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December 6, 1991

Dr. Jamie Gardner and
Ms. Celina Vigil
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**Subject: Final Report for the Evaluation of Potential Surface Rupture
and Review of Current Seismic Hazards Program at LANL;
Subcontract 9-XT1-Q8540-1**

Dear Dr. Gardner and Ms. Vigil:

Please find enclosed three revised letter reports which comprise our final report for the above subcontract. We have incorporated the review comments by Dr. Gardner and Dr. Leigh House into these reports. We have very much enjoyed working on this project and look forward to future endeavors.

Best regards,

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Ivan

Ivan G. Wong
Senior Seismologist/Associate

Enclosure

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LETTER REPORT NO. 1



POTENTIAL FOR SURFACE RUPTURE

Facility TA-55 is located on the Pajarito Plateau along the north-northeast-trending Pajarito fault system. In the site area, the fault system consists of several fault traces within a 6- to 7-km-wide zone (Wachs et al., 1988). These include a segment of the Pajarito fault (Frijoles Canyon segment [Gardner et al., 1990]) which appears to be the principal fault, and two possible splays, the Rendija Canyon and the Guaje Mountain faults (Gardner et al., 1990). The fault system borders the western margin of the active Rio Grande rift, and in Los Alamos County exhibits both down-on-the-west (Frijoles Canyon segment) and down-on-the-east displacements (Rendija Canyon and Guaje Mountain faults) (Golombek, 1983; Gardner and House, 1987). Based on geologic evidence of multiple late-Quaternary displacements, Gardner and House (1987) propose that the Pajarito fault system is active and capable of generating large-magnitude earthquakes.

Geomorphic expression suggestive of late-Quaternary faulting is prominent along several traces of the Pajarito fault system in Los Alamos County, particularly along the Frijoles Canyon segment located along the western margin of the LANL. This approximately 20-km-long segment is characterized by an east-facing topographic scarp up to 125 m high in the 1.1 to 1.4 million year old Bandelier Tuff. This scarp is a result of down-on-the-east Quaternary displacement with a possible right-lateral component (Gardner and House, 1987).

Prominent west-facing topographic scarps up to about 30 m high are also present along the north-trending Rendija Canyon and Guaje Mountain faults north of Rendija Canyon, where Tertiary dacite is juxtaposed with Bandelier Tuff (Gardner and House, 1987). These two faults exhibit down-on-the-west vertical displacement and may be splays of the Pajarito fault zone that branch from the main trace north of Guaje Canyon. The total mapped lengths of the surface traces of the Rendija Canyon and Guaje Mountain faults are



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7.5 km and 13.5 km, respectively (Gardner and House, 1987). Based on displacement of the Bandelier Tuff and on geomorphic expression, the surface trace of the Rendija Canyon fault terminates near Los Alamos Canyon, and the surface trace of the Guaje Mountain fault extends southward to Pajarito Canyon (Gardner and House, 1987). However, a structure contour map of the pre-Bandelier surface (Gardner and House, 1987; Dransfield and Gardner, 1985) suggests that both of these faults displace pre-Bandelier rocks south of Los Alamos Canyon, with the Rendija Canyon fault extending south to Canon de Valle for a total fault length of 12 km. In addition, analysis of fractures in the upper Bandelier Tuff near TA-55 suggests that both faults may extend at least to Canon del Valle (Gardner, 1990).

Because the southern projection of the Rendija Canyon fault is less than 250 m west of the western boundary of the TA-55 facility (Gardner et al., 1990), an accurate assessment of the likelihood of surface rupture along this fault is required. Because the southern part of the Guaje Mountain fault lies about 0.5 km east of the facility, surface rupture along this fault is not considered to pose a significant hazard to the TA-55 site. However, strong ground shaking from rupture of the Guaje Mountain fault could produce ground cracking, differential settlement, or subsidence at TA-55.

Based on the potential presence of the Rendija Canyon fault in the subsurface south of Los Alamos Canyon, and on the presence of numerous fault splays within the 7-km-wide Pajarito fault system, Gardner and House (1987) suggest that there is a high potential for surface rupture in the area encompassing TA-55. However, detailed paleoseismic characteristics of the Rendija Canyon fault, such as the amount, timing, and lengths of late-Quaternary fault displacements, are undocumented. These data are necessary to confidently assess the likelihood of surface rupture along the fault within the operational life of engineered structures. In the absence of detailed paleoseismic data, it is necessary to estimate surface-rupture potential based on geomorphic expression and on structural associations with other faults for which paleoseismic data are available.



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The Rendija Canyon fault is expressed geomorphically as a prominent, linear, west-facing scarp between Guaje and Pueblo Canyons that appear to be a result of tectonic and erosional processes. West-facing scarps are particularly well-expressed where resistant dacite on the east side of the fault is juxtaposed against Bandelier Tuff on the west side, suggesting that the scarps, at least in part, are fault-line erosional scarps controlled by rock type. Fault-line erosion is supported by reversals in scarp aspect that coincide with changes in lithology along the traces of both the Rendija Canyon and Guaje Mountain faults. For example, in the vicinity of Rendija and Cabra Canyons, a west-facing scarp occurs along the Guaje Mountain fault where Bandelier Tuff is juxtaposed against resistant Tertiary dacite on the east side of the fault, whereas an east-facing scarp occurs where the tuff is juxtaposed against less resistant sand and gravel of the Puye Formation on the east side of the fault (Gardner and House, 1987). This substantial change in scarp aspect over a distance of less than 1 km suggests that rock type strongly influences the size and aspect of the topographic scarps along both the Rendija Canyon and Guaje Mountain faults. We conclude that the prominent west-facing topographic scarps along both faults are in part fault-line scarps and may not necessarily reflect the amount or recency of tectonic displacement.

The scarps along the Rendija Canyon and Guaje Mountain faults also reflect, in part, tectonic displacement. Prominent west-facing scarps along both faults occur on Barrancas Mesa, where Bandelier Tuff is present on both sides of the fault. Based on a 13-m-high scarp across Barrancas Mesa along the Guaje Mountain fault, Gonzalez and Gardner (in preparation) indicate that there has been post-1.1 Ma surface faulting. Additionally, Gonzalez and Gardner (in preparation) suggest that a Quaternary erosion surface (possibly 180-250 ka) has been displaced about 12 m along the Guaje Mountain fault. Nevertheless, scarps are not present along the Rendija Canyon fault on mesas underlain by Bandelier Tuff south of Barrancas Mesa. These relations suggest that post-1.1 Ma fault displacement



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decreases to the south along the fault, and that there has been no discrete post-1.1 Ma displacement on the Rendija Canyon fault south of Los Alamos Canyon. Nevertheless, Gardner (1990) indicates that extensive fracturing within the upper Bandelier Tuff exposed in roadcuts near the TA-55 facility is coincident with the Rendija Canyon fault. He further suggests that there is about 2.6 m of vertical displacement across the fault, and there is a zone of distributed deformation up to 900 m wide in the vicinity of TA-55 facility. However, no evidence of discrete surface rupture was observed within this zone. These relations suggest that if a large-magnitude earthquake were to occur on the Rendija Canyon fault, ground cracking may occur over a portion of the TA-55 site.

Similarities between the Rendija Canyon and Guaje Mountain faults, such as similar amount and sense of vertical displacements and similar fault length, geometry, and orientation, suggest that these two faults may have similar displacement histories. If so, paleoseismic data from the Guaje Mountain fault (Gardner et al., 1990) may be applicable to the Rendija Canyon fault. Based on exploratory trench data, Gardner et al. (1990) indicate that the youngest episode of faulting on the Guaje Mountain fault occurred between about 3700 and 6000 years ago. Although there are no paleoseismic data on the late Quaternary behavior of the Rendija Canyon fault, these relations and the interpretation that both the Rendija Canyon and Guaje Mountain faults are elements within the Pajarito fault system (Golombek, 1983; Wachs et al., 1988; Gardner et al., 1990) suggest that Holocene displacement on the Rendija Canyon fault is possible.

SUMMARY

Although Holocene displacement on the Rendija Canyon fault may be possible, several geologic and geomorphic relations suggest that discrete surface rupture probably would not extend southward to the TA-55 site. These relations include: (1) the apparent southward decrease in vertical displacement of the Bandelier Tuff, suggesting a decreasing rate of



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activity from north to south along the fault zone; (2) the absence of geologic evidence of discrete post-1.1 Ma surface rupture along projection of the fault trace south of Los Alamos Canyon; and (3) the lack of geomorphic expression of the fault south of Los Alamos Canyon. However, paleoseismic data and adequate fault behavioral data for the Rendija Canyon fault are undocumented at present. Based on these relations, coupled with the location of the site within the Pajarito fault system and possible tectonic fracturing (Gardner, 1990), we conclude that the potential for surface rupture along the Rendija Canyon fault at the TA-55 site is low to moderate. Quantifying the probability of occurrence of surface faulting is not possible at this time because of the absence of reliable displacement, recurrence, and slip rate data. Future studies will be required to obtain such information. Because the site lies about 0.5 km west of the Guaje Mountain fault, potential surface rupture along this fault is not considered to pose a significant hazard to the TA-55 site. Of possibly greater significance is that a moderate to large earthquake on either the Rendija Canyon, Guaje Mountain, or Pajarito fault could produce strong ground shaking at the facility, and resultant ground cracking, differential settlement, or subsidence in areas possibly underlain by soils and unconsolidated sediments.



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LETTER REPORT NO. 2



REVIEW OF METHODS AND CONCLUSIONS
OF EXISTING SEISMIC HAZARDS PROGRAM

EXECUTIVE SUMMARY

This report summarizes our review and evaluation of the existing seismic hazards program at Los Alamos National Laboratory (LANL). The current program, based on guidelines provided by the 1985 Code of Federal Regulations, Title 10, Part 100, Appendix A (10 CFR 100-A), uses a deterministic approach to seismic hazards assessment. This approach identifies potential seismic sources that are capable of generating moderate to large earthquakes and assumes such events will occur during the operational lifetime of the subject facilities. We recommend that this approach be augmented with a probabilistic analysis of seismic hazards involving assignment of weighted probabilities of occurrence to all potential sources. This approach yields a more realistic evaluation of the likelihood of large earthquake occurrence particularly in regions where seismic sources may have recurrence intervals of several thousand years or more.

Based on a critical review of existing literature pertinent to seismic hazards assessments at LANL, Gardner and House (1987) conclude that additional data on the nature, amount, and timing of displacements on the Pajarito fault zone, on the nature and level of historic seismicity, and on potential ground motions and site response, are required to fully assess seismic hazards of LANL. Issues of particular importance to such an assessment include:

- o Previous studies indicate that the 1.4 to 1.1 million year old Bandelier Tuff provides a marker from which to measure vertical fault displacements. However, additional detailed subsurface data



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are required to better constrain locations and amounts of possible displacements of the Bandelier Tuff.

- o Geologic and geomorphic evidence suggests that several faults within the Pajarito fault zone may be capable (as defined in 10 CFR 100-A). In Los Alamos County, however, only the Guaje Mountain fault segment has been shown to be capable (Gardner et al., 1990). Although other fault segments in Los Alamos County, such as the Frijoles Canyon and Rendija Canyon segments, may be capable, additional information is needed to adequately assess their seismic potential.
- o Because of the considerable uncertainty in the epicentral locations of historic earthquakes in the LANL region, it is difficult to assess possible associations between seismicity and geologic structures.
- o Because the maximum earthquake magnitude is dependent in a large part on the dimensions of the fault that ruptures, assessment of the potential seismic hazard posed by the Pajarito fault zone to the LANL requires a better understanding of potential rupture dimensions and of the interactions between structures along the northern and southern extensions of the fault system. Fault segmentation models should be refined to incorporate detailed paleoseismic data, and structural relations between the Pajarito fault zone and fault zones to the north and south should be assessed to adequately estimate potential rupture lengths.
- o At present, there are only limited data on the nature, amount, and timing of surface displacements along faults in the LANL region. Indirect evidence suggests that the Pajarito fault zone has had multiple episodes of faulting in the past 1.1 million years. However, there is no direct evidence of Holocene faulting along the



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Frijoles Canyon fault segment along the western border of LANL. Exploratory trench data indicate that the Guaje Mountain fault segment has been displaced in the past 6,000 years. Additional paleoseismic studies of major faults in the Los Alamos area are required to adequately address seismic hazards at LANL.

- o The existing map showing potential surface rupture hazard is based primarily on displacement of the 1.1 to 1.4 million year old Bandelier Tuff. Because zonations in areas of similar active deformation in the western United States typically use criteria that address hazards over shorter periods of time, there is a possibility that the LANL zonation may be misinterpreted, resulting in a possible overestimation of risk. We suggest that zonation criteria for the Los Alamos area be developed that better reflect (1) the probable average recurrence intervals along faults in the northern Rio Grande rift, and (2) the level of acceptable risk appropriate for the various types of LANL facilities.
- o The current instrumental monitoring of seismic activity in the LANL area, though quite valuable, can be improved considerably to likewise improve the data quality necessary for seismic source characterization. Because of the localized extent of the network, possible seismic sources that can generate strong and potentially damaging ground shaking at LANL are not being adequately monitored. In addition, determinations of focal mechanisms and improved locations of earthquake hypocenters are required to evaluate existing tectonic stresses and styles of deformation, and therefore to adequately assess seismic hazards at LANL.
- o Assessment of earthquake strong ground shaking and the development of seismic design criteria at LANL have been based to a large extent on a study performed in 1972. This evaluation, though probably a state-of-the-practice study at that time, does not incorporate the



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current understanding of seismic sources in the LANL region nor does it employ current and improved techniques for strong ground motion estimation. Because possible variations in subsurface stratigraphy and topographic effects can lead to a wide range in strong ground motions, in situ measurements of the thicknesses of subsurface geologic units, shear wave velocities, and dynamic properties at several localities throughout LANL are crucial for characterizing site-specific geologic effects on ground motions.

In conclusion, the current seismic hazard program has made significant progress toward assessing seismic hazard issues at LANL, and existing data provide a solid basis from which future studies can be performed. Future studies should focus on (1) characterizing the nature, amount, and timing of late Quaternary fault displacements (2) characterizing the tectonic setting of the LANL area, (3) reevaluating the recorded seismicity in the LANL region, (4) assessing subsurface geologic conditions required for estimation of strong ground motions and site response, and (5) estimating potential strong ground shaking and developing seismic design criteria.



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Introduction

The current seismic hazards assessment program at the Los Alamos National Laboratory (LANL) is based on guidelines provided by the 1985 Code of Federal Regulations, Title 10, Part 100, Appendix A (10 CFR 100-A). These guidelines are designed to provide quantitative assessments of seismic hazards at nuclear facilities based on deterministic evaluations of specific seismic sources. We support the use of this approach in regions where seismic sources that are significant to the seismic design bases of critical facilities can be readily identified through geologic and seismologic studies. Because of the proximity of LANL to probable capable faults within the Pajarito fault zone (Gardner and House, 1987), the deterministic approach provides an important estimation of the seismic hazards at LANL.

However, as reflected in the analyses performed by Tera Corporation (1984) for LANL (UCRL-53582: "Natural Phenomena Hazards Modeling Project: Seismic Hazard Models for DOE Sites") and implementation of these results in UCRL-15910 ("Design and Evaluation Guidelines for DOE Facilities Subjected to Natural Phenomena Hazards"), probabilistic seismic hazard analyses are also used by DOE as a basis for establishing seismic design criteria. We believe such analyses are particularly appropriate for less than high-hazard facilities. In our opinion, coupling of the deterministic approach with a probabilistic analysis of all possible known seismic sources provides the most complete and thorough assessment of seismic hazards. Probabilistic analysis involves assignment of weighted probabilities to all possible seismic sources and quantitative evaluation of seismic hazards at a given site from these sources. Our recommendation is that both deterministic and probabilistic evaluations be performed in the future to fully address the issues of seismic hazards at LANL.

Gardner and House (1987) developed and began implementation of a program to provide deterministic evaluations of seismic sources for subsequent seismic



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hazard assessment. Their deterministic evaluation incorporated information from seven principal data sets. These data sets, each of which are addressed in the 10 CFR 100-A, include:

- Critical review of pertinent literature
- Determination of subsurface geology
- Identification of capable faults
- For capable faults, determination of:
 - the nature of associated earthquakes
 - relationship to regional structures
 - fault length (e.g., segmentation, potential rupture length, total length)
 - the nature, amount, and history of fault displacements
- Evaluation of surface-rupture potential for tectonic structures, including buried potential seismic sources
- Instrumental monitoring of seismic activity
- Determination of seismic response of geologic materials at specific sites

This report provides a critical review of the methods used to collect and interpret these data, and the conclusions reached regarding the deterministic assessment of specific seismic sources. The following sections summarize our review concerning each data set.

Critical Review of Pertinent Literature

Gardner and House (1987) provide critical reviews of pertinent literature concerning the tectonic setting of the LANL area, previous field studies of the Pajarito fault zone, previous seismologic and site-response investigations for specific LANL facilities and for the LANL area in general, and previous studies of large-magnitude historical earthquakes in northern New Mexico. They provide sufficient critical review of previous



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investigations and list other pertinent references. We support the conclusions of Gardner and House (1987) based on this critical review that additional data on the nature, amount, and timing of displacements on elements within the Pajarito fault zone, on the nature and level of historic seismicity, and on site response and potential strong ground motions, are required to fully assess seismic hazards at LANL.

Determination of Subsurface Geology

Major stratigraphic and structural relations in the LANL region are adequately known from numerous detailed investigations (Doell et al., 1968, Smith et al., 1970; Budding, 1978; Manley, 1979; Golombek, 1983; Gardner and Goff, 1984; Gardner, 1985; Aldrich, 1986; Gardner et al., 1986; Gardner and House, 1987). These investigations provide a sufficient stratigraphic and structural framework for assessment of Quaternary faulting and seismic hazards in the LANL area. More detailed geologic maps and analyses of subsurface geology are provided by Gardner and House (1987), Dransfield and Gardner (1985), and Gardner et al. (in preparation). A major conclusion derived from or stated in these investigations is that the 1.4 to 1.1 Ma Bandelier Tuff provides an excellent stratigraphic marker from which vertical fault displacements can be assessed. In addition, these studies document the locations and amounts of displacements on major late Quaternary faults.

A primary concern regarding the knowledge of subsurface geology in the LANL area is the adequacy of subsurface data to assess deformation of the base of the Bandelier Tuff. Dransfield and Gardner (1985) provide a structure contour map of the pre-Bandelier surface. This map, which is based on well data, surface outcrops, and interpretations of seismic reflection lines, shows considerable paleotopographic detail where there are few water well or geophysical data and few surface outcrops of the base of the Bandelier Tuff. Additional detailed subsurface data (e.g., drillhole, seismic reflection) may be necessary to better constrain the base of the tuff in critical areas, such as in the area bordered by the Frijoles Canyon fault



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segment, Los Alamos Canyon, the Guaje Mountain fault segment and Rendija Canyon.

Accurate definition of the base of the Bandelier Tuff is significant to the seismic hazards assessment because (1) site response is dependent on underlying lithology, (2) the distribution and thickness of the Bandelier Tuff provides important information regarding the timing and amount of post-1.1 Ma displacements within the Pajarito fault zone, and (3) the thickness of the tuff in areas adjacent to faults may provide data on displacement history. Gardner and House (1987) note that the Bandelier Tuff varies considerably in thickness in the LANL area. We believe that isopach maps of members of the Bandelier Tuff would be useful to graphically illustrate the distribution and thickness of the tuff. In addition, if the Bandelier Tuff accumulated on a paleotopographic surface containing large, east-flowing drainages, as suggested by the structure contour map, these canyons may provide excellent indicators of vertical and horizontal displacements. Thus, additional constraint on the locations and orientations of possible paleo-canyons may provide estimates of the sense and amounts of post-1.4 Ma fault slip.

Identification of Capable Faults

Several previous investigations have identified faults exhibiting Quaternary displacement in the LANL area (Griggs, 1964; Smith et al., 1970; Golombek, 1983; Gardner, 1985; Gardner and House, 1987; Wachs et al., 1988). Although prominent topographic scarps in the 1.1 Ma Tshirege Member of the Bandelier Tuff within the Pajarito fault zone clearly suggest multiple late-Quaternary displacements, the only direct evidence of fault capability (as defined in 10 CFR 100A) in the Los Alamos area is described by Gardner et al. (1990). They report post-6 ka displacement of strata exposed in a trench across the Guaje Mountain fault in Cabra Canyon. Gonzalez and Gardner (in preparation) also suggest that a 180- to 250- ka-old geomorphic surface is displaced approximately 12 m in a down-to-the-west sense along the Guaje Mountain fault. Possible uncertainties in the



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estimates of the age and displacement of this geomorphic surface are discussed in a later section.

Several other lines of geologic or geomorphic evidence suggest, but do not unequivocally indicate that other faults within the Pajarito fault system in the Los Alamos area are capable. For example, along the Frijoles Canyon segment of Gardner et al. (1990), topographic scarps up to 125 m high in Bandelier Tuff indicate post-1.1 Ma displacements (Gardner and House, 1987). It is possible that some of this post-1.1 Ma displacement occurred during the past 500 ka. However, conclusive evidence of multiple post-500 ka displacements or a single post-35 ka displacement on this segment has not been obtained. Although Keller (1968) suggested that displacements south of Los Alamos post-date deposition of the 130 ka El Cajete pumice, Wachs et al. (1988) indicate that the relationships of the pumice to the fault zone are unclear. At present, there is no unequivocal evidence of displacement of the El Cajete pumice.

Gardner and House (1987) identified displaced Quaternary alluvium along the Bland-Sanchez Canyon segment of the Pajarito fault zone about 11 km south of the LANL. The age of this alluvium is poorly constrained. The number and sense of displacements represented in the Bland Canyon exposure are unknown, but it is possible that the 6 m of apparent vertical separation was produced by more than one event. Thus, this displacement suggests that there have been multiple displacements during the late Quaternary and therefore that this fault segment may be capable (as defined in 10 CFR 100-A). Because the extent of individual paleoseismic ruptures along different segments of the fault system is not documented, the direct application of these data to the Frijoles Canyon segment near Los Alamos is tenuous. Thus, these data suggest, but do not prove, that fault segments in the LANL area are capable.

Based on abrupt changes in stream gradients across the Frijoles Canyon fault segment, Wachs et al. (1988) suggest that this segment has had



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Pleistocene or possibly Holocene activity. However, stream gradients may be influenced by numerous non-tectonic factors (Schumm and Lichty, 1965; Kelson, 1986; Kelson and Wells, 1989), including:

- Rock type
- Orientation of strata
- Climate
- Changes in base-level elevation
- Source-area water and sediment discharge
- Unit stream power

Wachs et al. (1988) do not explicitly address the potential influences of these non-tectonic factors on stream gradients in the Los Alamos area. Because of the number of potential influences, there is no reason to assume that the stream nickpoints observed in the vicinity of the Frijoles Canyon fault segment are primarily a result of fault activity. Many, if not all, of the major streams draining the Pajarito Plateau have incised substantially into the Bandelier Tuff and older rocks as a result of incision along the Rio Grande, suggesting that non-tectonic processes have had a substantial influence on stream longitudinal profiles. This is supported by the presence of stream nickpoints at locations not associated with post Bandelier faulting (e.g., lower Frijoles Canyon). In addition, if the stream nickpoints noted by Wachs et al. (1988) were a result solely of fault displacement, their presence provides no data on the timing of faulting, other than indicating post-Bandelier (1.1 Ma) movement. Rates of nickpoint retreat must be documented to obtain information as the timing of displacements, particularly in resistant bedrock terrane. In conclusion, we believe that stream gradient nickpoints in the vicinity of the Frijoles Canyon fault segment cannot be used to assess fault activity without a better understanding of the tectonic and non-tectonic influences on stream longitudinal profiles on the Pajarito Plateau.



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Wachs et al. (1988) summarize several investigations of the timing of fault displacement on faults north and east of Los Alamos, and note that several lines of indirect geomorphic evidence are suggestive of post-500 ka displacement. Although these investigations (Harrington, 1986; Harrington and Dethier, 1987; Dethier et al., 1988) suggest post-500 ka displacement on either the Embudo (Santa Clara) fault zone or the northern Pajarito fault system north of Los Alamos, we note that the structural linkage between and segmentation of the Embudo and Pajarito fault zones is poorly understood, and note that paleoseismic data on the Embudo fault zone may not be directly applicable to seismic hazards assessments of the Pajarito fault zone in Los Alamos County. The northward change in sense of slip from dip-slip to oblique to lateral slip along the Pajarito fault zone (Gardner and House 1987), right-lateral displacement along the Embudo fault zone (Aldrich, 1986), the presence of several fault splays and cross structures between Los Alamos and Santa Clara Canyon (Golombek, 1983; Gardner and House, 1987), and a substantial change in fault strike north of Santa Clara Canyon (Wachs et al., 1988) all suggest that fault behavioral characteristics north of Santa Clara Canyon may differ substantially from those along the Pajarito fault zone near Los Alamos. In short, based on structural complexities in the northern Pajarito fault zone, we feel that the nature, amount, and history of displacements along faults studied by Harrington and Aldrich (1984), Harrington (1986), and Harrington and Dethier (1987) may not necessarily apply to the segment or segments of the Pajarito fault zone near Los Alamos. Therefore, it is apparent that detailed paleoseismic data are needed for the fault segments in Los Alamos County.

Lastly, Gardner and House (1987, p.31) collected seismic refraction data across the Guaje Mountain fault "to test the hypothesis that recent vertical fault movements (down-to-the-west) may have dammed the east-flowing drainages of Guaje and Rendija Canyons." Gardner and House (1987) interpret that valley alluvium is thicker on the upstream (downthrown) side of the fault in both canyons. Wachs et al. (1988, p. 18) suggest that the



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bedrock surface has at least 5.2 m of down-on-the-west vertical separation in Guaje Canyon. Because of the possibility of fault-line erosion (non-tectonic scarp-forming processes), these data alone do not document the presence of late-Quaternary displacement. However, in conjunction with trench exposures documented by Gardner et al. (1990), these data indicate that at least the Guaje Mountain fault is active.

In conclusion, the only direct evidence indicating fault capability within the Pajarito fault zone in the Los Alamos area is the post-6 ka displacement of strata along the Guaje Mountain fault (Gardner et al., 1990). Thus, the available data support the statement by Gardner and House (1987) that the Guaje Mountain fault is capable as defined in the 10 CFR 100-A. However, the data are not adequate to assess the possibility that the fault can generate large-magnitude earthquakes. There are no conclusive data documenting that the Frijoles Canyon or Rendija Canyon fault segments are capable. Several geologic and geomorphic features suggest that they may be capable, such as the prominent east-facing scarp along the Frijoles Canyon segment and evidence of probable late Quaternary displacement in Bland Canyon. We conclude that both the Frijoles Canyon and Rendija Canyon fault segments may be capable, but that additional information is necessary to adequately address fault behavioral characteristics such as the nature, amount, and timing of late-Quaternary displacements.

Determination of the Nature of Earthquakes Associated with Capable Faults

In 1973, LANL initiated seismic monitoring in the vicinity of the lab and in a large portion of northern New Mexico through the installation and operation of a high-gain seismographic network. This network, which appears to have begun with six stations, was later expanded to more than 15 stations. The results of this monitoring have been summarized by House and Cash (1988). In 1985 the network was greatly reduced in size, areal coverage, and funding. Presently the network consists of 7 stations, which is only sufficient to monitor the immediate area of LANL.



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The accuracy of the epicentral locations of events recorded and located by the LANL seismographic network from 1973 through 1985 is highly variable due to data quality and monitoring capabilities. Epicentral uncertainties range from 1 to 15 km, depending upon the location of the event relative to the network geometry (Cash and Wolff, 1984; L. House, personal communication, 1991). Focal depths were generally not well determined as is common for networks with widely-spaced stations (e.g., Sanford et al., 1981). Most earthquakes were constrained to a focal depth of 5 km in their location determinations.

Because of these location uncertainties, it is difficult to reliably evaluate possible associations of seismicity with geologic structures. On a gross scale, it is apparent that some earthquakes may be associated with large regional structures, such as the Nacimiento uplift and Gallina-Archuleta arch. However, detailed associations with specific faults, such as those of the Pajarito fault zone, are only speculative based on the current earthquake locations because of the possibly large hypocentral errors. The assessment of focal depths and the thickness of the seismogenic crust is critical in evaluating the downdip widths of capable faults and estimations of their maximum earthquakes. Few focal mechanisms have been determined for the LANL region. Such data is critical for seismic source characterization.

The recent reevaluation of arrival time data and relocation of a subset of events in the Los Alamos area by Leigh House is a major step in fully utilizing these valuable data. Future efforts should be concentrated on expanding the area of study, improving the velocity model and station corrections for improving hypocentral accuracy, and determining focal mechanisms. The analysis of seismicity in the Los Alamos region can provide important information on the sources, mode and style of regional deformation.



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Determination of the Relations of Capable Faults to Regional Structures

The Pajarito fault zone is a major structural element within the Rio Grande rift that separates the Jemez Mountains volcanic pile on the west from the central Espanola Basin on the east (Kelley, 1978; Manley, 1979; Aldrich, 1986). Muehlberger (1979) and Aldrich (1986) present a regional tectonic model that highlights the importance of the Pajarito fault zone in the development of the Espanola Basin and to the present-day tectonic setting. This model suggests that the structural block bordered by the Pajarito fault zone on the west, the Embudo fault zone on the northwest, the Picuris-Pecos and Tijeras-Canoncito fault zones on the east, and the La Bajada fault on the southwest, is rotating counterclockwise. On a regional scale, this model suggests that the northern termination of the Pajarito fault zone occurs at its intersection with the Embudo fault zone, and that the southern termination of the fault system occurs at its intersection with the La Bajada fault zone. However, the northern extent of the Pajarito fault zone is poorly understood, in part because of its complex intersection with the Embudo fault. Gardner and House (1987) state that there is no structural basis for differentiating between the two faults, and that the Embudo fault zone may be the continuation of the Pajarito fault zone nearly to Taos. This interpretation may be based on the observation that there is a change in the sense of slip along the Pajarito fault zone, with the southern part of the fault characterized by predominantly down-on-the east dip-slip, the central part by right-oblique slip, and the northern part by predominantly right-lateral slip (Gardner and House, 1987). This might suggest that right-slip along the Embudo fault zone is being transferred, in part, to the northern part of the Pajarito fault zone. Aldrich (1986), on the other hand, considers the Pajarito fault zone to be truncated by the Embudo fault zone. This intersection coincides with a structural change in the Embudo fault zone from a series of en echelon, left-stepping faults on the east of the intersection to a structural discontinuity on the west. This change in the structural character of the Embudo fault zone is problematic in that it suggests that the Pajarito fault zone disrupted movement along the Embudo



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fault zone. Additionally, several other authors (Golombek, 1983; Harrington and Aldrich, 1984; Wachs et al., 1988) present slightly different interpretations of the northern termination of the Pajarito fault zone. Thus, additional geologic data on the location and character of the northern termination of the Pajarito fault zone is required to evaluate potential rupture lengths, fault segmentation, kinematic interactions with other regional structures, and therefore seismic hazards assessments.

The transition from the southern Pajarito fault zone to the La Bajada fault also is not clearly understood. The Pajarito fault zone apparently branches into a southwest-trending trace and a southeast-trending trace east of St. Peter's Dome (Gardner and House, 1987). Apparent vertical displacement on the southeast-trending trace diminishes to where the fault becomes geomorphically indistinct. However, Gardner and House (1987, p. 17) suggest that this trace crosses the Rio Grande and joins the down-to-the-west La Bajada fault. The structural relations between the down-to-the-east southern Pajarito fault zone and the down-to-the-west La Bajada fault are at present poorly understood.

In order to assess the potential seismic hazard posed by the Pajarito fault zone to the LANL, a better understanding of the interactions between this major fault zone and adjacent structures clearly is needed. Interactions between faults may play important roles in fault segmentation, which in turn influences potential fault rupture lengths. Because potential rupture length is an important parameter in estimating maximum earthquake magnitude, assessment of fault interactions and terminations is important to seismic hazards evaluations. We conclude that further studies are required along the northern and southern extents of the Pajarito fault zone to fully assess seismic hazards at LANL.

Determination of the Lengths of Capable Faults

The length of each capable fault must be estimated to adequately assess its potential seismic hazard. For example, the anticipated moment magnitude



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can be estimated for a given fault based on estimates of fault rupture area. Such evaluations require estimates of: (1) total fault length; (2) segment lengths (i.e., portions of the fault that exhibit structural or geomorphic differences, possibly resulting from differences in fault behavior); (3) lengths of potential surface ruptures based primarily on paleoseismic evidence; and (4) down-dip rupture width. Because of the large uncertainties in factors such as the locations of the Parajito fault zone termini, the interaction between faults within the Parajito fault zone, and rupture histories of faults within the zone, only preliminary estimates for the various fault and segment lengths exist.

The total length of the Pajarito fault zone based on Smith et al. (1970) is at least 40 km and may be slightly longer if the sinuosity of the system is taken into account. Two segmentation models have been developed for the Pajarito fault zone. Golombek (1983) proposes four segments based solely on along-strike structural and stratigraphic changes. Gardner et al. (1990) define individual fault segments based primarily on fault geometry, sense of displacement, vertical slip rates for about the past 1 million years, and long-term history.

Each segmentation method has its merits and drawbacks. Golombek (1983) groups individual fault traces within a segment (e.g., the Guaje Mountain segment contains several traces) without regard to characteristics of individual faults such as slip rate, mode of slip, and timing of events. However, Golombek (1983) incorporates prominent structural changes, such as fault discontinuities and abrupt orientation changes that may affect rupture propagation along the fault. Gardner et al. (1990) base their model primarily on long-term slip rate and also changes in fault orientation. Both schemes are valid given the amount of paleoseismic data that are available. However, in order to adequately define rupture segments, geomorphic and structural evidence must be combined with paleoseismic data on fault behavior to establish recent segmentation patterns.



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In conclusion, additional geologic and paleoseismic data are needed to adequately estimate total fault lengths, segment lengths and potential surface rupture lengths. Segmentation models established by Golombek (1983) and Gardner et al. (1990) should be supplemented by detailed geologic mapping and paleoseismic investigations to define the late-Quaternary segments of the faults.

Determination of the Nature, Amount, and History of Displacements Along Capable Faults

Limited direct paleoseismic data are available to quantify the amount and timing of surface displacement along faults within the Pajarito fault zone. Except for the single exploratory trench excavated across the Guaje Mountain fault at Cabra Canyon (Gardner et al., 1990), no direct evidence of Holocene activity has been established for any of the faults in the Los Alamos area. Ample geomorphic evidence for Quaternary activity exists along these faults, including a 125-m-high scarp in the 1.1 Ma Bandelier Tuff along the Frijoles Canyon fault segment (Gardner et al., 1990). A structure contour map depicting the pre-Bandelier topography lacks sufficient subsurface control to adequately assess the height of the scarp prior to deposition of the tuff. Therefore, estimates of slip based on the present scarp height might only be maxima. The position of geologic and geomorphic units relative to the local faults has also been used to estimate the timing and amount of fault rupture. For example, Keller (1968) suggests that the 130 ka El Cajete pumice has been faulted along the Pajarito fault zone; however, Gardner and House (1987) imply that it is also probable that the deposits accumulated along the lee-side of an already existing scarp. Thus it is uncertain whether: (1) surface rupture initiated after the El Cajete pumice was deposited across an unfaulted Bandelier Tuff surface; (2) faulting continued after the El Cajete pumice was deposited across an already existing smaller scarp; or (3) the 125 m-high scarp that exists at present was already formed by the time the El Cajete pumice was deposited and little or no surface rupture has occurred since about 130 ka.



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Similarly, Gonzalez and Gardner (in preparation) suggest that a possibly 1.1 Ma to 350 ka erosional surface (Q1) is displaced 13 m along the Guaje Mountain fault at Barranca Mesa, a possibly 250 to 180 ka surface (Q3) is displaced 12 m along the same fault. Based on these data, it might be suggested that little displacement occurred along the fault prior to about 350 ka after which time about 12 m of vertical slip occurred, or that slip is not uniform along the length of the fault. This might suggest that the Guaje Mountain fault is segmented or that the area of maximum slip has shifted along the fault. However, ages of these geomorphic surfaces are not known and, as stated by Gonzalez and Gardner (in preparation), are tentatively based on correlations to surfaces along the Rio Grande. In addition, it is not evident that the Q1 and Q3 surfaces can be correlated across the fault. Because of the west-facing, upstream aspect of the scarp, it is possible that sediments associated with the Q3 surface on the down-thrown side of the fault were deposited against an existing scarp. The deposit on the opposite side of the fault might be considerably thinner and be associated with a younger or older geomorphic surface.

To adequately assess paleoseismic characteristics of potentially capable faults in the Los Alamos area, it is essential that Quaternary geomorphic deposits along the faults be mapped in detail. Additional constraint on the thicknesses and ages of deposits and associated surfaces will enable more detailed assessment of the nature, amount, and timing of late-Quaternary displacements.

The only direct evidence of Holocene faulting was observed in an exploratory trench excavated by Gardner et al. (1990) along the Guaje Mountain fault in Cabra Canyon. Based on radiometric dating of faulted and unfaulted strata, Gardner et al. (1990) suggest that the most recent surface rupture event occurred between about 3700 and 6000 years B.P. A major unconformity between paleomagnetically-dated lacustrine deposits more than 730,000 years old and sediments 6000 years old may indicate that



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evidence of several late-Pleistocene faulting events may not be preserved. Thus, no short-term recurrence for the fault can be established. Based on apparent offset of units and buried scarps formed in dacite boulders. Gardner et al. (1990) estimate the net vertical slip across faults exposed in the trench and acknowledge that the horizontal component of slip, if present, cannot be estimated from the trench exposure. If the lateral component of slip is large, then the estimate of slip based on the trench exposure is a minimum. However, if any lateral slip was involved during faulting, then it is possible that the apparent vertical offset of beds might be due to lateral juxtaposition of correlative units that were not originally at the same elevation. Based on empirical relations between displacement and magnitude (Slemmons, 1977) and on observations of vertical separation in the trench exposures, Gardner et al. (1990) suggest that Richter magnitude 6.9 to 7.2 earthquakes were responsible for these geologic relations. We believe that this assessment of magnitude, while not unreasonable, may be refined with additional data on the amount of vertical and horizontal displacement across the Guaje Mountain fault associated with individual earthquakes.

Geologically based estimates of probabilistic seismic hazards require detailed characterization of long-term fault slip rates and recurrence intervals. Both of these parameters are poorly understood for faults within the Los Alamos area. Because there are very few data regarding the timing of multiple late-Quaternary displacements on any of the potentially capable faults, recurrence intervals are poorly known. Long-term slip rate data in the Los Alamos area consist primarily of estimates based on the heights of scarps in the Bandelier Tuff or inset geomorphic surfaces (Gardner and House, 1987; Gonzalez and Gardner, in preparation). For example, Gonzalez and Gardner (in preparation) provide slip rates for the Guaje Mountain fault of 0.012 mm/yr based on a 13-m-high scarp in the 1.1 Ma tuff on Barranca Mesa and of 0.048 to 0.067 mm/yr based on a 12-m-high scarp across a 180 to 250 ka geomorphic surface. These rates reflect only the vertical component of slip, and therefore may be low if there is a



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substantial lateral component. On the other hand, actual vertical surface offset may be lower than scarp height if surfaces have substantial slopes, suggesting that the displacements noted by Gonzalez and Gardner (in preparation) may be too large. Therefore, actual cumulative displacement along the Guaje Mountain fault may be either smaller or larger than that indicated by Gonzalez and Gardner (in preparation). The potential uncertainties in existing slip-rate estimates should be quantitatively addressed.

In conclusion, there are presently only limited data on the nature, amount, and timing of surface displacements along faults near the LANL. Indirect evidence suggests that the Pajarito fault zone has had multiple episodes of Quaternary faulting; however, there is no direct evidence of Holocene faulting along the Frijoles Canyon segment near LANL. Exploratory trench data for the Guaje Mountain fault north of LANL indicate that Holocene rupture has occurred. However, the fault has poor geomorphic expression across mesas underlain by Bandelier Tuff (see discussion in Report #1), suggesting that it has either a relatively long recurrence between events, or that displacements typically are small. Additional studies of major faults in the Los Alamos area are required to adequately address seismic hazards at the LANL.

Evaluation of Potential for Surface Rupture

Evaluation of the potential for surface rupture in the LANL area by Gardner and House (1987) consists primarily of the delineation of five qualitatively defined zones of low, moderate, high, very high, or unknown potential. These classifications are relative only to each other within the LANL area, and are not intended to be compared to rupture-potential zones delineated in other seismically active areas. Areas classified as having very high potential encompass "active faults that break young deposits" (Gardner and House, 1987, Map IV-D). Areas having high potential include extensions of active faults and narrow zones between active faults; areas having moderate potential include pre-Bandelier (1.1 to 1.4 Ma)



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faults "with potential for re-activation." Areas having low potential encompass faults that apparently controlled pre-Bandelier topography. Areas of unknown potential are those that lack data on fault activity, which generally include the areas east of White Rock along the Rio Grande and west of the Pajarito fault zone in the eastern Jemez Mountains.

The approach of qualitatively classifying relative rupture potential through qualitative microzonation is a valid, well-documented, and commonly used method in assessing seismic hazards, particularly in seismically active regions of the western United States. A critical step in such classifications is the definition of specific criteria to be used for zonation, as was done by Gardner and House (1987). To enable application of the zones to existing or proposed engineered structures, these criteria need to adequately distinguish zones having different rupture potential over time spans that reflect the operational lifetime of the structures as well as estimates of the recurrence intervals of large-magnitude earthquakes. For example, Special Studies Zones in California, which delineate areas having high rupture potential, include only those faults that show geologic, geomorphic, or seismologic evidence of Holocene (post-10,000 years) activity. This time period probably reflects several recurrence intervals on most potential seismic sources in California. Gardner and House (1987) use displacement of the Bandelier Tuff as a criteria in zonation, which effectively means that the zonation reflects a time period of about a million years. Although it is clearly stated that this classification is not intended to be compared with rupture-potential zonations outside of the Los Alamos area, there is a possibility that this intent could be neglected and that the zonations would be inadvertently compared to existing zonations developed in areas having smaller recurrence intervals, such as those in California. Such a misinterpretation could result in an overestimation of risk. We suggest that zonation criteria for the Los Alamos area be developed that better reflect both (1) the probable average recurrence interval along faults in the northern Rio Grande rift, which are probably at least one order of magnitude less than the time span



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represented by the Bandelier Tuff (Machette, 1986), and (2) the level of acceptable risk appropriate for the various types of facilities that may be affected at LANL.

As an example, Gardner and House (1987) indicate that there is moderate potential for surface rupture along faults identified in the subsurface that do not displace the Bandelier Tuff but have the potential for re-activation. Stratigraphic and structural evidence suggest that the Pajarito fault zone became active about 4 Ma (Gardner and Goff, 1984), which in turn suggests that the present approximately east-west direction of regional extension in the Rio Grande rift has been in place for at least the past 4 Ma and possibly since 10 Ma (Zoback and Zoback, 1989). Based on these relations and the possible low strain rates associated with the Rio Grande rift, it seems unlikely that faults lacking displacement since 1.4 Ma would be reactivated in the present tectonic setting. Thus, the interpretation that areas underlain by pre-Bandelier faults have a moderate rupture potential (if mistakenly compared to other "moderate" potential zones in seismically active areas) may greatly overestimate rupture potential. Perhaps quantitative probabilities are required to better refine the rupture potential zonations.

Lastly, Gardner and House (1987) indicate that their zonation is preliminary. We agree that additional data concerning the amount and timing of surface ruptures along the three major post-Bandelier faults in the Los Alamos area (i.e., the Frijoles Canyon, Rendija Canyon, and Guaje Mountain fault segments) are required to better constrain the zones of potential rupture. Although prominent topographic scarps along all three of these faults suggest multiple Quaternary displacements, it is possible that the scarps are, at least in part, a result of fault-line erosion and therefore may not accurately reflect the possible extent of surface rupture. Possible refinement of the Gardner and House (1987) zonation map may include: detailed assessment of the extent and amount of late-Quaternary displacement along each of the faults, evaluation of the width



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of the zones of deformation (including possible folding or tilting) associated with each fault, and assessment of average recurrence intervals. Refinement of the existing zonation map based on these additional data would provide increased confidence in locations of possible future surface ruptures.

Instrumental Monitoring of Seismic Activity

Seismic monitoring with the intent of addressing issues of seismic hazards and as a possible means of hazard mitigation has long been recognized as a valuable tool by the scientific and engineering communities. DOE has also historically strongly supported the use of seismic monitoring for such purposes. For example, large regional networks exist at the Lawrence Livermore National Laboratory and the Idaho National Engineering Laboratory (INEL), and the current network at the Savannah River Laboratory is being greatly expanded.

The purpose of seismic monitoring is to provide data that will allow for the spatial, temporal, and source characterization of recorded seismicity, the possible association with geologic structures (and hence the possible identification and characterization of active faults), and an evaluation of the styles of deformation and tectonic stresses. Such information is basic data for any seismic hazards evaluation and also can be used to assess potential future seismic hazards. Seismographic networks should be configured to record data to optimize these objectives.

The data quality of the LANL seismographic network from 1973 to 1985 have been previously discussed. In terms of the current network, the network geometry needs to be reconfigured and stations added to adequately monitor seismicity in the vicinity of and around the LANL and to provide quality data for characterizing seismic sources. Possible seismic sources outside Los Alamos County that can generate strong and potentially damaging ground shaking at LANL are currently not being monitored because of the localized extent of the network. Such sources can be as distant as 70 km from the



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LANL. The present configuration of the network appears to be controlled by topography which effects both data transmission and vehicular access, and the level of funding.

Determination of Seismic Response of Geologic Materials

The assessment of earthquake strong ground shaking and the development of seismic design criteria at LANL have been based to a large extent on the Dames and Moore (1972) study for the Plutonium facility at TA-55. This study and the somewhat "generic" probabilistic seismic hazard analysis performed by Tera Corporation (1984) have been reviewed by Gardner and House (1987) and we concur with their evaluations. In particular, the attempt to correlate intensities with peak ground accelerations by Dames and Moore (1972) is an approach that can lead to significant errors in ground motion estimates. Because of possible differences in rupture processes, the use of the non-site-specific time histories of M 5 to 6 earthquakes (1935 Helena, Montana and 1957 San Francisco) can lead to a very different spectral content than for the design ground motions of a M 7 earthquake.

In general, the Dames and Moore (1972) study probably represented a state-of-the-practice evaluation at the time; however, 19 years have elapsed and considerable progress has been made in predicting site-specific strong ground motions and, possibly of greater significance, in the understanding of seismic sources significant to the LANL. Because of the apparent potential for a large or moderate magnitude earthquake on nearby faults, the probability of exceeding the peak horizontal ground acceleration of 0.33 g as recommended by Dames and Moore (1972) is high. Even if future studies of the Pajarito fault zone were to establish that nearby fault segments were not capable of generating a moderate to large earthquake, further strong ground motion studies are warranted due to the potential variability in site response, as described by House and Phillips (1989), and the possibility of significant ground motions being generated by seismic sources at greater distances than the Pajarito fault zone. The



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study by House and Phillips (1989), in particular, suggests that topographic amplification may be a significant factor in influencing ground motions. A possible limitation of their study, however, is that the use of nuclear explosions at large distances (which is commonly done) may result in significantly different spectral content and strain levels than for a nearby large earthquake.

The possible variations in subsurface stratigraphy and topographic effects can lead to a wide range in strong ground motions that cannot be represented by a single response spectrum (or time history) for one site at the LANL. Of particular importance to site response at LANL is an accurate characterization of the dynamic properties of the Bandelier Tuff. Because of its thickness and wide variability in shear wave velocities and damping properties (as evidenced by its welded to nonwelded nature), the tuff may be capable of controlling the level and spectral content of ground motions, particularly in the case of a near-field earthquake in which nonlinear soil behavior is possible. In situ measurements of these parameters at several locations throughout the LANL are crucial for characterizing site-specific geologic effects on ground motions. To the best of our knowledge, no detailed downhole shear-wave profiling has been conducted at the LANL.

A key element in assessing strong ground motions, the effects of the subsurface geology on such motions and the structural response of facilities are strong motion data. The M 7.3 1989 Borah Peak, Idaho earthquake, was recorded by 13 accelerographs located near or at the major facilities at the INEL. This data has been invaluable in evaluating potential strong ground shaking at the INEL. This strong motion network was installed despite the fact that the INEL had not been previously subjected to any significant levels of shaking in the past. Currently there are three strong motion recorders at LANL. To our knowledge, no data are available from these instruments because they have not been triggered. For a major DOE facility, the capability to record potential future strong ground shaking is inadequate. One or more accelerographs



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should be installed at all major facilities with some recorders located at free-field sites.

SUMMARY

Based on our review of available data, reports and other publications, discussions with the LANL staff and a brief geologic reconnaissance of the Pajarito fault system, we have performed a critical review of the methods and conclusions of the LANL seismic hazards program. Significant geologic efforts have been made toward assessing seismic hazard issues and the existing data provide a solid basis from which future studies can be performed. Future geologic studies must focus on characterizing the nature, amount, and timing of late-Quaternary fault displacements and the tectonic setting of the LANL area. Substantial paleoseismic investigations will be required to fully characterize the seismogenic potential and behavior of the Pajarito fault zone. In terms of seismological studies, very little has been done in evaluating the seismicity of the region and the operative tectonic stresses in an attempt to understand earthquake processes in the region. Essentially no up-to-date studies have been made since 1972 to evaluate potential strong ground shaking and site response at the LANL. Specific recommendations concerning future geological, seismological, and geophysical studies necessary to fully evaluate seismic hazards at the LANL will be contained in our third letter report.



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LETTER REPORT NO. 3



REVIEW OF CURRENT SEISMIC HAZARDS PROGRAM
AND
RECOMMENDATIONS FOR FUTURE STUDIES

This letter report provides a review of current activities, plans, and objectives of the seismic hazards program at the Los Alamos National Laboratory (LANL), and presents our recommendations for future studies to fully address seismic hazard issues at LANL. This report follows our second letter report dated 22 March 1991, which provided a review of the methods and conclusions of the existing seismic hazards program. Our evaluations contained herein and the previous two letter reports are based on our review of pertinent literature, discussions with researchers at LANL, geologic field reconnaissance, and limited analysis of aerial photography.

REVIEW OF CURRENT SEISMIC HAZARDS PROGRAM

Based on a review of the available literature referenced in our second report and of a briefing report on the seismic hazards investigation program (Gardner and House, 1990), we concur with the general objectives of the current program and believe they are obtainable and applicable to a comprehensive evaluation of seismic hazards at LANL. Gardner and House (1990) describe the current program which consists of nine objectives. Each objective is accompanied by a rationale and a general scope of work. Objectives 1, 2, 3, and 8 focus on the geologic and seismologic characterization of potential seismic sources. Objectives 4, 5, 6, and 7 focus on potential site effects on ground motions or site response, and Objective 9 focuses on initiation of interaction with LANL Management in the evaluation of site design, potential risk, and emergency response.

Gardner and House (1990) indicate that Objectives 1, 2, and 3 are designed to address the "characteristic earthquake" along specific faults in the



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LANL vicinity. Although the characteristic earthquake model is a useful model that adequately represents some seismic sources in the western United States, the valid application of this model to faults in the LANL vicinity will require substantially more data. Data necessary to quantitatively address seismic hazards through either deterministic or probabilistic analyses (see below), such as fault slip rates, maximum displacement per rupture event, and timing of most recent surface rupture, will address whether the characteristic earthquake model is applicable to nearby faults.

We agree with the general conclusion of Gardner and House (1990), and as described in our report dated 22 March 1991, that additional geologic, geomorphic, and seismologic data are required to adequately address potential seismic hazards at LANL. To obtain these data, we recommend that the following activities be conducted in a phased program of increasingly focused, technically sophisticated studies. Such a phased approach allows for continual refinement of the program as specific objectives and data needs are identified and revised.

TECHNICAL APPROACH

Assessments of site-specific seismic hazards typically use either a deterministic or probabilistic approach. In a deterministic approach, such as that addressed in 10 CFR 100, Appendix A, the Maximum Credible Earthquake (MCE) is estimated for each potential seismic source. In some cases, the MCE can be estimated from the historical earthquake record. More often than not, however, empirical relations between magnitude and specific fault parameters, such as rupture length, are used to estimate the MCE for seismic sources which can be identified through geologic, seismologic and/or geophysical studies. Ground motion parameters for the MCE are then calculated based on the distance from each potential source to a specific site, attenuation along the raypath, and site geology. These data are then used to develop seismic design criteria for specific facilities. In general, a deterministic approach implicitly assumes that



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the source will produce the MCE within the operational lifetime of the facility. Thus, this approach may yield overly conservative input to the seismic design, particularly if the recurrence interval of the MCE is large compared to the operational lifetime of the facility.

Probabilistic seismic hazard analyses are increasingly being used to provide an additional basis for developing seismic design criteria for critical facilities. For example, future revisions of 10 CFR 100, Appendix A will most likely include probabilistic analyses. The probabilistic approach utilizes earthquake recurrence information and the timing of the most recent event to provide a probability distribution of the occurrence of earthquakes within a range of magnitudes. In addition, a probabilistic approach provides a means to quantitatively assess uncertainties in seismic source characterization parameters and to incorporate them into the hazard analysis. Compared to a deterministic analysis, a probabilistic evaluation more accurately portrays the contributions of seismic sources that have relatively large recurrence intervals to the possible seismic hazard. Another advantage of the probabilistic approach is that random or "background" seismicity (seismicity that does not appear to be associated with specific faults) can be incorporated into the analysis. For these reasons, we recommend that the assessment of seismic hazards at LANL includes a probabilistic analysis.

RECOMMENDED GEOLOGIC AND SEISMOLOGIC TASKS

Based on our review of existing data and field reconnaissance in the LANL site area, several specific geologic and seismologic tasks are required to fully characterize potential seismic sources at a level sufficient to provide input to deterministic or probabilistic analyses.

These tasks provide an investigative framework that encourages flexibility and constant refinement and refocusing of the seismic hazard assessment. Many of these tasks were implemented during the current seismic hazard investigation program.



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Characterization of Regional Tectonic Setting

The purpose of this task is to understand the role of potential seismic sources within the context of the regional geologic and tectonic framework, to aid in the development of fault segmentation models, and to assess possible interactions among regional structures. Understanding the regional tectonic setting is critical for assessing the nature and location of inherited deformational structures and for determining the contemporary seismotectonic setting of the site area. This task should include a comprehensive review and analysis of literature and data relevant to Quaternary deformation, seismicity, and tectonic stresses in the site region. The characterization may include analysis of data concerning the nature, amount, rate and timing of fault or fold deformation along regionally significant structures. This task typically results in the analysis, development, and/or refinement of existing tectonic models. Primary objectives of this task should be to assess the nature and rates of regional crustal deformation and to assess the interactions between the Pajarito fault system and the Embudo and La Bajada fault zones. An anticipated result of this assessment would be the estimation of the northern and southern extents of the Pajarito fault zone. A major result of this task should be a map(s) illustrating the distribution of known and potential seismic sources and other related tectonic elements in the site region.

Analysis of Aerial Photography and Imagery

Aerial photography and imagery should be interpreted to refine existing maps of geologic units and potentially fault-related geomorphic features along the Pajarito, Rendija Canyon, and Guaje Mountain faults. Possible sites for paleoseismic investigations along these faults should be identified on the basis of geomorphic expression of deformation, availability of Quaternary deposits to record late Pleistocene and Holocene fault activity, and potential for obtaining well-constrained data on fault behavior and geometry. This task should include analysis of conventional



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black-and-white and color aerial photography, low-sun-angle aerial photography, color infra-red photography, and remote sensing imagery (e.g., SPOT or Landsat Thematic Mapper data).

Reconnaissance Field Investigations

Field investigations should be conducted to verify tectonic and geomorphic features identified during the aerial photography and imagery analysis, to identify additional potentially fault-related features or other significant landforms, to narrow the focus of subsequent investigations, and to assess the feasibility of using various geologic, geomorphic, and paleoseismic techniques to investigate the paleoseismic history of specific seismic sources. This task should include aerial reconnaissance via fixed-wing aircraft and/or helicopter, and ground reconnaissance.

Characterization of Subsurface Geology

The purpose of this task should be to provide additional subsurface information on the amount of deformation of the Bandelier Tuff in the Los Alamos area. The current structural contour map requires additional data control to adequately assess the amount of tectonic deformation along the fault system. Additional documentation of the elevation of the base of the tuff in the vicinity of major faults should allow construction of a well-constrained isopach map of the tuff, and enable interpretation of the amount of post-Bandelier deformation. In addition, elevation of the tuff should be determined through a program of field mapping, analysis of existing seismic and borehole data, and a limited program of additional exploratory drilling in areas of critical data needs.

Detailed Geologic Field Investigations

The purpose of this task should be to provide information on subsurface and near-surface geology, and to map Quaternary deposits and landforms that will yield information on the nature, amount, and timing of Quaternary deformation. In addition, information gathered during this and all previous tasks will be used to select specific paleoseismic trenching



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sites. This task should include shallow drilling, exploratory test pits and detailed mapping of geomorphic features such as fault scarps, displaced fluvial terraces and alluvial fans, and deflected stream channels.

Paleoseismic Trenching

Trenching investigations should be conducted to provide detailed site-specific information on the nature, amount, and timing of late Quaternary displacements on the Pajarito fault system. This task should include exploratory trenching at several sites along faults of the Pajarito fault system. We estimate that up to three trenching sites may be required along the Pajarito fault, depending on site characteristics identified in previous tasks. Multiple trench sites insure that anomalous data from a single site is not used to characterize the entire fault or fault segment. In addition, up to two sites may be required along the Rendija Canyon fault, and one site along the Guaje Mountain fault. Design of the trenching program at each site is dependent on specific site characteristics which will be assessed during previous tasks. We anticipate that 1 to 5 trenches will be excavated at each site. These investigations will provide data on the timing of the most recent surface rupture event, recurrence interval between events, amount of displacement per event, sense of fault slip, and fault geometry.

Age-Dating Studies of Deposits and Geomorphic Features

The age of displaced and undisplaced surficial deposits and landforms is critical to constrain the timing of paleoseismic earthquakes. Based on numerical dating techniques (e.g., radiocarbon, thermoluminescence, K-Ar, U-Th), correlative techniques (e.g., tephrochronology, archaeology, amino-acid racemization), and relative techniques (e.g., relative topographic position, relative soil development, relative scarp or surface morphology), this task will provide data from which to assess the age of faulted, unfaulted, and fault-related deposits, and consequently the timing and rates of deformation.



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Seismicity Evaluation

This task should consist of an evaluation of the contemporary seismicity in the LANL region since 1973 as recorded by the LANL network and adjacent networks operated by agencies such as the USGS and New Mexico Tech. The objective of such an evaluation is to characterize: (1) seismogenic sources in the Los Alamos region in terms of faulting parameters, (2) possible association of seismicity with faults or other geologic structures, and (3) the regional tectonic stresses. The network data should be reviewed for its accuracy, earthquakes relocated using an improved velocity model and station corrections, and focal mechanisms determined when possible. An assessment of the validity of the coda duration magnitude scale currently being used should be made. Estimates of the regional earthquake recurrence should also be made.

Landslide Susceptibility Analysis

A detailed landslide susceptibility map should be prepared for the LANL site based on existing geologic and topographic maps, analysis of aerial photography and imagery, field reconnaissance, and limited detailed mapping. Areas of substantial landslide susceptibility should be delineated and the processes responsible for landsliding evaluated so that mitigation measures can be initiated to reduce the hazard of earthquake-induced ground failure.

Seismic Source Characterization

All seismic sources in the LANL site region should be characterized in terms of capability, maximum magnitude, sense of slip, fault geometry, slip rate, most recent event, and recurrence interval. Such a characterization will be based primarily on data developed from the previous tasks. A logic tree approach will be used to capture the range of interpretations for each fault parameter and method used leading to the assessment of maximum earthquake magnitude. This approach also enables the explicit quantification of uncertainty for each fault parameter and the performance of sensitivity analyses to evaluate which parameters are critical for the



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assessment of maximum magnitude for any particular seismic source. Specific fault parameters to be characterized include segmentation, fault rupture lengths, down-dip rupture width, rupture area, displacement per event, slip rate, and recurrence interval.

Seismic Monitoring

The existing seismographic network at LANL provides critical information on the sources of seismicity in the immediate Los Alamos area. However, the network should be expanded by both increasing the number of stations and the areal extent (out to a radial distance of at least 50 km). The objective of such expansion is to adequately monitor all potential seismic sources that could produce significant strong ground shaking at LANL. Such an expansion would also bring the LANL network up to the technical level of other existing and planned DOE National Laboratory networks in the U.S. The existing network consists of 7 short-period high-gain stations. To maintain a detection threshold of approximately M_L 0 to 1, which is appropriate, the number of stations should be increased to 16 to 20 stations. Stations should be sited to provide sufficient azimuthal coverage for hypocentral determinations and focal mechanisms particularly for those events which may occur in the vicinity of the Pajarito fault system. All existing and new stations should be calibrated. In addition, the currently-used coda duration magnitude scale should be updated and revised if magnitude accuracy can be improved.

Strong Motion Program

The recording of strong earthquake shaking by strong motion instruments located in both the free-field and structures can provide critical data for the evaluation of strong ground motions and the structural performance of buildings and facilities. Even relatively weak motion records can be invaluable data and be used to model both future strong shaking and structural response. As is also the case for other DOE National Laboratories, one or more strong motion instruments should be located in all critical facilities. At present, there are a few instruments located



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at various facilities at LANL. These instruments should be incorporated into a unified strong motion network with a single organizational unit responsible for maintenance, operation and possibly data analysis.

Characterization of LANL Site Geology

It is well known, based on empirical data and observations, that the near-surface geology can significantly influence if not dominate the level and spectral content of strong ground motions. Based on our preliminary evaluation, the Bandelier Tuff beneath the LANL appears to be capable of strongly affecting ground motions. The objective of this task should be to characterize the subsurface geology beneath all critical facilities at least to depths beneath the Tuff. Boreholes should be drilled at these sites and logged for lithology. Downhole shear-wave velocity and damping measurements should be performed in each hole to provide the data necessary for strong motion estimates.

Deterministic Ground Motion Estimates

For high-hazard facilities, a deterministic approach is often used to assess seismic hazards as reflected in the use of Federal Regulatory Guidelines such as 10 CFR-100 Appendix A. Because of facilities such as the Plutonium Processing Facility at TA-55, deterministic estimates of potential strong ground motions may be required as a basis for assessing its seismic safety. In this task, site-specific deterministic estimates of the "worst-case" strong ground shaking should be made which incorporate the effects of a potential near-field earthquake source, site response and site topography. These estimates should be in the form of acceleration response spectra and time histories which can be used for input into seismic design or structural dynamic analysis.

Probabilistic Seismic Hazard Analyses

In the implementation of UCRL-15910 based on the analyses in UCRL-53582, DOE has used probabilistic seismic hazard analyses (PSHA) as the basis for the seismic design of its facilities. For low and moderate hazard hazard



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facilities, we believe the use of a probabilistically-based hazard analysis is appropriate, especially for tectonic regions such as the northern Rio Grande rift where the recurrence intervals of faults may be on the order of several to many thousands of years. Thus in this task, a state-of-the-art PSHA should be performed that incorporates the most up-to-date information on seismic sources considered significant to LANL. The data collected in the previously-described tasks are critical in an accurate assessment of seismic hazards at LANL.

Seismic Design Criteria

Seismic design criteria based on the most up-to-date assessments of potential strong ground motions should be developed for facilities at LANL. Based on the level of hazard for each existing facility (low, moderate, or high), design spectra should be developed from either deterministic or probabilistic criteria. Existing facilities should be evaluated for seismic safety based on their structural performance under loading from the estimated strong ground shaking characterized in the tasks previously described.

REFERENCES

- Gardner, J. N., and House, L., 1987, Seismic hazard investigations at Los Alamos National Laboratory, 1984 to 1985: Los Alamos National Laboratory Report LA-11072-MS, 76 p.
- Gardner, J. N., and House, L., 1990, Revised Briefing Report for the University of California, Health, Safety, and Environment Advisory Committee on the Los Alamos Seismic Hazards Investigations Program: memo to L. Sohlt, dated July 12, 1990, 7 p.

