COMPLIANCE DETERMINATION STRATEGY
RRT 3.2.2.8 POTENTIALLY ADVERSE CONDITION: STRUCTURAL DEFORMATION AND GROUNDWATER

APPLICABLE REGULATORY REQUIREMENTS:

60.122(c)(4)
60.21(c)(1)(ii)(B)
60.21(c)(1)(ii)(F)

TYPES OF REVIEW:

Acceptance Review (Type 1)
Safety Review (Type 3)
Detailed Safety Review Supported by Analysis (Type 4)

RATIONALE FOR TYPES OF REVIEW:

Acceptance Review (Type 1) Rationale:

This regulatory requirement topic (RRT) is considered to be license application-related because, as specified in the license application content requirements of 10 CFR 60.21(c) and in the regulatory guide of the U.S. Nuclear Regulatory Commission (NRC) on "Format and Content for the License Application for the High-Level Waste Repository" (FCRG), it must be addressed by the U.S. Department of Energy (DOE) in its license application. Therefore, the staff will conduct an acceptance review of the license application for this regulatory requirement topic.

Safety Review (Type 3) Rationale:

This regulatory requirement topic is related to containment and waste isolation. It is a requirement for which compliance is necessary to make a safety determination for construction authorization as defined in 10 CFR 60.31 (i.e., regulatory requirements in Subparts E, G, H, I) and 10 CFR 60.21. Therefore, the staff will conduct a Safety Review of the license application to determine compliance with this topic.

This regulatory requirement topic focuses on the potential for structural deformation (i.e., uplift, subsidence, folding, and faulting) to adversely affect the regional groundwater flow system. This is one of the potentially adverse conditions (PAC) in 10 CFR 60.122(c). Structural deformation could conceivably affect a high-level waste repository by directly causing damage to waste packages, a scenario addressed under Section 3.2.1.5 of the license application. This topic focuses on the regional groundwater flow system. The only regional groundwater scenarios that have been identified as potentially having adverse effects on repository performance are those that cause a rise of the potentiometric surface. Such a rise would result in a reduced thickness of the unsaturated zone between the repository and the water table.

In the rationale presented below, the staff examine various forms of structural deformation (i.e., uplift, subsidence, folding, and faulting) to evaluate their potential to adversely affect the regional flow system by causing water tables to rise. The hydrologic effects of earthquakes are also discussed. Quaternary deformation in the region has been extensional in nature, producing a terrane characterized by normal and strike-slip faults. Only minor folding has occurred, and that was in association with the faulting. Based on available information, this trend is not expected to change over the next 10,000 years.

Structural Geology: The proposed Yucca Mountain site is located in a tectonically active area. Tectonism and associated structural deformation may have effects on groundwater flow and water table elevations that are potentially adverse to waste isolation. During the last 10 to 15 million years the Yucca Mountain region has undergone strong tectonic extension (Wernicke et al., 1988) with resultant widespread development of both dip- and oblique-slip normal faults (Scott, 1990), low-angle extensional detachment systems (e.g., Scott, 1990; Maldonado, 1990; Fox and Carr, 1988; Hamilton, 1988) and regional-scale strike slip faults (Stewart, 1987; Wernicke et al., 1989; Zhang et al., 1990; Brogan et al., 1991). Winograd and Thordarson (1968) have suggested that regional-scale faults and fracture zones control interbasin groundwater flow, and are the primary mechanism for basin-scale hydraulic partitioning of the confined regional aquifer system. Naff et al. (1974) also indicate that regional groundwater flow in the southern Great Basin is strongly influenced by tectonic features. Sinton et al. (1989) indicate that major tectonic lineaments, which are primarily topographic expressions of fault systems or fracture zones, strongly influence regional groundwater flow patterns. For example, they interpret the northeast-southwest trending Forty Mile Wash (immediately east of Yucca Mountain) to be coincident with an extensional, perhaps dilatant, fault system or fracture zone. They interpret the northwest-southeast trending Amargosa Valley to be a strike-slip shear zone. Moreover, they conclude that models of regional groundwater flow that include these tectonic pathways will yield substantially different regional groundwater travel times than models that do not consider tectonic features. Thus, simulations of radionuclide transport within the regional aquifer may require models of groundwater flow that are highly anisotropic and discontinuous.

Faults may act either as conduits for flow or as barriers to flow. For example, faulting may produce dilatant zones that are high-conductivity conduits. In contrast, slip-induced granulation and gouge development within the fault zone may produce local zones of low permeability. Galloway et al. (1991) suggest that groundwater within the volcanic tuffs near Yucca Lake flows into a sink created by juxtaposition of the tuffs against the lower carbonate aquifer along the Yucca fault zone. Thus, faults may localize coupling of shallow water-table and perched aquifers to the underlying confined regional carbonate aquifer, thereby localizing flow into the regional aquifer. Alternatively, faulting may place the regionally extensive clastic aquitard section into contact with the carbonate aquifer, resulting in regional-scale barriers to flow (Bedinger et al., 1989).

Hydrologic Effects of Earthquakes: Earthquakes may cause significant, long-term changes in groundwater levels. Spectacular hydrologic effects (discharging wells, increased flows in springs and streams) are sometimes observed following major earthquakes. These phenomena are caused by rapid changes in aquifer storage. The most spectacular seismically caused effects are apparently associated with confined aquifers, where hydraulic pressures can build up more rapidly. In general, although hydrologic effects may sometimes be spectacular, they tend to be relatively short lived. Permanent effects on groundwater levels are reported to be of small magnitude. To look at the severity and duration of hydrologic effects caused by great earthquakes, it was necessary to review seismic events that occurred outside the Basin and Range province. Raney (1988) provides an excellent summary of hydrologic effects caused by earthquakes in western North America. Hsiung et al. (1993) describes analytical methods for simulation of hydraulic response of a rock mass to mining-induced seismicity.

Based on a preliminary review, earthquake seismicity alone is unlikely to raise water tables significantly and for extended periods of time. However, earthquakes are known to cause water tables to rise, and to cause substantially enhanced spring flow (e.g., Wood, 1991; Wood et al., 1985; Whitehead et al., 1985). Such effects tend to be short-lived, rarely lasting for more than a few months. Carrigan et al. (1991) describe the potential for water-table excursions induced by seismic events at Yucca Mountain. They performed numerical simulations of tectono-hydrologic coupling involving earthquakes typical of the Basin and Range province. These simulated earthquakes produced 2-3 m excursions of a water table that is 500 m below the land surface. Even extraordinary seismic events would cause water-table excursions of less than 20 m. Water table systems are less sensitive to seismic events than are confined aquifers, and thus would have reduced responses to earthquakes. Carrigan et al. (1991) conclude that their simulations compare well with observations of water-table rise following large earthquakes in the Basin and Range. For example, the 1954 Dixie Valley-Fairview Peak (Nevada) earthquake (magnitude ~7) produced water-table excursions of about 1-3 m, along with some long-term changes in regional hydrologic behavior. The 1983 Borah Peak, Idaho, earthquake (magnitude ~7.3) caused a rise in the water table of about 4 m. Following the Borah Peak event, water levels returned to normal within two weeks to two months. They considered longer-term changes in the groundwater system to be related to changes in hydraulic conductivity.

Water table fluctuations associated with the San Fernando, California, Earthquake of February 9, 1971, were noted by the Metropolitan Water District of California (MWD, 1973). This earthquake was assigned a magnitude of 6.4 and was followed by 55 aftershocks of magnitude 4.0 and greater. MWD (1973) states that 33 wells and observation holes were monitored monthly to evaluate groundwater levels prior to and during excavation of a tunnel. Water levels in most of the wells were measured three days after the earthquake. Groundwater levels dropped in 18 wells and rose in six wells. Water levels were essentially unchanged in nine wells. The average change was about 0.6 m. Groundwater levels dropped dramatically (8.5 to 30.5 m) in five wells. Most wells recovered slowly, but some wells had only partially recovered as of 1973.

O'Brien and Tucci (1992) describe earthquake-induced water table fluctuations at Yucca Mountain. The data were obtained from two wells instrumented to continuously monitor fluctuations in the water table and fluid pressure in a deeper, isolated interval. Two major earthquakes occurred in southern California on June 28, 1992. Both were about 300 km from the Yucca Mountain site, and were measured as having magnitudes of 7.5 (Landers) and 6.6 (Big Bear Lake). The Landers and Big Bear Lake quakes caused estimated local water table fluctuations of 0.9 m and 0.2 m, respectively. An earthquake of magnitude 5.6 occurred at Little Skull Mountain on June 29, 1992, about 30 km from the Yucca Mountain site. The maximum fluctuation of the water table was estimated at 0.4 m. This earthquake did not produce any known fault scarps in the land surface.

From a hydrogeologic perspective, one of the most spectacular earthquakes was the powerful (M = 7.3) Borah Peak, Idaho earthquake of October 28, 1983 (Wood et al., 1985). Hydrologic effects included increased stream discharges, a 35m surge in artesian pressure from carbonate bedrock near the epicenter, and the drying up of a major warm springs area for eight days, which then started flowing at an increasing rate until it stabilized at nine times the pre-quake flow. Also, increased groundwater seepage occurred at the Clayton Silver Mine, overwhelming available pumping capacity and flooding a significant portion of the deeper mine workings. The water rose 59.5 m in 10 days, even while being pumped at 62 l/s (980 gpm). Data presented by Wood et al., (1985) suggest that, through 1984, the regional aquifer system was recovering very slowly from the effects of this major earthquake.

Szymanski (1989) asserted that groundwater at Yucca Mountain had risen to repository level repeatedly in the past, primarily due to tectonic processes. A panel of the National Research Council (1992) evaluated the potential for future rises of the water table to occur at Yucca Mountain. Hydrologic effects of some historic earthquakes were discussed. The panel did not reach any definitive conclusions about how high the water table might rise in response to earthquakes. However, they concluded that there is no evidence to support the assertion that the water table has periodically risen hundreds of m from deep within the earth. The panel (National Research Council, 1992, p. 128) concluded that "... while there are uncertainties in current interpretations because specific site data are not available, ... there is nevertheless sufficient confidence in the aseismicity of the site and in the inability of earthquakes to generate large water table changes at the site ... to warrant further characterization of the site to determine its suitability ... ."

There is some evidence that relatively strong earthquakes may not have occurred at Yucca Mountain for thousands of years. This evidence takes the form of precariously balanced boulders of welded tuff that have been found along steep slopes at the site. Brune (1992) describes rockfalls that occurred near the epicenter at Little Skull Mountain during the earthquake on June 29, 1992. A large number of precariously balanced rocks had previously been identified in Solitario Canyon near the Yucca Mountain site. None of these were toppled by the earthquake at Little Skull Mountain, suggesting that the proposed repository site has not experienced large ground accelerations (greater than about 0.2 g) in the last few thousand years. However, the fact that precarious rocks in Solitario Canyon were not toppled does not rule out the possibility that earthquakes like the Little Skull Mountain event may be relatively common. Brune and his coworkers are developing a research technique to quantitatively estimate upper limits on ground motion for the last several thousand years, and perhaps for the Holocene epoch. Part of this technique relies on using rock varnish coatings to estimate how long the precarious rocks have been subareally exposed.

The work of Brune (1992) and his coworkers may eventually provide estimates for upper limits on Holocene ground accelerations. However, this research involving precarious rocks is controversial, and the NRC staff should await the publication of peer-reviewed, scientific reports before deciding on its technical merits. In the meantime, methods exist to estimate the intensity of earthquakes that may accompany fault movements. Examination of the various active faults in the Yucca Mountain region - such as the Paintbrush Fault, or the Solitario Fault, and comparison of the length of these faults with standard charts (such as are found in Campbell, 1981, or Joyner and Boore, 1982) would suggest that earthquakes in the range of magnitude 6.5 to 7 could occur in the Yucca Mountain site area and should be considered in evaluating the effects of earthquakes on groundwater. The actual magnitude range which should be considered must await the results of site characterization, and a determination of whether fault movements could occur gradually and aseismically.

To summarize this discussion about the hydrologic effects of earthquakes; at present there is no evidence that even a great earthquake near Yucca Mountain could elevate water levels high enough to inundate the proposed repository, even for a short period of time. There is also no evidence that earthquakes will cause water levels to permanently rise to a significant degree. In parts of the world where spectacular hydrologic effects have been caused by earthquakes, confined hydraulic conditions were associated with phenomena like groundwater shooting out of wells. Examples include the 1983 earthquake at Borah Peak, Idaho and the Alaskan earthquake of 1964. Unconfined aquifers, like the uppermost part of the saturated zone at Yucca Mountain, respond much less to seismic energy than confined aquifers.

Uplift, Subsidence, and Faulting: Potential for significant uplift and subsidence (and accompanying faulting) to occur over the next 10,000 years have also been examined. These processes are occurring in the region, and over millions of years have produced the terrane and climate observed today in southern Nevada. Uplift of the Sierra Nevada and Transverse ranges has been occurring since Pliocene time, producing the rain-shadow effect that causes the extremely arid climate observed in southern Nevada. Three million years ago, the Sierra Nevada range is estimated to have been about 950 m lower (Winograd and Szabo, 1988). The Death Valley basin is continuing to slowly subside, a process that has produced a large closed basin and the lowermost hydraulic potential in the region. The lowest topography in Death Valley is below sea level, and the basin serves as the ultimate sink for surrounding regional groundwater systems.

Paleo-climatic and paleo-hydrologic evidence indicates that groundwater levels in the south-central Great Basin may have slowly declined throughout the Quaternary. At a given location, apparent declines may be caused by tectonic uplift, erosional history, climate change, or a combination of these. For example, if a local area experiences uplift, the potentiometric surface will tend to maintain equilibrium with surrounding areas and maintain the same relative altitude. However, as uplift progresses, the potentiometric surface will grow deeper with respect to land surface and will appear to have been lowered, when in fact it was the land surface that was raised. Winograd and Szabo (1988) concluded that, during the early and middle Pleistocene, the water table at Ash Meadows, the Amargosa Desert, and at Furnace Creek Wash was tens to hundreds of meters above the modern water table. The field evidence for this water level change is based on locations of paleo-groundwater discharge (vein calcite, tufa), indicators of paleo-water levels, and isotopic dating of calcite veins and laminations. The evidence pertains to the regional Paleozoic carbonate-rock aquifer, but Winograd and Szabo (1988) suggest that groundwater levels in this regional aquifer exert a major control on the altitude of the potentiometric surface in overlying Cenozoic welded tuff and valley-fill aquifers. Winograd and Szabo concluded that, based on a synthesis of regional hydrogeologic, tectonic, and paleoclimatologic data, a progressive and absolute lowering of the potentiometric surface likely occurred throughout the south-central Great Basin during the Quaternary.

Overall, Winograd and Szabo (1988, p. 147) conclude that "Wastes buried a few tens to perhaps 100 m above the modern water table — that is above possible water level rises due to future pluvial climates -- are unlikely to be inundated by a rising water table in the foreseeable geologic future." They further conclude (pages 151-152) that "the continuing uplift of the Sierra Nevada...and Transverse Ranges, and lowering of Death Valley...relative to surrounding regions, should result in a continued progressive decline of the regional water table in the next 100,000 to 1 million yr (and beyond?) in response to increasing aridity and to lowering of groundwater base level."

There is evidence of a higher water table in the past, but if the cause is solely tectonic, it means that Yucca Mountain has subsequently risen in absolute altitude. A higher water table could have been caused by a wetter and cooler climatic period characterized by increased precipitation, infiltration, and recharge. Marshall et al. (1993) describe strontium isotopic evidence for a higher water table at Yucca Mountain. They conclude that the water table may have been about 85 m higher in the past. This rise in the water table is similar to predictions made by Czarnecki (1985), who simulated the effects of a future increase in precipitation and recharge on water levels. Czarnecki concluded that a doubling of precipitation in the future could lead to a maximum water table rise of 130 m beneath Yucca Mountain. Ahola and Sagar (1992) concluded that the water table could rise as much as 275 m due to conditions including increased precipitation/recharge and intrusion of igneous dikes.

Fault Displacements: Carr (1984, p. 2) states that "Tertiary structure of the Yucca Mountain area was greatly influenced by volcano-tectonic processes, and the youngest significant faulting appears to be spatially and temporally related to igneous activity. At Yucca Mountain, evidence for general long-term stability is good, as nearly all of the fault displacement occurred prior to about 10 m. y. ago, in harmony with a dramatic decrease in silicic volcanism in the late Miocene." Carr notes the dramatic decrease in rates of faulting since that time, and that nearly all persistent faulting has occurred through the reactivation of preexisting faults.

At present, there is no evidence that significant uplift or subsidence have occurred at Yucca Mountain during the Holocene, although minor fault displacements have likely happened during this time. Carr (1984) states that probable Holocene displacement has occurred on the Yucca Fault in Yucca Flat, located east of Yucca Mountain. He also reports that slight Holocene movement cannot be ruled out on several other faults. Extensive work involving trench excavations is continuing at the site to evaluate whether Holocene movements have occurred on major faults near Yucca Mountain. Carr estimated the average rate of displacement for two of the largest faults. The rate has been estimated to be less than 0.03 m/1000 yr for the Paintbrush Canyon fault and less than 0.11 m/1000 yr for the Windy Wash Fault et al., Carr (1984) describes the difficulty of determining the amount and rate of Quaternary fault displacements at Yucca Mountain, but notes that the amounts of Quaternary movement cannot have been very large.

DOE (1988, p. 1-128) describes the Quaternary history of faulting at Yucca Mountain. Quaternary deposits are offset by 32 faults in the 1100 km^2 area that surrounds the site. Studies suggest that 23 of these faults moved 1.2 to 2 million years ago, four moved about 1 million years ago, and at least five moved during the past 270,000 yr. Estimated rates of Quaternary fault displacements are provided by DOE (1988, p. 1-132 to 1-133), as shown below:

FAULT NAME	ESTIMATED RATE OF MOVEMENT
Bare Mountain Fault	0.1 to 0.01 mm/yr
Windy Wash Fault	0.0015 mm/yr
Solitario Canyon Fault	No evidence of movement over past 270,000 yr
Bow Ridge Fault	No evidence of movement over past 28,000 to 48,000 yr
Paintbrush Canyon Fault	0.005 mm/yr

There is considerable uncertainty regarding rates of deformation (Scott, 1990). Ongoing site characterization work raises questions about the rates of movements that were quoted in the SCP. For example, during the NRC/DOE site visit of May 25-26, 1993, volcanic ash believed to have come from the Lathrop wells cone was observed in Trench T-8. It appears that three or four faulting episodes may have occurred after deposition of this ash (personal communication from John Whitney [USGS] to John Trapp [NRC]). Based on the uncertainty of the age of this ash it would appear that the late Pleistocene recurrence rate may vary from about one surface faulting episode every 30,000 years to about one episode every 10,000 years. For surface displacement to occur, this would generally require an earthquake on the order of magnitude 6 or greater (unless the movement was aseismic). It is not clear whether any of these movements occurred during the Holocene. Rates of tectonic deformation will continue to be intensively studied, and more extensive and reliable data should be available prior to receipt of a license application.

In a recent report, Menges et al. (1993) documented five or six discrete fault movements and between 76 and 132 cm of slip on the Bow Ridge fault. These fault movements are believed to have occurred since the middle to late Pleistocene. They estimated an average slip rate of 0.001 mm/yr.

Significant fault offsets have occurred on the Nevada Test Site in response to nuclear tests. For example, a small graben formed in western Yucca Flat following a test in the summer of 1977, with surface displacements (fault scarps) of 1.5-2 meters (Coleman, 1977). This displacement forced the closure of a road that ran perpendicular to the trend of the previously unknown faults.

It should be mentioned that some faults may remain undiscovered throughout site characterization. A buried fault will remain undiscovered unless it: (1) is coincidentally intersected by a borehole (an unlikely occurrence given many high-angle faults and the use of vertical drillholes); (2) has a significant geophysical signature; (3) produces a hydrologic anomaly; or (4) is encountered during underground excavations. For faults not detected in these ways, researchers must rely on the presence of alluvial fault scarps or subdued topographic evidence of former scarps to infer their presence. Given current climatic conditions at the site, it is reasonable to assume that buried faults have been relatively inactive during the Holocene unless represented by fault traces or scarps.

DOE is not solely relying on direct examination of fault zones to estimate rates of tectonic movement. Detailed geodetic data are being collected to detect whether any slight shifts in the positions of major geologic blocks can be observed during the period of site characterization. Study Plan 8.3.1.17.4.10 (DOE, 1991b) will evaluate the historical and contemporary displacement of significant Quaternary faults within 100 km of Yucca Mountain. This study is intended to directly assess whether gradual uplift or subsidence are occurring at the Yucca Mountain site. Two specific evaluations will be made: (1) to determine the probability of exceeding 30-m elevation change in 10,000 yr; and (2) to determine the probability that the repository will be lowered by 100 m through faulting over the next 10,000 yr. It is possible that subsidence and uplift could occur incrementally rather than gradually, and thus may be undetected during the period of site characterization. However, this geodetic work should continue through the performance confirmation period, providing a much longer and more reliable baseline regarding contemporary fault displacements and relative tectonic stability of the site.

Detailed Safety Review Supported by Analyses (Type 4) Rationale:

The staff considers that there may be high potential risk of noncompliance with applicable regulatory requirements because, for the Yucca Mountain site, there exists a Key Technical Uncertainty (KTU). Therefore, the staff will conduct a Detailed Safety Review Supported by Analysis of the License Application to determine compliance with this regulatory requirement.

The KTU for this CDS concerns the nature of the large hydraulic gradient that occurs north of the Yucca Mountain site. Groundwater levels in wells G-2 and WT-6 are much higher than wells a few kilometers to the south. The cause of this high gradient has not been confirmed. If the cause is a fault, then future tectonic disruptions of the regional flow system must be considered. If not, then concern about structural deformation on the regional flow system may be reduced. DOE has specific plans to explore the large hydraulic gradient to ascertain its nature and characteristics. These include the drilling of a number of new wells. Wells WT-23 and WT-24 will be located at intermediate distances between two of the wells that define the high gradient, H-1 and G-2 (DOE, 1991d). Borehole UZ-14, which will be drilled in Drill Hole Wash in 1993, may also help to define the nature of the high gradient. Proposed borehole G-5 (DOE, 1993a) is also intended to help determine whether lithological or structural causes are responsible for the steep hydraulic gradient.

In addition, DOE is presently planning a series of geophysical investigations to better define the characteristics of this steep gradient. Proposed work includes such things as detailed gravity, magnetic, electrical and seismic reflection/refraction work in the area of the gradient and Yucca Wash (NRC/DOE Technical Exchange on Geophysics Integration, June 8, 1993 - minutes not yet published). The exact work which will be performed is not yet finalized. It will include seismic investigations in a series of boreholes north of the proposed site. DOE (1992e) shows the locations of these boreholes along a one-km line, just west of well WT-6. The boreholes are designated U-25 Seismic #1 to #19.

Czarnecki (1989), and Sinton (1989) suggest that a fault zone coincident with Yucca Wash is a barrier to flow and is the cause of the anomalously high potentiometric gradient across the north end of Yucca Mountain. Fridrich et al. (1991) hypothesize that the fault zone provides a conduit for local flow from the volcanic aquifer into the underlying regional carbonate aquifer, and that the apparent gradient is the result of laterally variable capture of flow across the fault zone. Thus, until planned studies are completed, significant uncertainties will remain in hydrogeologic models of faults at Yucca Mountain. Furthermore, the lateral extent, stratigraphic relationships, and structural configuration of the carbonate aquifer below Yucca Mountain are not well known (Winograd and Thordarson, 1975).

Czarnecki (1990) developed a transient version of his regional groundwater flow model (Czarnecki, 1985) to investigate the large hydraulic gradient located north of the Yucca Mountain site. One scenario he analyzed was the simulated tectonic disruption of a postulated hydrologic barrier. Such a scenario, which could arise due to faulting associated with an earthquake, could cause large volumes of groundwater to be released to flow southward toward the repository site. This scenario caused a maximum rise of about 40 meters in the simulated water-level at Yucca Mountain (National Research Council, 1992, citing a personal communication with J. Czarnecki). Ahola and Sagar (1992) also investigated the potential for the water table at Yucca Mountain to rise in future. However, their preliminary results were obtained using a non-calibrated model that did not represent surface topography and drainage or the potential for springs to form under scenarios of water table rise. The simulated water table rise would be significantly less if springs had been permitted to form in the model. Ahola and Sagar (1992) evaluated future scenarios including: (1) increased recharge due to climatic change; (2) a rise of water level at the Alkali Flats (Franklin Lake Playa) discharge area; (3) geologic activity south of Yucca Mountain, creating a flow barrier 20 km long; and (4) geologic activity north of the site, breaking a theorized flow barrier. They developed a finite-difference model to evaluate these scenarios and reported that simulated rises in the water table varied from several meters to as much as 275 m. The simulated intrusion of an igneous dike 20 km in length, located southeast of Yucca Mountain, caused a simulated rise in the water table of 175-200 m. In another geologic scenario, the steep hydraulic gradient was assumed to be caused by a low-permeability feature that could be disrupted by tectonic activity. The permeability of this postulated feature was suddenly increased, allowing extensive groundwater flow from north to south. This increased groundwater flow caused a simulated water table rise of about 275 m beneath Yucca Mountain.

According to Ahola and Sagar (1992, p. 1-1), their "analysis results should be considered as very preliminary...[and] likely to change when actual field data are used in simulations." As mentioned above, their model was not calibrated; rather, parameter values from previous studies were used. Unlike Czarnecki's (1985) model, Ahola and Sagar did not compare the simulated water table surfaces with land surface altitudes, which would have permitted the simulated occurrence of springs. As stated by Ahola and Sagar (1992, p. 7-1), "incorporating the effect of springs and increased evaporation as the water table approaches the land surface would lower the extent of water table rise in adjacent areas." It should be added that there is no evidence at present that an igneous dike is likely to form southeast of the Yucca Mountain site in the relatively short time span (geologically speaking) of 10,000 years. Also, the source of the high hydraulic gradient north of the site is presently unknown, but is planned to be explored and studied by DOE (see previous section).

The following KTU is considered to require a Type 4 review because there is a high risk of noncompliance with the overall system performance objective specified in 10 CFR 60.112. This concern of high risk of noncompliance necessitates analyses above and beyond that required for a Type 3 review in order to assure that uncertainties and potential adverse effects on performance have been adequately evaluated and minimized to the extent possible. The analysts conclude that a safety determination could be made by evaluating information submitted by DOE in the License Application and by acquiring and using codes and models developed by DOE. At this time, a Type 5 review is not considered necessary because the NRC's independent use of existing codes and models should be adequate to evaluate future hydrologic changes related to the large hydraulic gradient.

Key Technical Uncertainty Topic: The cause of the large hydraulic gradient located north of Yucca Mountain, and potential for tectonic disruption of fault-related barriers.

Description of Uncertainty: The cause of the large hydraulic gradient located north of Yucca Mountain is unknown. Whatever geologic feature causes the high gradient appears to function as a groundwater barrier. This causes hydraulic heads in the saturated zone north of Yucca Mountain to be much higher than those underlying the site. At Yucca Mountain, the water table occurs at depths of about 150-360 m below the proposed underground facility (DOE, 1988, p. 3-41).

Performance Objectives at Risk: 10 CFR 60.112, 10 CFR 60.113(a)(1), and 10 CFR 60.113(a)(2).

Explanation of Risk: The geologic feature that causes the high hydraulic gradient may be susceptible to seismic disruption. If site characterization demonstrates this, then a performance assessment scenario will have to be developed in which the feature would be removed, permitting the southward flow of groundwater previously stored behind the barrier. In these scenarios, released groundwater would flow southward in sufficient amounts to significantly raise the potentiometric surface. Although a rise of the water table under such a scenario would probably not be great enough to inundate the repository, it would reduce the thickness of the unsaturated zone. Since the unsaturated zone at Yucca Mountain is considered the principal component of the natural barrier, a thinner zone would reduce the ability of the natural barrier system to isolate wastes.

Description of Resolution Difficulty: It is not expected that there will be any difficulty in determining the cause of the high hydraulic gradient. DOE has plans to drill new exploratory holes to identify the geologic source of the high gradient, and additional geophysical work is also planned. However, if the source is found to be fault-related, then modeling scenarios involving disruption of the fault will need to be analyzed to evaluate whether the potentiometric surface beneath Yucca Mountain is susceptible to dramatic changes. This kind of groundwater modeling can help estimate the magnitude of hydrologic changes that may occur, but it is subject to all of the uncertainties that exist within the hydrologic testing and groundwater modeling programs, including the uncertainties of model calibration. Also, the potential for new flow "barriers" to evolve south of Yucca Mountain will be difficult to estimate. Such estimates will probably be based heavily on expert opinions.

The isolation of high-level nuclear wastes is considered to be favored by building the disposal facility in an unsaturated zone. It is thought that waste canisters may last longer if not immersed in water, and that any wastes that may escape will travel more slowly under unsaturated conditions. However, these perceived advantages could vanish if the repository were to become saturated in the future, or if the thickness of the unsaturated barrier were significantly reduced in thickness.

To address this potential concern, DOE may need to address the following technical concerns in site characterization work: (1) What is the elevation of the highest historical water table beneath Yucca Mountain? (2) Has the candidate horizon (Topopah Spring) ever been saturated since this tuff unit was first deposited? (3) What is known about water table changes in the past? (4) What projections can be made about future water table elevations? (5) What is the cause of the large hydraulic gradient located north of the Yucca Mountain site? Other technical concerns include those related to characterizing and modeling the site and regional hydrogeology. These include uncertainties in well distributions, boundary conditions, structural controls on groundwater flow, and regional evaluation of recharge and other hydrogeologic parameters.

Summary: The following assumptions have been made in assigning a Type 4 level of review to this CDS:

(1) The Yucca Mountain site is located in a region which is tectonically and seismically active. Geological faults, both seismic and perhaps aseismic, are common tectonic features at Yucca Mountain.

(2) Estimates of aseismic, coseismic and interseismic strain at Yucca Mountain are very uncertain. It is likely that some faults at Yucca Mountain are active, and that fault slip will continue over the 10,000 year period of regulatory concern. To date, based on apparent rates of Holocene movements, site characterization suggests that rates of future fault movements can be expected to be low.

(3) Geological faults affect regional groundwater conditions in the Basin and Range region. The ability to detect geological faults, evaluate their hydrogeologic characteristics, and interpret results of hydrogeologic analyses is limited by the geological complexity of the Yucca Mountain region.

(4) The large hydraulic gradient north of the Yucca Mountain site is assumed to have a structural origin (not stratigraphic), meaning that future tectonic events could significantly change the local and regional flow system. Under this assumption, it should be expected that water levels could rise in future as a result of tectonic effects, resulting in an unsaturated zone of reduced thickness.

(5) If the large hydraulic gradient is caused by a fault zone (as is assumed), then an analogous feature could form south of Yucca Mountain, altering regional flow patterns and causing a local rise in the potentiometric surface.

(6) At the present time, there is no evidence that significant folding, uplift, or subsidence have occurred in the site vicinity during the Holocene.

(7) Known regional patterns of uplift (Sierra Nevada and Transverse ranges) and subsidence (Death Valley) are climatically and tectonically favorable with respect to long-term waste isolation at Yucca Mountain.

(8) Future seismic events are not expected to adversely affect the regional groundwater flow system.

(9) The depth of the potentiometric surface and the prevailing unconfined conditions in the upper part of the saturated zone make short-term flooding of a repository at Yucca Mountain unlikely due to seismic pumping.

(10) For individual faults, and for the region of southern Nevada, the rate of structural deformation during the Quaternary may serve as a good model for estimating the kind and degree of structural deformation that will likely occur over the next 10,000 years.

(11) Evidence of previous higher stands of the water table indicates that the climate was formerly somewhat wetter and cooler, or that Yucca Mountain may have been gradually uplifted. Paleoclimatic data collected to date suggest that climate change alone could account for the lowering of the potentiometric surface.

Reassessment: The level of review for this section of the license application may have to be reassessed in the future if characterization shows the presence of either of the following conditions at Yucca Mountain. Neither of these conditions are now known to be present, but their possible existence or future occurrence must be evaluated as part of site and regional characterization:

1. Evidence of paleo-changes in water table elevation beneath Yucca Mountain is not consistent with paleo-climatic data. In other words, there is evidence of a significant water table rise during periods of similar or dryer climate, or evidence of a decline in the water table during periods of wetter or similar climate.

2. The proposed disposal horizon is susceptible to inundation due to catastrophic changes in subsurface conditions. For example, the geologic conditions responsible for causing the large hydraulic gradient north of the site may be susceptible to rapid tectonic changes that could result in a massive release of groundwater from north to south. The cause of the large hydraulic gradient is presently unknown.

REVIEW STRATEGY:

Acceptance Review:

In conducting the acceptance review of the potentially adverse condition (PAC) concerning structural deformation and groundwater, the reviewer should determine if the content of the license application is complete in technical depth and breadth with respect to the information requested by Section 3.2.2.8 of regulatory guide "Format and Content of the License Application for the High-Level Waste Repository" (FCRG). The reviewer should determine whether the license application contains all appropriate information with respect to this PAC that the staff needs to support the safety review (described below) and total system and subsystem performance assessments.

The information contained in the license application should be presented in such a way that the assumptions, data, and logic lead to a clear demonstration of compliance with the requirements. The reviewer should not be required to conduct extensive analyses or literature searches. The reviewer should also determine whether an appropriate range of alternative interpretations and models has been described. Finally, the reviewer shall determine if the U.S. Department of Energy (DOE) has either resolved all the NRC staff objections that apply to the applicable regulatory requirements or provided all the information requested in Section 1.6.2 of the FCRG, for unresolved objections. The reviewer will evaluate the effects of any unresolved objections, both individually and in combination with others, on: (1) the ability of the reviewer's to conduct a meaningful and timely review; and (2) the ability of the Commission to make a decision regarding construction authorization within the three-year statutory period.

Safety Review:

The regulatory requirement topic is limited to considering the potential for structural deformation, such as uplift, subsidence, folding, or faulting to adversely affect the regional groundwater flow system. It does not directly address other phenomena that may influence the regional flow system. The potential for climate change to adversely affect the hydrologic system will be covered under Section 3.2.4.2 of the license application (PAC - Changes to the Hydrologic System from Climate). The potential for foreseeable human activities to adversely affect the hydrologic system is considered under Section 3.2.2.6 (PAC - Human Activity and Groundwater). The potential for the potentiometric surface to rise and flood a repository is covered under Section 3.2.2.11 (PAC - Potential for the Water Table to Rise and Inundate a Repository). Section 3.2.2.9 (PAC - Changes in Hydrologic Conditions) covers the potential for changes in hydrologic conditions that would affect radionuclide migration to the accessible environment. It does not focus on the individual future events that would cause the hydrologic changes, which would include climatic change, tectonic effects, and human activities. Rather, it addresses the combinations of these processes and the corresponding effects they could have on the migration of radionuclides to the accessible environment. It is emphasized that Section 3.2.2.8 (this topic) addresses effects on the regional flow system, and thus relates only to the saturated zone, not the unsaturated zone. Unsaturated zone conditions are mainly of interest at the scale of the proposed repository block. Section 3.2.2.9 will address the potential for changes in unsaturated zone conditions.

Section 3.2.2.7 of the license application (PAC - Naturally Produced Surface Water Impoundments) will address the potential for natural phenomena such as landslides, subsidence, or volcanic activity to create large-scale surface water impoundments that could adversely affect the regional groundwater system. These phenomena would generally be associated with structural deformation and tectonics. Accordingly, some overlap should be expected in the work under Sections 3.2.2.8 (this topic) and 3.2.2.7, mainly under the topic of enhanced recharge. However, Section 3.2.2.7 focuses strictly on natural impoundment scenarios. If such impoundments were to form southeast of Yucca Mountain along Forty Mile Wash, it would result in the capture and recharge of runoff from extreme precipitation events in this drainage basin. That would serve to somewhat elevate the water table beneath the mountain. To significantly affect Yucca Mountain, such impoundments would have to form very close to Yucca Mountain, would have to persist for a long time by strongly resisting erosion, and would have to be simultaneously accompanied by dramatically increased precipitation and runoff. Without greatly increased runoff there would be insufficient surface water to fill the hypothesized impoundments. In general, the staff considers it unlikely that the simultaneous processes and events required to affect the regional flow system will occur, or that any corresponding water table rise would be so great as to inundate the repository.

Section 3.2.1.5 of the license application (PAC - Structural Deformation) will address the degree to which structural deformation (i.e., Quaternary uplift, subsidence, folding, and faulting) is characteristic of the controlled area or may affect isolation within the controlled area. The manner in which structural deformation may adversely affect the regional groundwater system is covered under Section 3.2.2.8 (this topic).

In conducting the Safety Review, the reviewer will, at a minimum, determine the adequacy of the data and analyses to support DOE's demonstrations of compliance with 10 CFR 60.122(c)(4). Specifically, DOE must (1) provide information to determine whether, and to what degree, the PAC is present; (2) provide information to determine to what degree the PAC is present, but undetected; (3) assure the sufficiency of the lateral and vertical extent of the data collection; and (4) evaluate the information presented under the first two items above, with assumptions and analysis methods that adequately describe the presence of the PAC and ranges of relevant parameters.

Following the acceptance review, the first step will be to evaluate DOE's analyses to determine if the following basic assumptions have been met:

(1) The Yucca Mountain site is located in a region which is tectonically and seismically active. Geological faults, both seismic and perhaps aseismic, are common tectonic features at Yucca Mountain.

(2) Estimates of aseismic, coseismic and interseismic strain at Yucca Mountain are very uncertain. It is likely that some faults at Yucca Mountain are active, and that fault slip will continue over the 10,000 year period of regulatory concern. To date, based on apparent rates of Holocene movements, site characterization suggests that rates of future fault movements can be expected to be low.

(3) Geological faults affect regional groundwater conditions in the Basin and Range region. The ability to detect geological faults, evaluate their hydrogeologic characteristics, and interpret results of hydrogeologic analyses is limited by the geological complexity of the Yucca Mountain region.

(4) The large hydraulic gradient north of the Yucca Mountain site is assumed to have a structural origin (not stratigraphic), meaning that future tectonic events could significantly change the local and regional flow system. Under this assumption, it should be expected that water levels could rise in future as a result of tectonic effects, resulting in an unsaturated zone of reduced thickness.

(5) If the large hydraulic gradient is caused by a fault zone (as is assumed), then an analogous feature could form south of Yucca Mountain, altering regional flow patterns and causing a local rise in the potentiometric surface.

(6) At the present time, there is no evidence that significant folding, uplift, or subsidence have occurred in the site vicinity during the Holocene.

(7) Known regional patterns of uplift (Sierra Nevada and Transverse ranges) and subsidence (Death Valley) are climatically and tectonically favorable with respect to long-term waste isolation at Yucca Mountain.

(8) Future seismic events are not expected to adversely affect the regional groundwater flow system.

(9) The depth of the potentiometric surface and the prevailing unconfined conditions in the upper part of the saturated zone make short-term flooding of a repository at Yucca Mountain unlikely due to seismic pumping.

(10) For individual faults, and for the region of southern Nevada, the rate of structural deformation during the Quaternary may serve as a good model for estimating the kind and degree of structural deformation that will likely occur over the next 10,000 years.

(11) Evidence of previous higher stands of the water table indicates that the climate was formerly somewhat wetter and cooler, or that Yucca Mountain may have been gradually uplifted. Paleoclimatic data collected to date suggest that climate change alone could account for the lowering of the potentiometric surface.

If one or more of these assumptions is not met, the staff review may require a different strategy for evaluating DOE's compliance demonstration. It is expected that any significant deviation will be known in advance of submittal of a license application, and that this strategy shall be revised accordingly.

If the above assumptions have been met, the reviewer will determine the adequacy of the data and analyses presented in the license application regarding the presence or absence of this PAC. The staff should confirm that DOE has submitted the following: (1) information on the approximate range of altitudes at which the water table had existed during the Holocene; (2) evidence concerning the highest altitude attained by the water table beneath Yucca Mountain - this evidence would probably consist of mineralogic, geochemical and isotopic data from drill cores; it may also include information on the physical and textural properties of volcanic glass and minerals within the tuffs, and how those properties may change during saturation by groundwater; (3) paleoclimatic data on past levels of recharge and discharge; (4) field evidence of Holocene springs that existed near Yucca Mountain, and their structural controls; (5) data on the nature and rates of structural deformation and tectonic processes during the Quaternary, and particularly the Holocene; (6) data on the cause of the large hydraulic gradient that exists north of Yucca Mountain, and an analysis of its hydrologic characteristics; and (7) all available data on the hydrologic properties of fault zones in the saturated zone at Yucca Mountain.

DOE will also need to explain how models are supported that are used to assess the presence or absence of the PAC. Analyses and models that will be used to predict future conditions and changes in the geologic setting shall be supported by an appropriate combination of methods such as field tests, laboratory tests that are representative of field conditions, monitoring data, and natural analog studies. For purposes of determining the presence or absence of this PAC, investigations should extend from the ground surface to a depth sufficient to determine critical pathways for radionuclide migration from the underground facility. Investigations should be sufficient to demonstrate a suitable understanding of potential effects of structural deformation and tectonic processes on groundwater conditions such that reasonable bounds can be placed on the different conceptual models.

In general, the reviewer should assess the adequacy of the investigations of the PAC for evidence of potential effects of structural deformation on groundwater conditions, both within the controlled area and outside the controlled area, as necessary. The specific aspects of the license application on which the reviewer will focus are discussed in the FCRG, and the acceptance criteria will be identified in Section 3.0 of this Review Plan.

In conducting the aforementioned evaluations, the reviewer should determine that DOE uses: (1) analyses that are sensitive to evidence of the PAC; and (2) assumptions which are not likely to underestimate its effects. In general, the reviewer will assess the adequacy of DOE's investigations regarding the likelihood of this PAC, both within the controlled area and outside the controlled area, as necessary, in the manner defined in 10 CFR 60.21(c)(1)(ii)(B).

Reviewers will rely on staff expertise and independently-acquired knowledge, information, and data such as the results of research activities being conducted by the NRC Office of Regulatory Research, in addition to that provided by the DOE in its license application. The reviewer should focus on additional data which can refine knowledge of the PAC, and should perform, as necessary, additional analyses to confirm the resolution capabilities of the methods. The reviewer must have acquired a body of knowledge regarding these and other critical considerations in anticipation of conducting the review to assure that site characterization has been sufficient in scope and depth to provide the information needed to resolve the concerns.

Finally, investigations in the following DOE site characterization program study plans are expected to produce data and analyses needed to help in the review described above to address the presence or absence of this PAC:

STUDY PLAN NO.	TITLE
8.3.1.2.1.3	Characterization of the Yucca Mountain Regional Ground-Water Flow System (DOE, 1991a)
8.3.1.2.1.4	Regional Hydrologic Synthesis and Modeling (DOE, 1992c)
8.3.1.2.2.7	Hydrochemical Characterization of the Unsaturated Zone (DOE, 1990a)
8.3.1.2.3.1.1-6	Characterization of the Site Saturated-Zone Groundwater Flow System (DOE, 1991d)
8.3.1.2.3.2	Characterization of the Yucca Mountain Saturated-Zone Hydrochemistry (DOE, 1992d)
8.3.1.2.3.3	Site Saturated-Zone Hydrologic System Synthesis and Modeling (DOE, 1992a)
8.3.1.3.2.1	Mineralogy, Petrology, and Chemistry of Transport Pathways (in preparation)
8.3.1.3.2.2	History of Mineralogic and Geochemical Alteration of Yucca Mountain (DOE, 1992b)
8.3.1.3.3.4	Conceptual Model of Mineral Evolution (in preparation)
8.3.1.4.2.1	Characterization of the Vertical and Lateral Distribution of Stratigraphic Units Within the Site Area (1993a)
8.3.1.4.2.2	Characterization of the Structural Features Within the Site Area (DOE, 1992h)
8.3.1.4.3.1	Systematic Acquisition of Site-Specific Subsurface Information (DOE, 1992f)
8.3.1.5.1.4	Analysis of the Paleoenvironmental History of the Yucca Mountain Region (DOE, 1991e)
8.3.1.5.1.5	Paleoclimate-Paleoenvironmental Synthesis (in preparation)
8.3.1.5.2.1	Characterization of the Quaternary Regional Hydrology (DOE, 1992g)
8.3.1.8.3.2	Analysis of the Effect of Tectonic Processes and Events on Changes in Water-Table Elevation (in preparation)
8.3.1.8.3.3	Analysis of the Effects of Tectonic Processes and Events on Local Fracture Permeability and Effective Porosity (in preparation)
8.3.1.17.3.3	Ground Motion from Regional Earthquakes and Underground Nuclear Explosions (in preparation)
8.3.1.17.4.1	Historical and Current Seismicity (DOE, 1990b)
8.3.1.17.4.3	Quaternary Faulting Within 100 km of Yucca Mountain, Including the Walker Lane (DOE, 1993b)

8.3.1.17.4.4	Quaternary Faulting Proximal to the Site Within Northeast-Trending Fault Zones (DOE, 1993c)
8.3.1.17.4.6.	Quaternary Faulting Within the Site Area (DOE, 1991c)
8.3.1.17.4.10	Geodetic Leveling (DOE, 1991b)
8.3.1.17.4.12	Tectonic Models and Synthesis (in preparation)

Reports presenting the results from additional study plans related to this PAC, when available, will also be reviewed.

Detailed Safety Review Supported by Analysis:

A Detailed Safety Review will be needed to evaluate the Key Technical Uncertainty. This will ensure that the DOE has adequately demonstrated Items (1)-(4) listed above in the previous section on Safety Review. Activities performed in this Detailed Safety Review will help to assure that DOE has adequately addressed and resolved the Key Technical Uncertainties so that they do not lead to noncompliance with the total system performance objective.

Examples of specific review activities that will be required include: (1) a complete review and evaluation of all site characterization-related work related to the large hydraulic gradient located north of Yucca Mountain; (2) review and analysis of the geophysical tests which have been conducted in the vicinity of Yucca Mountain to assess the characteristics and distribution of faults and fractures; (3) review and analysis of results of field mapping programs to assess the distribution and hydrogeologic characteristics of faults and fractures; (4) review of information provided by the drilling programs; and (5) review of geodetic studies. The analysis should focus on the sensitivity, resolution and detection capabilities of the different techniques; and the degree to which the separate techniques can provide independent assessments of the various features and characteristics of concern; and the degree to which the techniques provide information which either corroborates or contradicts results of other techniques.

It is important that DOE clearly establish in a license application the cause of the steep hydraulic gradient, and the potential for tectonic disruption of fault-related barriers, as this is the focus of the identified Key Technical Uncertainty. The cause of this steep gradient must be known in order to realistically estimate future water table changes that may be related to the feature. If the cause of the gradient is structural, as assumed here, the staff will carefully evaluate the data regarding hydrologic properties of the structure. Staff will then derive scenarios under which the structure may be disrupted. Then, independent hydrologic simulations will be performed to estimate the resulting effects on the water table beneath Yucca Mountain.

The staff will need to independently address several other questions. First, given a structural origin for the steep gradient (Czarnecki, 1989 and Sinton, 1989), what is the potential for other, similar structures to form or be reactivated near Yucca Mountain? Second, what is the potential for the structure to be disrupted during the next 10,000 years? And finally, if the structure is disrupted due to fault slip, what will be the consequences with respect to the regional groundwater system and repository performance? It is expected that available hydrologic models will be adequate to evaluate hydrologic consequences under specified scenarios. The use or solicitation of expert opinion will be required to describe appropriate disruption scenarios.

On the other hand, site characterization may show that the steep hydraulic gradient is not caused by a fault zone. It may be caused by stratigraphic features that are much less susceptible to tectonic disruption. Such a determination will need to be made by the DOE, and evaluated by the NRC staff. In such a case, there may be considerably less concern about possible dramatic changes in the water table caused by tectonism. Under these circumstances the staff may determine that a Detailed Safety Review may not be needed, and that a Safety Review would suffice.

RATIONALE FOR REVIEW STRATEGY:

In view of the complexity of the key technical uncertainty addressed above, it is appropriate that the NRC conduct the independent activities described in order to (1) develop the licensing tools and technical basis necessary to judge the adequacy of DOE's license application, (2) assure sufficient independent understanding of the basic physical processes taking place at the geologic repository, and (3) maintain independent but limited confirmatory research capability under NRC auspices.

Contributing Analysts:

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CNWRA: Stephen Young

Date of Analysis: June 14, 1993

APPLICABLE REGULATORY REQUIREMENTS FOR EACH TYPE OF REVIEW:

Type 1:

60.122(c)(4)
60.21(c)(1)(ii)(B)
60.21(c)(1)(ii)(F)

Type 3:

60.122(c)(4)
60.21(c)(1)(ii)(B)
60.21(c)(1)(ii)(F)

Type 4:

60.122(c)(4)
60.21(c)(1)(ii)(B)
60.21(c)(1)(ii)(F)

REFERENCES:

Ahola, M. and B. Sagar, "Regional Groundwater Modeling of the Saturated Zone in the Vicinity of Yucca Mountain, Nevada," prepared by Center for Nuclear Waste Regulatory Analyses for the U.S. Nuclear Regulatory Commission, NUREG/CR-5890, 58 p., 1992.

Bedinger, M.S., K.A. Sargent, and W.H. Langer, "Studies of geology and hydrology in the Basin and Range Province, southwestern United States, for isolation of high-level radioactive waste - Characterization of the Death Valley region, Nevada and California," U.S. Geological Survey Professional Paper 1370-F, Washington DC: 49, 1989.

Brogan, G.E., K.S. Kellogg, D.B. Slemmons, and C.L. Terhune, "Late Quaternary faulting along the Death Valley-Furnace Creek fault system, California and Nevada," U.S. Geological Survey Bulletin 1991:23, 1991.

Brune, J., "The Little Skull Mountain Earthquake of June 29, 1992:" unpublished paper prepared for U.S. Geological Survey and attached to a memorandum from L. Hayes (USGS) to J. R. Dyer (DOE), dated August 5, 1992.

Campbell, K. W., "Near-Source Attenuation of Peak Horizontal Acceleration," Bulletin of the Seismological Society of America, Vol. 71, No. 6, p. 2039-2070, 1981.

Carr, W. J., "Regional Structural Setting of Yucca Mountain, Southwestern Nevada, and Late Cenozoic Rates of Tectonic Activity in Part of the Southwestern Great Basin, Nevada and California:" Open-File Report 84-854, U.S. Geological Survey, Denver, Colorado, 1984.

Carr, W.J., "Geology of the Devils Hole area, Nevada," U.S. Geological Survey Open-File Report OFR-87-560: 32, 1988.

Czarnecki, J.B., "Preliminary simulations related to a large horizontal hydraulic gradient at the north end of Yucca Mountain, Nevada," EOS Trans., AGU 70(15): 321, 1989.

Carrigan, C. R., G. C. P. King, G. E. Barr, and N. E. Bixler, "Potential for Water-Table Excursions Induced by Seismic Events at Yucca Mountain, Nevada:" Geology, v. 19, p. 1157-1160, December 1991.

Coleman, N., (Personal observations following an underground nuclear test in Yucca Flat, Nevada Test Site, July-August, 1977).

Czarnecki, J. B., "Preliminary Simulations Related to a Large Horizontal Hydraulic Gradient at the North End of Yucca Mountain, Nevada" [Abstract]: Proceedings, American Institute of Hydrology Spring Meeting, Las Vegas, March 12-16, 1990.

Czarnecki, J. B., "Simulated Effects of Increased Recharge on the Ground-Water Flow System of Yucca Mountain and Vicinity, Nevada-California," Water-Resources Investigations Report 84-4344, U.S. Geological Survey, Denver, Colo., 33 p., 1985.

Fox, K.F., Jr. and M.D. Carr, "Neotectonics and volcanism of Yucca Mountain and vicinity, Nevada," Radioactive Waste Management and the Nuclear Fuel Cycle 13(1-4):37-50, 1989.

Fridrich, C.J., D.C. Dobson, and W.W. Dudley, "A geologic hypothesis of the large hydraulic gradient under Yucca Mountain, Nevada," EOS Trans. AGU 72(17): 121, 1991.

Galloway, D.L., E.M. Ervin, M.P. Chornack, and A.C. Riggs, "Hydrogeologic overview and field trip of the regional ground-water flow system in relation to Yucca Mountain, Nevada," Walawender, M.J., and B.B. Hanan, eds., Geological Excursions in Southern California and Mexico, Guidebook, 1991 Annual Meeting Geological Society of America, San Diego, CA: 463-503, 1991.

Hamilton, W.B., "Detachment faulting in the Death Valley region, California and Nevada," M.D. Carr and J.C. Yount, eds. Geologic and Hydrologic Investigations of a Potential Nuclear Waste Disposal site and Yucca Mountain, Southern Nevada; U.S. Geological Survey Bulletin 1790:51-85, 1988.

Hsiung, S.M., A.H. Chowdhury, W. Blake, and J. Philip, "Field Investigation of Mining-Induced Seismicity on Local Geohydrology" in Proceedings of the Fourth Annual International Conference on High-Level Waste Management, April 26-30, 1993, Las Vegas, Nevada: 913-920.

Joyner, W. B., and D. M. Boore, "Prediction of Earthquake Response Spectra," USGS-OFR-82-977, Open-File Report, U.S. Geological Survey, 14 p., 1982.

Maldonado, F., "Structural geology of the upper plate of the Bullfrog Hills detachment fault system, southern Nevada," Geological Society of America Bulletin 102:992-1006, 1990.

Marshall, B. D., Z. E. Peterman, and J. S. Stuckless, "Strontium Isotopic Evidence for a Higher Water Table at Yucca Mountain:" in Proceedings of the Fourth Annual International Conference on High Level Radioactive Waste Management, Volume 2, Las Vegas, Nevada, April 26-30, pp. 1948-1952, 1993.

Menges, C. M., G. Vadurro, R. Cress, J. Coe, and F. W. Simonds, "Stratigraphic Evidence for Multiple Small Quaternary Displacements on the Bow Ridge Fault at Northeast Yucca Mountain, Nye County, Nevada," Abstracts with Programs, Cordilleran and Rocky Section Meeting, Geological Society of America, May 19-21, Reno, Nevada, Vol. 25, No. 5, p. 120, 1993.

MWD (Metropolitan Water District of Southern California), "Geology, Earthquake Damage, and Water Table Fluctuations - Metropolitan Water District Facilities, Sylmar Area," in San Fernando, California, Earthquake of February 9, 1971 (Vol. 3): U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, Environmental Research Laboratories, Washington, D.C., 1973.

Naff, R.L., G.B. Maxey, and R.F. Kaufmann, "Interbasin ground-water flow in southern Nevada," Nevada Bureau of Mines and Geology, Report 20: 28, 1974.

National Research Council, "The Great Alaska Earthquake of 1964 - Hydrology": Committee on the Alaska Earthquake, Division of Earth Sciences, National Research Council, Publication 1603, National Academy of Sciences, Washington, D.C., 1968.

National Research Council, "Ground Water at Yucca Mountain: How High Can it Rise? Final Report of the Panel on Coupled Hydrologic Tectonic/Hydrothermal Systems at Yucca Mountain," Board on Radioactive Waste Management; Commission on Geosciences, Environment, and Resources; National Research Council; National Academy Press, Washington, D.C., April 1992.

Nuclear Regulatory Commission, "Draft Regulatory Guide DG-3003: Format and Content for the License Application for the High-Level Waste Repository," Office of Nuclear Regulatory Research, November 1990.

O'Brien, G. M. and P. Tucci, "Earthquake-Induced Water-Level and Fluid-Pressure Fluctuations of Yucca Mountain, Nevada," Abstract from 1992 Fall Meeting, American Geophysical Union, San Francisco, California, 1992.

Raney, R. G., "Reported Effects of Selected Earthquakes in the Western North American Intermontane Region, 1852-1983, On Underground Workings and Local and Regional Hydrology: A Summary:" Prepared for Division of Waste Management, Office of Nuclear Material and Safeguards, by U.S. Dept. of the Interior, Bureau of Mines, Spokane, Washington, 114 p, April, 1988.

Scott, R.B., "Tectonic setting of Yucca Mountain, southwestern Nevada," B.P. Wernicke, ed. Basin and Range Extensional Tectonics Near the Latitude of Las Vegas, Nevada; Geological Society of America Memoir 176:251-282, 1990.

Sinton, P.O., K.E. Kolm, and J.S. Downey, "Conceptual model of the lineament/fracture zone controlled regional groundwater flow in the vicinity of Yucca Mountain, Nevada," EOS Trans. AGU 90(43): 1088, 1989.

Stewart, J.H. "Tectonics of the Walker Lane belt, western Great Basin - Mesozoic and Cenozoic deformation in a zone of shear," in W.G. Ernst, ed., Metamorphism and Crustal Evolution of the Western United states: Rubey Volume VII, Prentice-Hall Inc., New Jersey, p. 683-713, 1987.

Szymanski, J. S., "Conceptual Considerations of the Yucca Mountain Groundwater System with Special Emphasis on the Adequacy of this System to Accommodate a High-Level Nuclear Waste Repository," U.S. Dept. of Energy, Nevada Operations Office, Yucca Mountain Project Office, Las Vegas, Nevada, July 26, 1989.

U.S. Department of Energy (DOE), "Site Characterization Plan, Yucca Mountain Site, Nevada Research and Development Area, Nevada," Office of Civilian Radioactive Waste Management, DOE/RW-0199, Volumes 1 and 2, December 1988.

U.S. Department of Energy (DOE), "Study Plan 8.3.1.2.2.7, Hydrochemical Characterization of the Unsaturated Zone," prepared for Dept. of Energy by U.S. Geological Survey, July, 1990a.

U.S. Department of Energy (DOE), "Study Plan 8.3.1.17.4.1, Historical and Current Seismicity," prepared for Dept. of Energy by U.S. Geological Survey, September 18, 1990b.

U.S. Department of Energy (DOE), "Study Plan 8.3.1.2.1.3, Rev. 0: Characterization of the Yucca Mountain Regional Ground Water Flow System," prepared for Dept. of Energy by U.S. Geological Survey, January 25, 1991a.

U.S. Department of Energy (DOE), "Study Plan 8.3.1.17.4.10, Rev. 0: Geodetic Leveling," prepared for Dept. of Energy by U.S. Geological Survey, January 25, 1991b.

U.S. Department of Energy (DOE), "Study Plan 8.3.1.17.4.6, Rev. 0: Quaternary Faulting Within the Site Area," prepared for Dept. of Energy by U.S. Geological Survey, February 1, 1991c.

U.S. Department of Energy (DOE), "Study Plan 8.3.1.2.3.1.1-6, Rev. 0: Characterization of the Site Saturated-Zone Groundwater Flow System," prepared for Dept. of Energy by U.S. Geological Survey, February 26, 1991d.

U.S. Department of Energy (DOE), "Study Plan 8.3.1.5.1.4, Rev. 0: Analysis of the Paleoenvironmental History of the Yucca Mountain Region," prepared for Dept. of Energy by U.S. Geological Survey, June 10, 1991e.

U.S. Department of Energy (DOE), "Study Plan 8.3.1.2.3.3, Rev. 0: Site Saturated-Zone Hydrologic System Synthesis and Modeling," prepared for Dept. of Energy by U.S. Geological Survey, January 14, 1992a.

U.S. Department of Energy (DOE), "Study Plan 8.3.1.3.2.2, Rev. 0: History of Mineralogic and Geochemical Alteration of Yucca Mountain," prepared for Dept. of Energy by Los Alamos National Laboratory, January 15, 1992b.

U.S. Department of Energy (DOE), "Study Plan 8.3.1.2.1.4, Rev. 0: Regional Hydrologic Synthesis and Modeling," prepared for Dept. of Energy by U.S. Geological Survey, January, 1992c.

U.S. Department of Energy (DOE), "Study Plan 8.3.1.2.3.2, Rev. 0: Characterization of the Yucca Mountain Saturated-Zone Hydrochemistry," prepared for Dept. of Energy by U.S. Geological Survey, April 15, 1992d.

U.S. Department of Energy (DOE), "Yucca Mountain Site Characterization Project, Existing and Proposed Drillholes Within 10 KM of the Site," YMP-92-081.0, EG&G/EM Remote Sensing Laboratory, June 1992e.

U.S. Department of Energy (DOE), "Study Plan 8.3.1.4.3.1, Rev. 0: Systematic Acquisition of Site-Specific Subsurface Information," prepared for Dept. of Energy by Sandia National Laboratories, October 14, 1992f.

U.S. Department of Energy (DOE), "Study Plan 8.3.1.5.2.1, Rev. 2: Characterization of Yucca Mountain Quaternary Regional Hydrology," prepared for Dept. of Energy by U.S. Geological Survey, November 16, 1992g.

U.S. Department of Energy (DOE), "Study Plan 8.3.1.4.2.2, Rev. 2: Characterization of Structural Features in the Site Area," prepared for Dept. of Energy by U.S. Geological Survey, December 22, 1992h.

U.S. Department of Energy (DOE), "Study Plan 8.3.1.4.2.1: Characterization of the Vertical and Lateral Distribution of Stratigraphic Units Within the Site Area," prepared for Dept. of energy by U.S. Geological Survey, January 14, 1993a.

U.S. Department of Energy (DOE), "Study Plan 8.3.1.17.4.3, Rev. 0: Quaternary Faulting Within 100 Km of Yucca Mountain, Including the Walker Lane," prepared for Dept. of Energy by U.S. Geological Survey, January 22, 1993b.

U.S. Department of Energy (DOE), "Study Plan 8.3.1.17.4.4, Rev. 0: Quaternary Strike-Slip Faulting Proximal to the Site Within Northeast-Trending Fault Zones," prepared for Dept. of Energy by U.S. Geological Survey, May 3, 1993c.

Wernicke, B.P., G.J. Axen, and J.K. Snow, "Basin and Range extensional tectonics at the latitude of Las Vegas, Nevada," Geological Society of America Bulletin 100:1738-1757, 1988.

Wernicke, B.P., J.K. Snow, G.J. Axen, B.C. Burchfiel, K.V. Hodges, J.D. Walker, and P.L. Guth, "Extensional Tectonics in the Basin and Range Province Between the Southern Sierra Nevada and the Colorado Plateau," Field Trip Guidebook T138. 28th International Geological Congress; American Geophysical Union, Washington, D.C.:80, 1989.

Whitehead, R.L., R.W. Harper and H.G. Sisco, "Hydrologic changes associated with the October 28, 1983 Idaho earthquake," Pure and Applied Geophysics 122:280-293, 1985.

Winograd, I. J. and B. J. Szabo, "Water-Table Decline in the South-Central Great Basin During the Quaternary: Implications for Toxic Waste Disposal," in Geologic and Hydrologic Investigations of a Potential Nuclear Waste Disposal Site at Yucca Mountain, Southern Nevada, M. D. Carr and J. C. Yount (eds.), U. S. Geological Survey Bulletin 1790, U. S. Geological Survey, p. 147-152, 1988.

Winograd, I. J. and W. Thordarson, "Structural control of ground-water movement in miogeosynclinal rocks of south-central Nevada," in Eckel, E. B., ed., Studies of Geology and Hydrology, Nevada Test Site, Geological Society of America Memoir 110:35-48, 1968.

Winograd, I. J. and W. Thordarson, "Hydrogeologic and Hydrochemical Framework, South-Central Great Basin, Nevada-California, with Special Reference to the Nevada Test Site," U.S. Geological Survey Professional Paper 712-C, Washington, DC, 126 p., 1975.

Wood, S.H., "Observations and subsequent history of spectacular ground water flows and aquifer pressure increases," 1983 Borah Peak and 1957 Hebgen Lake earthquakes (abs.), EOS 72(17):115, 1991.

Wood, S. H., C. Wurts, T. Lane, N. Ballenger, M. Shaleen, and D. Totorica, "The Borah Peak, Idaho Earthquake of October 28, 1983 - Hydrologic Effects," Earthquake Spectra, 2:127-150, 1985.

Zhang, P., M. Ellis, D.B. Slemmons, and F. Mao, "Right-lateral displacements and the Holocene slip rate associated with prehistoric earthquakes along the southern Panamint Valley fault zone: implications for southern Basin and Range Tectonics and Coastal California Deformation," Journal of Geophysical Research, 95(B4):4857-4872, 1990.