series of structured workshops. The goal of the process is to have differences in experts' interpretations result from true differences in judgment and not differences in access to data, definition, or lack of full understanding of each other's interpretations. This report summarizes the second in the series of workshops for characterizing ground motion: the Methods, Models, and Preliminary Interpretations Workshop.

The Workshop proceedings included discussions of Yucca Mountain and site-specific issues as they relate to ground motion modeling. An understanding of these issues is necessary to evaluate whether and to what extent existing models of ground motion may require modification to adequately estimate motions at the proposed repository. Several models have been developed or revised since the first Workshop (Data Needs, April 1995) and these were presented in detail. Finally, results of a preliminary modeling exercise (posed to the Experts in advance of the Workshop) was discussed. Each speaker provided copies of presentation materials and these are included as an Attachment to this Summary.

The Workshop was attended by a representative of the DOE, Tim Sullivan, and members of the Project Management Team, John Whitney, Carl Stepp, Ivan Wong, and Richard Quittmeyer. All Ground Motion Team Experts were present: John Anderson, David Boore, Kenneth Campbell, Art McGarr, Walter Silva, Paul Somerville, and Marianne Walck. Members of the Ground Motion Facilitation Team in attendance were: Norman Abrahamson and Ann Becker. Also present were Robin McGuire, Seismic Design Team Leader; Gabriel Toro, PSHA Calculations Team Leader; and Review Panel members Allin Cornell, Tom Hanks, and James Brune. Technical Observers included representatives from the NRC, NWTRB, ACNW, and the CNWRA.

THURSDAY, JANUARY 9, 1997

The full scope of the Experts' involvement was detailed by Norman Abrahamson, the Ground Motion Facilitation Team Leader. They must develop ground motions as a series of point estimates for specified magnitudes and source - site geometries. Both strike-slip faulting on a vertical surface and normal slip on a moderately dipping fault are to be considered. The site is representative rock with dynamic properties equivalent to the existing conditions at repository level (called "repository outcrop"). The repository outcrop is based on the velocity profile with the top 300 m removed. Horizontal and vertical motions will be estimated for peak ground acceleration, peak ground velocity, and spectral acceleration at frequencies of 0.5, 1, 2, 5, 10, and 20 Hz. The Experts must document in detail the reasoning underlying their interpretations. The median ground motion, aleatory uncertainty, and the epistemic uncertainties of both are to be provided. The importance of quantifying uncertainty was discussed in the context of the elicitation process by an expert in these techniques (Peter Morris, Wednesday joint session with Seismic Source Characterization Team). This was elaborated on (Gabriel Toro, Thursday) and the partitioning of uncertainty as parametric or modeling and (orthogonally) as aleatory or epistemic was discussed. Several relevant examples of the partitioning as it relates to ground motion modeling were presented to thoroughly inform the Experts of the process.

A fundamental question which the Experts must address is whether ground motions at Yucca Mountain differ from the motions represented by the data set which forms the basis for empirical models. Differences could be caused by source effects (extensional vs. compressional regimes and normal vs. strike-slip faulting), path effects (crustal differences), or site effects (site response). It was shown that significant differences in near fault ground motions for normal and reverse faults are observed in foam rubber models (James Brune). The propagating wavefront in dip-slip faulting is greatly affected by normal stresses. In reverse faulting, the surface reflected wave is dilatational and reduces normal stress on the slip surface. Foam rubber models show the reflected wave destabilizes the fault and results in increased particle motions in the hanging wall and at the fault tip. In normal faulting, the reflected wave is compressional, which stabilizes the fault and results in weak motions. Additionally, weak surficial layers were shown to significantly reduce the ground motion from near-surface slip due to increased rise-time. This supports ground motion modeling experience which consistently shows reduced high frequency motion radiated from near-surface layers.

The USGS (Paul Spudich) has compiled a data base of strong ground motion records in extensional tectonic regimes. The criteria for inclusion were that the data were: (1) available in digital form; (2) recorded in the free field or in structures less than 3 stories high; (3) triggered before the S-wave arrival; (4) resulted from earthquakes with moment magnitude at least 5; and (5) recorded at distances no greater than 105 km. Nine normal faulting events in the data base were inverted for stress drop and kappa using a Brune ω^2 spectral form with a single corner frequency (Ann Becker). The median stress drop was about 30 bars for several cases using site transfer functions developed by Silva and about 60 bars using site transfer functions by Boore and Joyner. The median kappa obtained was about 0.04 to 0.06 sec for all sites and the inversion results confirmed that the Little Skull Mountain recording sites have particularly low kappas (about 0.015 sec). This compares with stress drops for western North American events of 70 to 100 bars (Boore-Joyner, using Boore-Joyner amplifications) and for six California earthquakes of about 37 bars (Silva, using Silva's amplifications).

The faults in the Yucca Mountain region are generally characterized by low slip rates. However, slip rate has not been included in regressions of fault length on magnitude (John Anderson). Comparisons between regressions including and excluding slip rate show that ignoring slip rate may underestimate the magnitude. Or, for a given rupture length, larger earthquakes occur on faults with lower slip rates than on faults with high rates implying a larger static stress drop for low slip-rate faults. Anderson also presented the composite source model and showed how it can be used to estimate energy and several stress parameters. The key stress parameters for ground motion are dynamic stress drops, not the static stress drop. Anderson noted that lower ground motions from extensional regimes can be modeled by lower than average dynamic stress drops even if the static stress drop is larger than average. Anderson also briefly summarized the Dinar, Turkey M 6.4 normal faulting earthquake (1 Oct 1995) which caused surface rupture. Records were obtained at close distances to the fault plane and an analysis of the event has been initiated. The results should be available in February.

Site response issues were discussed in terms of measured nonlinear response of tuff samples obtained from Yucca Mountain (Kenneth Stokoe). Resonant column and dynamic torsional shear testing was performed on two welded and one unwelded tuff specimens. The specimens are not homogeneous and results of the resonant column testing are robust whereas the torsional shear tests are less so. The modulus degradation with increasing shear strain is less nonlinear than granular samples, but the low-strain modulus is significantly greater than granular soils. Similarly, material damping is low. Measured low-strain shear wave velocities are 4200, 5800, and 8100 fps (1300, 1800, 2500 m/sec) for the unwelded and welded tuffs, much greater than the approximately 600 m/sec measured in-situ (Schneider et al., Ground Motion Modeling of Scenario Earthquakes at Yucca Mountain, Final Report for Activity 8.3.1.17.3).

The effect of source, site, and regional crustal differences was evaluated using the point-source Band-Limited-White-Noise (BLWN) source model combined with Random Vibration Theory (RVT) (Kenneth Campbell). Ratios of synthetic motions (horizontal motion; response spectra ratios) for California- and Yucca Mountain-type sites showed the largest sensitivity to site kappa at frequencies higher than about 10 Hz and to stress drop at all frequencies. Regional effects other than event stress drop also cause significant amplification at high frequency for Yucca Mountain-type sites. At high frequencies, significant differences between Campbell's results and a similar analysis by Silva were noted. These differences were primarily due to different site amplifications models developed by Boore and Silva. Differences in Q models also contributed to the differences. Campbell and Silva are working to resolve these differences.

The empirical data base at Yucca Mountain consists of data recorded from underground nuclear tests. The records have been interpreted by Walck (Workshop #1) for two-dimensional crustal structure. The very shallow blasts result in large surface waves. There are also unusual wave propagation effects observed at some locations in NTS (not Yucca Mountain) which are not well understood (Paul Somerville). Confined shallow sources, such as the blasts, are not common in large earthquakes so the variability from typical earthquake depths may be much less than observed in the blast data.

Existing empirical relationships were next examined. The USGS extensional regime study (Paul Spudich) focused on calculating correction factors for empirical relations to better fit the extensional data, and on developing a new predictive relation derived from the extensional data. The factors include a bias correction and a standard deviation correction for all distances and also for distances less than 20 km. Many of the factors show a period dependence. Spudich also presented the new attenuation relation developed using extensional regime data only. This model should be applicable to Yucca Mountain without changes to the source.

FRIDAY, JANUARY 10, 1997

The second day of the Workshop continued with discussions of proponent models arising from empirical data. The Abrahamson and Silva (1996) relationship was not available at the time of the USGS study; style-of-faulting modification factors were provided (Norman Abrahamson) as well as a discussion of the regression procedure.

An advantage to numerical simulations is the ability to modify input parameters to evaluate the sensitivity of ground motions to the parameters (and thus uncertainties) and compute scaling factors. Walter Silva presented results using the point source RVT model, and Kenneth Campbell for the hybrid empirical model. (The attached notes for Dr. Silva's presentation are not complete; much of his work was performed under separate contract to the DOE and was not authorized for release in print form.) Silva has calibrated the point source model using data from 16 earthquakes. This calibration exercise also provides estimates of the modeling uncertainty term. Silva's point source model will be presented to the experts with variable stress-drop so the experts can select their own estimate of the stress drop in applying the model.

Campbell's approach is to estimate ground motions by scaling existing empirical relationships. He develops the scaling factors from comparisons of California motion estimates to Yucca Mountain motion estimates, both developed using the BLWN RVT point source model. The examples he presented correspond to a postulated M 6.5 earthquake at 10 km distance and considered both strike-slip and normal faulting. The correction factors for peak ground acceleration were presented for three discrete values of stress drop and ranged from 1.053 to 1.832. Campbell will provide a complete set of estimates for other magnitudes, distances, and periods as part of his proponent model.

A third class of proponent models arises from the blast data base consisting of thousands of recordings at NTS (T. Joseph Bennett). Three alternative methods were presented for defining the attenuation relationship using information from the blast data. The first model uses the NTS data directly with a conversion from explosion yield to earthquake magnitude. The second model uses the attenuation rates from the blast data but with the spectral shape defined by California empirical attenuation models. This second method addresses the issue of different spectral content in explosions and earthquakes. The third method uses the attenuation rate from explosions but with a spectral shape from the Little Skull Mt. earthquake.

Because of the lack of an empirical earthquake ground motion data base at Yucca Mountain, the relevance and applicability of numerical models was the focus of the USGS report Ground Motion Modeling of Scenario Earthquakes at Yucca Mountain (J. F. Schneider *et al.*, WCFS, written communicaiton, 1996). Predictions from six methods were included in the study (Abrahamson) which covered the range of modeling methods commonly used in ground motion estimation. In the Scenario exercise, the investigators calibrated their models to data recorded in the 1992 Little Skull Mountain event and then computed motions for scenario earthquakes occurring on tectonic sources which could potentially affect Yucca Mountain. The suite of scenario earthquakes consist of five normal faulting sources and two strike-slip. The simulated motions for the normal faulting case were higher than attenuation relations derived from western U. S. data by about 60% at distances less than about 5 km and by about 20% at 15 km. The variation at short distance was attributed to differences in kappa and at longer distance due to crustal amplification and directivity. For the strike-slip event, the computed motions exceeded existing attenuation relationship predictions by about 30 % at 25 km, again attributed to kappa, but were consistent with predictions at 50 km distance.

Recent results from finite element modeling of a postulated rupture on the Bare Mountain fault beneath the repository region was presented (David Ferrill). The model assumes the regional faults are connected at depth along a subhorizontal detachment. Slip on an initially rupturing segment is transferred up-dip towards the surface and down-dip to the detachment. The modeling indicates that the rupture can trigger slip on other faults and result in higher accelerations than if it were confined to a single faulting surface. At distances approximating the location of the proposed repository, peak horizontal ground accelerations at the surface may exceed predicted values from empirical attenuation relationships by about 50%.

Although the Yucca Mountain region has not experienced a major earthquake in historic times, the western boundary of the Basin and Range has and clues to ground motion attenuation may be found in studies of the numerous precariously balanced rocks found region-wide (James Brune). The distance of balanced rocks from the ruptures combined with the acceleration required to topple these rocks provide physical evidence of the attenuation of motion surrounding an historic earthquake. This information is currently being collated to provide a constraint on ground motion attenuation in the region. Near the repository itself, balanced rocks could be toppled by about 0.3 g accelerations, and semiprecarious rocks by about 0.4 g. Age-dating the rock varnish indicates that they have been precariously positioned for about 40,000 to 80,000 years, suggesting a bound on these acceleration levels.

At the conclusion of the Workshop, the Experts presented trial estimates of median ground motion (and uncertainties) for a M 6.5 earthquake occurring 10 km from both strike-slip and normal faulting earthquakes. The purpose of this exercise was to familiarize the experts with the process and the form of the estimates that they will have to provide. Several of the experts only presented proponent models rather than evaluating the suite of alternative models. As a result there was a large variability in their estimates; their estimates of the median peak ground acceleration varied by about a factor of 2 for the strike-slip case, up to 3 for the hanging wall of the normal case, and over 3 for the footwall.

In the comments by observers, Jerry King indicated that the seismic design will include tall structures whose natural periods are beyond 1.0 sec. It was decided that this observation needed to be verified given the fact that the planned period range to be characterized by the Experts only went to 2.0 sec (0.5 Hz). Attached is a memorandum addressing this issue; the requested period range extends to 3.0 seconds.

Civilian Radioactive Waste Management System
Management & Operating Contractor

Summary of Feedback on Ground Motion Interpretations Workshop on Ground Motion Characterization at Yucca Mountain

Salt Lake City, UT
April 16, 17 and 18, 1997

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INTRODUCTION

The United States Geological Survey (USGS) is currently performing a probabilistic seismic hazards analysis (PSHA) of the proposed high-level radioactive waste repository at Yucca Mountain, Nevada. The study is an element of the Department of Energy's (DOE) site characterization activities. The PSHA will result in the annual probability of exceedance of various levels of vibratory ground motion and fault displacement.

Input to the PSHA is being developed by two panels of experts: one characterizes seismic sources and fault displacement and the second estimates vibratory ground motion. Their interpretations are being facilitated in a series of structured workshops. The goal of the process is to have differences in experts' interpretations result from true differences in judgment and not differences in access to data, definition, or lack of full understanding of each other's interpretations. This report summarizes the third in the series of workshops for characterizing ground motion: the Feedback on Ground Motion Interpretations Workshop.

The Workshop began with a joint session with the Seismic Source Characterization Team in which the preliminary models developed by each team were discussed. The remainder of the Workshop proceedings focused solely on the experts' preliminary ground motion interpretations and the proponent models on which they were based. Each speaker provided copies of presentation materials and these are included as an Attachment to this Summary.

The Workshop was attended by a representative of the DOE, Tim Sullivan, and members of the Project Management Team, John Whitney, Carl Stepp, Ivan Wong, Jean Savy, and Richard Quittmeyer. All Ground Motion Team Experts were present: John Anderson, David Boore, Kenneth Campbell, Art McGarr, Walter Silva, Paul Somerville, and Marianne Walck. Members of the Ground Motion Facilitation Team in attendance were Norman Abrahamson and Ann Becker. Also present were Robin McGuire, Seismic Design Team Leader; Gabriel Toro, PSHA Calculations Team Leader; and Review Panel members Allin Cornell, Tom Hanks, and James Brune. Technical Observers included representatives from the NRC, NWTRB, ACNW, and the CNWRA.

WEDNESDAY, APRIL 16, 1997

In this joint session held together with the Seismic Source Characterization Team, Kevin Coppersmith and Norman Abrahamson summarized the preliminary models developed by the experts. Although the source characterization teams are developing models with numerous fault geometries, the ground motion experts are developing motion estimates for specified fault geometries. These specified geometries are representations of 'average' geometries in the models, and fault geometry variation within a range is incorporated as added uncertainty in the motion estimates. Source characteristics which introduce additional uncertainty in the motion estimates include deviations from the specified fault dip and depth extent, multiple ruptures on parallel faults, and a subhorizontal detachment fault. The latter two faulting cases may deviate too far from the average models to be covered by aleatory variation. These cases were discussed subsequently during the 3-day meeting. The experts will develop simple scaling rules to make the models applicable to these multiple rupture cases.

THURSDAY, APRIL 17, 1997

Because the focus of the Workshop was feedback and discussion among the experts, the experts each outlined their approach to developing their ground motion estimates. Generally, most experts developed weighting schemes for the proponent models, applied the weights, and evaluated the output. Two experts used approaches different from the other five experts. Marianne Walck developed a method to identify outlier points within the proponent values and eliminated these from consideration. John Anderson implemented three schemes which he then weighted to develop estimates. In the first, he accommodated all relevant proponent models and developed a uniform distribution between the maxima and minima. In the second scheme he emphasized a preferred empirical proponent model, and in the third he emphasized a preferred numerical proponent model. Norman Abrahamson presented results of regression analyses on the experts' preliminary estimates and facilitated discussions of the regressed models.

Preliminary hazard computations were presented by Gabriel Toro. The computations were based on the preliminary models developed by the source characterization teams and the regressions based on the preliminary ground motion point estimates. Large magnitude earthquakes on distant faults dominate the hazard at long period and the contribution from faults and areal sources more local to the site dominates at all other periods. Significant hazard arises from multiple ruptures on parallel faults (faults which coalesce at depth) in those models which incorporate this style of rupture. In general, the results show that the largest contribution to uncertainty in the hazard is the uncertainty in the ground motion models.

Each of the experts employed some means of weighting mean values to compute their estimates. They developed several methods of combining weighted values and some developed different objective schemes to obtain weights, all of which were discussed. Because of the importance of uncertainty, its partitioning as epistemic or aleatory and as parametric or modeling was reiterated by Norman Abrahamson. A standard statistical procedure for evaluating the epistemic uncertainty was agreed to by the experts.

FRIDAY, APRIL 18, 1997

To facilitate comparisons between the individual experts' point estimates, Norman Abrahamson showed a series of plots of these estimates and the proponent model estimates on which they are based. For a given earthquake magnitude and distance, and at a given response frequency, the proponent model estimates are bimodally distributed. Empirical estimates are generally tightly grouped separately from the numerical estimates, which are less closely clustered. Because the experts weighted both empirical and numerical proponent estimates, in general their point estimates lie between the two distributions. The experts discussed differences in the numerical proponent models at length to determine if differences in modeling would require further adjustments (changes in weighting) in their point estimates.

James Brune summarized his study of precarious rocks. At four locations near large historic earthquakes, he computed the motion required to topple the rocks and compared it to motions for a magnitude 6.5 earthquake estimated by the experts. In general, the expert estimates exceeded the toppling motions suggesting that the estimates were in turn larger than the motions which actually had occurred. However, because the study evaluated only rocks which had not toppled, and not those which had, and because the effects of motion duration, frequency content, and location in a possible shadow zone could not be quantified in the case of the precarious rocks, the consensus of opinion among the experts was that it could not be incorporated in their studies in its current form.

Ann Becker updated work presented in Workshop #2 on stress drops in normal faulting earthquakes. The earlier computations were updated to include the Dinar, Turkey earthquake and the distance measure was revised to reflect the equivalent point source distance. The median stress drops are about 10 bars higher than those previously reported, largely due to the inclusion of the Dinar event.

Two sources have been defined by the seismic source characterization teams which are significantly different than the strike-slip and normal faulting cases the ground motion experts have evaluated. The two rupture scenarios are (1) multiple ruptures on parallel faults, perhaps coalescing at depth and (2) rupture on a low-angle detachment zone. The multiple rupture scenario has a large contribution to the hazard computation whereas the contribution from a low-angle rupture has had little effect. The first scenario has been investigated in numerical modeling studies by Paul Somerville and by Walter Silva. For multiple ruptures on parallel faults, whether or not they coalesce at depth, the results suggest that the rate of attenuation is approximately the same whether several faults rupture or whether only the central fault ruptures. Issues which pertain to estimating these motions include: moment partitioning among the rupture planes, the relative timing of the ruptures, and the distances of each plane to the site. Regarding rupture on a low-angle detachment fault, issues which affect ground motions include the stress drop of these events, and the geometry. Because these issues cannot be determined a priori, the experts will address any changes to their point estimates by incorporating additional uncertainty.

Following these discussions, Carl Stepp provided guidance on the level of detail the experts are required to provide to document their work. Data sources and all references must be thoroughly documented.

At the close of the Workshop, each expert briefly described potential changes to their point estimates based on the presentations in the Workshop. None anticipated major modifications to their procedures, but rather refinements based on closer evaluations of various proponent models.

ELICITATION SUMMARY

JON AKE, BURT SLEMMONS, AND JIM McCALPIN

TABLE OF CONTENTS

1.0 INTRODUCTION ASM-1

2.0 TECTONIC MODELS ASM-2
2.1 COMPARISON OF TECTONIC MODELS ASM-2
2.1.1 Caldera Model ASM-2
2.1.2 Volcanic-Tectonic Model ASM-3
2.1.3 Detachment Model ASM-4
2.1.4 Planar Fault Blocks Model (Pure Shear) ASM-5
2.1.5 Lateral Shear Models ASM-7
2.2 PREFERRED TECTONIC MODEL ASM-8

3.0 SEISMIC SOURCES ASM-11
3.1 THICKNESS OF THE SEISMOGENIC CRUST ASM-11
3.2 DETACHMENT AS SEISMIC SOURCE ASM-11
3.2.1 Seismogenic Potential ASM-12
3.2.2 Geometry ASM-15
3.2.3 Maximum Magnitude ASM-16
3.2.4 Recurrence ASM-16
3.3 BURIED STRIKE-SLIP FAULT SOURCE ASM-17
3.3.1 Seismogenic Potential ASM-18
3.3.2 Maximum Magnitude ASM-18
3.3.3 Recurrence ASM-19
3.4 LOCAL FAULT SOURCES ASM-19
3.4.1 Seismogenic Potential ASM-20
3.4.2 Geometry Models ASM-21
3.4.3 Behavioral Models ASM-24
3.4.4 Maximum Magnitude ASM-26
3.4.5 Recurrence ASM-27
3.5 REGIONAL FAULT SOURCES ASM-30
3.5.1 Estimation of Quaternary Ages ASM-31
3.5.2 Maximum Magnitude ASM-32
3.5.3 Slip Rate ASM-32
3.5.4 Recurrence Intervals ASM-33
3.5.5 Recurrence Models ASM-35
3.6 REGIONAL SOURCE ZONES ASM-35
3.6.1 Recurrence ASM-36
3.6.2 Maximum Magnitude ASM-37
3.6.3 Stationarity of Seismicity ASM-38

TABLE OF CONTENTS

4.0 FAULT DISPLACEMENT ASM-40

4.1 INTRODUCTION ASM-40

4.2 METHOD OF CHARACTERIZING THE POTENTIAL FOR FAULT DISPLACEMENT ASM-42

4.2.1 Method for Principal Faulting ASM-42

4.2.1.1 Frequency of Potential Principal Faulting Events ASM-43

4.2.1.2 Probability of Principal Faulting Surface Displacement During Earthquakes ASM-43

4.2.1.3 Characterization of Displacement at a Point.................. ASM-43

4.2.2 Method for Distributed Faulting ASM-44

4.2.2.1 Probability Feature Can Slip.. ASM-44

4.2.2.2 Frequency of Potential Distributed Faulting Events....... ASM-46

4.2.2.3 Probability of Distributed Displacement on a Feature.... ASM-46

4.2.2.4 Characterization of Distributed Displacement................ ASM-48

5.0 FAULT DISPLACEMENT ASM-55

TABLES

Table ASM-1 Average and maximum displacements for Yucca Mountain faults

Table ASM-2 Surface rupture lengths for Yucca Mountain faults

Table ASM-3 Weighting criteria for maximum magnitudes for Yucca Mountain faults

Table ASM-4 Slip rates for Yucca Mountain faults

Table ASM-5 Recurrence for Yucca Mountain faults

Table ASM-6 Regional fault data

Table ASM-7 Ratio of average to maximum displacement

Table ASM-8 Inferred number of events

Table ASM-9 Fault classes for displacement potential

FIGURES

Figure ASM-1 Logic tree for local sources

Figure ASM-2 Details of logic tree for detachment model

TABLE OF CONTENTS

Figure ASM-3	Map showing hypothetical buried strike-slip fault and detachment fault in the vicinity of Yucca Mountain included in the seismic source model
Figure ASM-4	Map showing local fault sources included in the seismic source model
Figure ASM-5	Logic tree for Crater Flat group (CFG) behavior
Figure ASM-6	Schematic of method used to develop downdip geometries of local faults
Figure ASM-7a	Schematic cross section of preferred merging geometry, northern transect
Figure ASM-7b	Schematic cross-section of deep, merging geometry. Depth of secondary faults constrained by aspect ratio
Figure ASM-7c	Schematic cross-section of shallow, merging geometry, northern transect. Depth of secondary faults constrained by aspect ratio
Figure ASM-7d	Schematic cross-section of non-merging geometry. Depth of secondary faults constrained by aspect ratio
Figure ASM-8	Simultaneous rupture scenarios and relative frequencies
Figure ASM-9	Map showing regional faults included in the seismic source model
Figure ASM-10	Map of regional seismic source zones within 300 km
Figure ASM-11	Map showing boundaries of zones used in the seismic source model
Figure ASM-12	Space-time comparing Youngs and Reasenberg declustering methods
Figure ASM-13	Annual frequency of earthquake recurrence as a function of time before Jan. 1, 1997, based on the catalog declustered by approach of Youngs *et al.*
Figure ASM-14	Logic tree used to characterize seismic source zones
Figure ASM-15	*Deleted*
Figure ASM-16a	Logic tree for principal faulting hazard
Figure ASM-16b	Logic tree for distributed faulting hazard
Figure ASM-17	Relationships between earthquake magnitude and probability of surface rupture
Figure ASM-18	Normalized "Wheeler" curve (adapted from Wheeler, 1989)
Figure ASM-19	Probability (frequency) of distributed slip as a function of distance from rupture
Figure ASM-20	Schematic illustration of ASSD method

TABLE OF CONTENTS

Figure ASM-21 Borah Peak geodetic curve

APPENDICES

APPENDIX ASM-1 GRAPHS SHOWING THE CUMULATIVE FREQUENCY OF LONG-TERM SLIP RATES FOR 10 LOCAL YUCCA MOUNTAIN FAULTS

APPENDIX ASM-2 GRAPHS SHOWING THE CUMULATIVE FREQUENCY OF INTERVAL SLIP RATES FOR 10 LOCAL YUCCA MOUNTAIN FAULTS

APPENDIX ASM-3 GRAPHS SHOWING FREQUENCY HISTOGRAMS OF LONG-TERM MEAN RECURRENCE INTERVAL FOR 10 LOCAL YUCCA MOUNTAIN FAULTS.

APPENDIX ASM-4 GRAPHS SHOWING CUMULATIVE FREQUENCY DISTRIBUTIONS OF LONG-TERM MEAN RECURRENCE INTERVAL FOR 10 LOCAL YUCCA MOUNTAIN FAULTS

APPENDIX ASM-5 GRAPHS SHOWING CUMULATIVE FREQUENCY DISTRIBUTIONS OF INDIVIDUAL RECURRENCE INTERVALS FOR 10 LOCAL YUCCA MOUNTAIN FAULTS

APPENDIX ASM-6 REGIONAL SEISMIC SOURCE CHARACTERIZATION

ELICITATION SUMMARY
JON AKE, BURT SLEMMONS, JIM McCALPIN

1.0
INTRODUCTION

This document describes the authors' seismic sources for seismic hazard assessment and characterization of fault displacement hazard at the Yucca Mountain site. These evaluations relied on available data (either provided by the Yucca Mountain hazards management team or literature known and available to us). No additional data were gathered and only limited analyses were performed as part of this assessment.

The evaluations incorporate uncertainties through the use of logic trees. Some elements of the logic trees portray objective, statistical weights. However, for many elements of the tree no objective data were available, and subjective weights had to be applied. We attempted to follow a simple set of rules to aid in applying weights to those more subjective elements. If we considered a model or parameter was virtually certain, we applied a weight of 0.99 (or 0.01 if virtually unbelievable). If we considered a model or parameter strongly supported or strongly unsupported, we applied a subjective weight of 0.9 or 0.1. If we evaluated two competing models to be equally likely or we had a high degree of uncertainty between them, we applied a weight of 0.5 to each. Likewise, if three models or parameters were considered equally likely, we applied a weight of 0.333 to each. For regional seismic sources where the likelihood of the preferred interpretation was greater than the maximum and minimum values, the preferred interpretation was assigned a value of 0.6 and the extreme values were weighted as 0.2. If uncertainties were available in the form of standard deviations (usually assumed as Gaussian), we weighted the results of median ± one standard deviation as 0.15, 0.7, and 0.15. For a few elements we attempted to capture the uncertainty by defining a preferred value and then ninetieth and tenth percentile values.

This summary begins with a discussion of tectonic models, followed by a description of the local seismic sources implied by the permissible tectonic models and then a summary of the regional and areal sources considered in this evaluation. The final part of the summary describes the team's characterization of fault displacement hazard.

2.0
TECTONIC MODELS

We considered several alternative tectonic models (as we presented in SSC Workshop 4) to explain the observations and data of the Yucca Mountain region. Our interpretations are summarized in this section. Of the seven tectonic models proposed by others in SSC Workshops 1 through 3, we assigned the greatest credibility to the planar fault blocks model, followed by the detachment model, the lateral shear model, and the volcanic-tectonic model.

In Section 2.1, we discuss each tectonic model in turn, first defining what we mean by the model, then listing the strengths and weaknesses of the model compared to available field evidence (both from Yucca Mountain and from similar extensional provinces worldwide) and theoretical considerations of seismicity and tectonics. Based on the ratio of strengths to weaknesses, we assign each model a subjective degree of belief. This rating expresses our consensus that the model correctly explains the seismotectonic setting of the Yucca Mountain region. These subjective probabilities form our basis for weighting the existence of critical structures (e.g., the detachment fault, buried strike-slip fault, planar faults) that appear in our logic tree for seismic source characterization. In Section 2.2 we discuss our preferred model that incorporates those aspects of the alternative tectonic models that we feel best explain the seismotectonic setting of the Yucca Mountain region.

2.1 COMPARISON OF TECTONIC MODELS

2.1.1 Caldera Model

Definition: Crustal blocks are sliding into a structural depression beneath Crater Flat. This depression was made by Tertiary caldera collapse or by westward detachment faulting. This model includes the caldera-detachment model of Carr (1990).

Strengths:

(1) The caldera complex is centered on a deep north-south trough or rift (Amargosa Desert rift); however, it is not clear whether the calderas are a result of the rift, or the reverse.

(2) Crater Flat/Yucca Mountain faults make a distributed fault system that mirrors the faults north of the caldera complex. This symmetry about the calderas suggests a causal connection.

Weaknesses: (USGS, written communication, 1996, p. 8-61)

(1) The calderas have been inactive since 14 Ma, so how could they affect current faulting?

(2) The calderas don't explain the change from rhyolitic to basaltic eruptions in Crater Flat in the past 3 Ma.

(3) The model doesn't explain vertical axis rotations.

(4) The model doesn't explain post-10 Ma uplift of Bare Mountain block.

Conclusion: Weaknesses much more compelling than strengths, model unlikely.

2.1.2 Volcanic-Tectonic Model

Definition: Surface-rupturing earthquakes in Crater Flat are accompanied by dike injection.

Strengths:

(1) With continuing Quaternary eruptions in Crater Flat and south, some connection between volcanic and tectonic processes is likely.

(2) Yucca Mountain faulting is widely distributed, like faulting in other volcanic-tectonic areas such as Mammoth Lakes. If USGS scenario earthquakes (USGS, written communication, 1996, Chapter 5) are single events, then such distributed rupture is also characteristic of volcanic-tectonic events.

(3) The ash event at 70 ka (see USGS, written communication, 1996, Chapter 5) appears to be connected with basaltic eruptions.

Weaknesses:

(1) Most of the 12 large (or 35 total) paleoearthquakes in the past 500 ka at Yucca Mountain are not associated with episodes of volcanic eruption.

(2) There is no direct evidence that the rift beneath Crater Flat was formed by volcanic action. Other possible origins: (1) a deep graben created by east-west tectonic extension, (2) a more northerly trending part of an Amargosa Desert rift, which thinned the crust until subcrustal magma was tapped, or (3) a northerly jog in the N50W-trending Amargosa River-Pahump-Stewart Valley strike-slip fault zone.

Conclusion: Some volcanic-tectonic connection may operate some of the time, the calderas do not appear to control currently active faulting.

2.1.3 Detachment Model

Definition: A major low-angle, west-dipping detachment fault underlies Yucca Mountain and Crater Flat, at a mid- to low-crustal position. This detachment truncates all high-angle faults observed at the surface.

Strengths:

(1) A detachment fault would explain the many narrow, parallel fault blocks as domino-style blocks above a detachment.

(2) Tertiary detachment faults exist in the region surrounding Yucca Mountain.

(3) Normal faults may utilize parts of older detachments, as in the Overthrust Belt (Smith and Arabasz, 1992).

Weaknesses: (USGS, written communication, 1996, p. 8-74)

(1) General:

(a) Historical earthquakes show planar faulting (e.g., the Little Skull Mountain event of 1992); no evidence of low-angle seismicity has been recorded, either in southwest Nevada, or in any other extensional terranes of the western US.

(b) The known detachments to the east and west are old (> 6 Ma).

(c) Basaltic volcanism requires deeply penetrating structures.

(2) Applies to shallow detachments:

(a) No shallow (< 5 to 6 km) reflectors that could be interpreted to be a detachment are seen on the seismic line (T. Brocher, SSC Workshop 2).

(b) Elsewhere in the region, there is no detachment at the boundary between Tertiary and Paleozoic rocks (that contact is an unconformity).

(c) Movement on the Bare Mountain Fault would have truncated any detachment.

(3) Applies to deep detachments:

(a) A deep (6 to 15 km) detachment could not produce the observed dip rollovers and opposed slip on some faults.
(b) A deep detachment requires tensile behavior at the base of the individual dominos, which is unlikely.

Conclusion: Weaknesses are compelling, however, a deep (>6 km) detachment cannot be ruled out by geophysics.

2.1.4 Planar Fault Blocks Model (Pure Shear)

Definition No. 1: East-west Basin and Range-type extension, with diffuse dextral shear in the south part of Crater Flat.

Strengths:

(1) The Amargosa Desert rift and all north-south-trending parallel faults suggest an east-west horst and graben system.

(2) The largest historical earthquakes in the local area (e.g., Little Skull Mountain) show planar faulting to depth.

(3) Seismic lines show no detachments within the upper 5 to 6 km.

(4) Rifting can explain basaltic volcanism.

(5) Boundary element modeling can replicate the seismic section using planar faults.

(6) Diffuse dextral shear can explain the increasing vertical axis rotation of fault blocks in southern Crater Flat.

Weaknesses:

(1) Pure horizontal extension does not explain the vertical axis rotations.

(2) Net slip (and slip rate) on the Bare Mountain fault (the supposed master fault to which Yucca Mountain faults are antithetic) must be greater than the sum of all the slips (and slip rates) on all the antithetic (Yucca Mountain) faults. This does not appear to be the case. However, some of the faults in the Bare Mountain fault zone may be buried by Holocene and late Quaternary alluvium up to 150k years old.

(3) Boundary element models show that, to produce a slip event on antithetic faults, multiple slip events on the main (Bare Mountain) fault are required. This does not appear to be the case.

(4) Planar faulting doesn't explain the ash event, which may have involved coeval rupture on six to seven parallel faults.

Conclusion: Strengths more compelling than weaknesses, model plausible.

Definition No. 2: Crater Flat is a transtensional rhombochasm (pull-apart) due to a right step in the Walker Lane. The east, south, west, and north boundaries of the rhombochasm are the Paintbrush Canyon/Stagecoach Road fault, the Carrara feature, the Bare Mountain fault, and a fault near Yucca Wash, respectively.

Strengths:

(1) The model explains the inferred oblique component of normal faulting in/near Yucca Mountain.

(2) The model explains the oblique nature of focal mechanisms observed in the instrumental seismicity (Rogers *et al.*, 1991 and K. Smith, SSC Workshop 2).

(3) The model may explain why fault behavior in the past 500 ka does not match the results of boundary element models, which assume pure east-west extension.

(4) The extreme northern limit on the main Yucca Mountain faults is at or near the linear northwest-trending Yucca Wash on the north. The faults have displacements that decrease toward this geophysical lineament, which has no known fault origin in the shallower units, and does not appear to be a seismic source. [Only the Paintbrush Canyon fault clearly crosses this feature, and it may change in character across Yucca Wash.] The extreme southern limit to Crater Flat and Yucca Mountain faults is near the linear northeast-trending inferred fault shown by Fridrich and Price (1992). The orientation of N45W suggests that it may be a right-lateral oblique fault.

Weaknesses:

(1) There is ambiguity about the existence of the required dextral faults at the north and south ends of the rhomboid.

Conclusion: Strengths more compelling than weaknesses, model plausible.

2.1.5 Lateral Shear Models

Definition No. 1: The transtensional nappe model applies (Hardyman and Oldrow, 1991).

Strengths:

(1) The model explains how Walker Lane shear could produce observed fault blocks.

(2) The Cedar Mountain earthquake of 1932 displayed distributed faulting having a high oblique component.

Weaknesses: (USGS, written communication, 1996, p. 8-80)

(1) "None of the criteria or geometry required for Hardyman's model exist at Yucca Mountain." Hardyman originally proposed this model for the Gillis Range-Cedar Mountain area, for a well-bedded pyroclastic sequence above a sheared unconformity with Mesozoic rocks that is cut by a lateral fault. We find no evidence for this type of mechanism at Yucca Mountain.

Conclusion: Compelling weaknesses, questionable applicability of model to Yucca Mountain area, model unlikely.

Definition No. 2: There is a buried, 250-km-long strike-slip fault beneath Yucca Mountain; it is a buried subvertical dextral fault, such as that proposed by R. Schweickert at SSC Workshop 3.

Strengths:

(1) The model would explain the observed vertical axis rotations in southern Crater Flat.

Weaknesses: (USGS, written communication, 1996, p. 8-84)

(1) There is no surface evidence of strike-slip faults at Yucca Mountain/Crater Flat, nor of any single, continuous strike-slip fault southeast of Crater Flat along the state line.

(2) Vertical axis rotations in the area are variable in time and space. They would be expected to be uniform if there was only one, long strike-slip fault.

(3) There is no evidence for a 25-km dextral offset of volcanics in Crater Flat.

Conclusion: Weaknesses more compelling than strengths, model unlikely.

2.2 PREFERRED TECTONIC MODEL

Our preferred tectonic model for Yucca Mountain is a composite based primarily on the Planar Fault Model, which has the following characteristics.

(1) Generally, the fault azimuth may be a first-order control on the type of fault, with conjugate relationships (a la Wright, 1976). Regionally northwest-trending faults are right-lateral; northerly-trending faults are normal; and northeast-trending are left-lateral. By far the most active faults are the strike-slip faults; normal faults have slip rates of 1% to 10% of the strike-slip faults. Most of the Yucca Mountain faults expressed at the surface are northerly-trending, normal faults.

(2) Major, block-bounding faults are planar (or weakly curved) to seismogenic depths.

(3) Faults that are closely spaced in plan view may merge above seismogenic depths. For those that are so closely spaced that they may merge above 15 km,