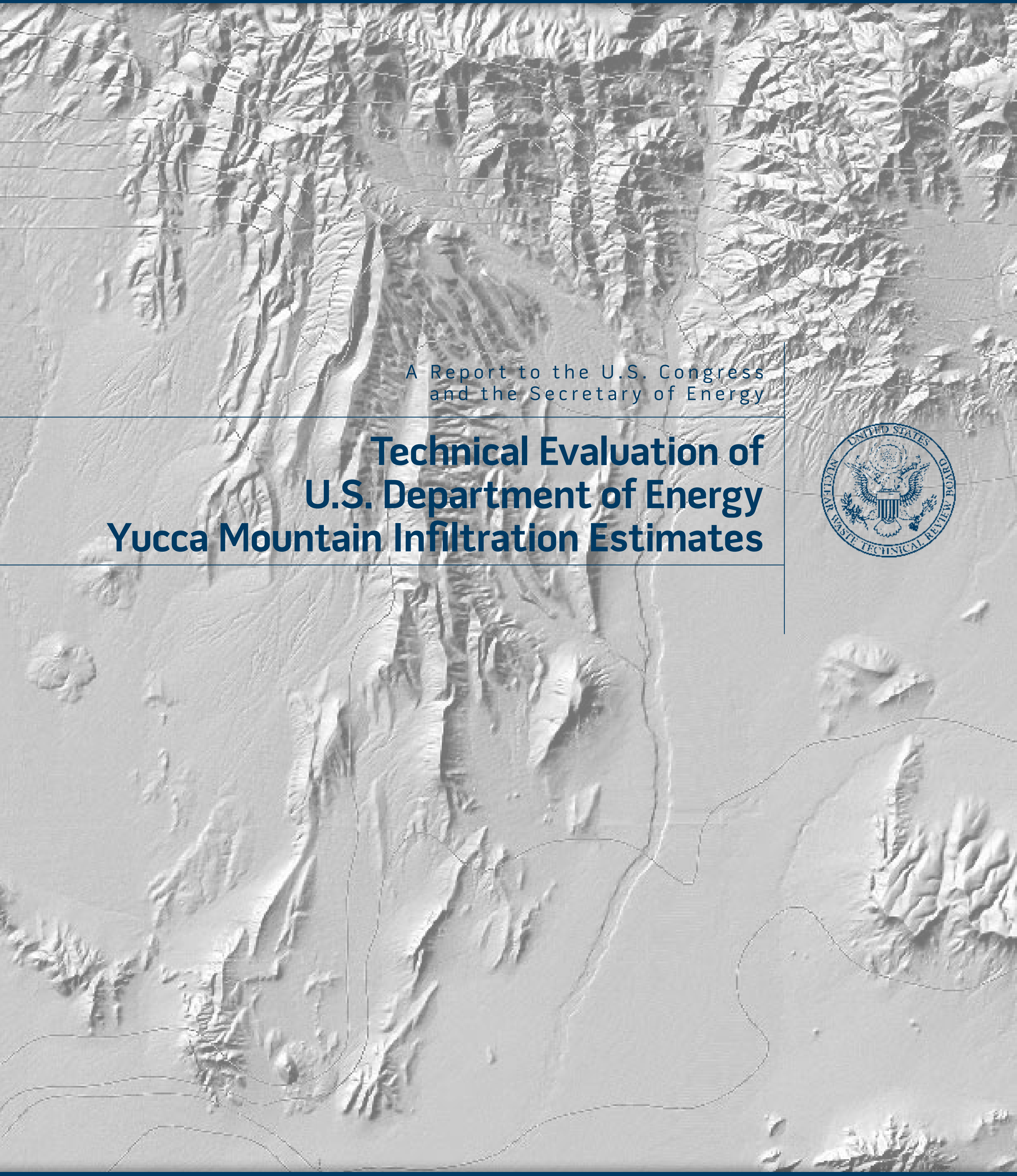
U.S. NUCLEAR WASTE TECHNICAL REVIEW BOARD



A Report to the U.S. Congress
and the Secretary of Energy

Technical Evaluation of U.S. Department of Energy Yucca Mountain Infiltration Estimates

DECEMBER 2007

Cover: Digital elevation model of Yucca Mountain and vicinity. Contour lines of equal water table elevation are for early 20th-century conditions (prior to extensive ground-water withdrawals), as determined by calculations from the U.S. Geological Survey Death Valley Regional Flow System model (Belcher, 2004). Contours are for illustration purposes only.

U.S. Nuclear Waste Technical Review Board

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UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
2300 Clarendon Boulevard, Suite 1300
Arlington, VA 22201-3367

December 2007

The Honorable Nancy P. Pelosi
Speaker of the House
United States House of Representatives
Washington, DC 20515

The Honorable Robert C. Byrd
President Pro Tempore
United States Senate
Washington, DC 20510

The Honorable Samuel W. Bodman
Secretary
U.S. Department of Energy
Washington, DC 20585

Dear Speaker Pelosi, Senator Byrd, and Secretary Bodman:

The U.S. Nuclear Waste Technical Review Board was created by Congress in 1987 and charged with performing an independent evaluation of the technical and scientific validity of the Department of Energy's (DOE) activities related to disposing of, packaging, and transporting high-level radioactive waste and spent nuclear fuel. The Board is required to report its findings and recommendations at least twice yearly to Congress and the Secretary of Energy. A major focus of the Board's review is DOE's efforts to develop a proposed permanent repository for such wastes at Yucca Mountain in Nevada.

In accordance with provisions of the Nuclear Waste Policy Amendments Act, Public Law 100-203, the Board submits this report, which presents the Board's evaluation of revised DOE estimates of water infiltration at Yucca Mountain. The report fulfills a commitment I made on behalf of the Board to evaluate the revised estimates and to report to Congress and the Secretary on their validity.

The Board looks forward to continuing to provide its technical and scientific perspective on these and other important issues to Congress and the Secretary.

Sincerely,

B. John Garrick
Chairman

con255vF

Telephone: 703-235-4473 Fax: 703-235-4495

U.S. Nuclear Waste Technical Review Board
2007

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Executive Summary

The U.S. Nuclear Waste Technical Review Board was created by Congress in 1987 and was charged with performing an ongoing independent evaluation of the technical and scientific validity of the U.S. Department of Energy's (DOE) activities related to disposing of, packaging, and transporting high-level radioactive waste and spent nuclear fuel. A major focus of the Board's review is DOE's efforts to develop a proposed permanent repository for the wastes at Yucca Mountain in Nevada. The Board is required to report its findings and recommendations at least twice yearly to Congress and the Secretary of Energy.

In this report, the Board presents its evaluation of revised DOE estimates of water infiltration at Yucca Mountain. The infiltration estimates were revised because violations of quality assurance (QA) procedures were alleged to have been committed by U.S. Geological Survey (USGS) employees who were involved in gathering and analyzing infiltration data at Yucca Mountain in the 1990's.

At a congressional subcommittee hearing held shortly after these issues were raised, Board Chairman Dr. B. John Garrick noted in his testimony that monitoring compliance with the QA program is not part of the Board's technical and scientific mandate. However, he stated that as part of the Board's ongoing technical and scientific peer review, the Board would evaluate the results of DOE's planned investigations and would report to Congress and the Secretary on the significance of the results to the validity of DOE's infiltration estimates. This report fulfills that commitment.

As part of its response to questions about USGS infiltration estimates, DOE undertook two parallel investigations. First, DOE commissioned an independent review by the Idaho National Laboratory (INL) of both the technical validity of USGS infiltration estimates and the compliance of those analyses with QA protocols. That review has been completed. The primary findings of the INL study are that the USGS infiltration estimates have a sound technical basis and that deficiencies associated with the USGS analyses are confined primarily to inconsistencies with some QA protocols. Concurrently with the INL effort, DOE contracted with Sandia National Laboratories (SNL) to develop a new procedure for calculating infiltration at Yucca Mountain that would enable DOE to replace USGS infiltration estimates in all future assessments of repository performance, if necessary. The work by SNL has been completed. Thus, there are two sets of infiltration estimates for Yucca Mountain: the USGS estimates and the SNL estimates.

In evaluating the technical basis supporting DOE infiltration estimates, the Board engaged in various activities, including reviewing findings of the inspectors general from the Department of the Interior and DOE; reviewing DOE's technical assessments; and conducting field interviews with scientists and engineers at SNL, INL, and USGS. On March 14, 2007, the Board's Panel on Postclosure Performance held a one-day public meeting in Berkeley, California, on the scientific and technical basis of USGS and SNL estimates of infiltration.

On the basis of its technical evaluation of DOE Yucca Mountain infiltration estimates, the Board makes the following findings and recommendations.

Findings

• Calculating infiltration in a desert environment is a challenging technical and scientific undertaking. Infiltration is estimated using computer models in which factors such as rainfall, soil depth, water extraction from soil and rocks by plants and evaporation, and a host of other variables, must be specified. Minor deficiencies in the USGS model were identified by DOE and USGS reviewers, but no significant errors in USGS infiltration estimates were found. The Board found no significant errors in the computational approach used for infiltration estimates by either the USGS model or the SNL model.

When the values of variables and the simulated natural processes are specified as being the same in the USGS and SNL models, the infiltration estimates from the two approaches are similar. The Board's opinion is that if all available relevant site-specific data at Yucca Mountain are used in both the USGS model and the SNL model, then repository performance estimates that are based on the infiltration estimates from either model should be essentially the same.

• Information presented at the Board's March 14 panel meeting made clear that USGS estimates of infiltration are based on an extensive suite of site-specific data and are consistent with multiple independent lines of evidence. Furthermore, the Board's opinion is that the USGS program produced valuable results that are important for understanding the mountain hydrology and for building confidence in the estimated performance of the proposed repository.

In contrast, the SNL model does not include consideration of all available site-specific data that were used by USGS, such as soil depth and soil and rock hydraulic parameters. As a result, SNL estimates of present-day infiltration at Yucca Mountain are approximately three times higher than the USGS estimates, and the SNL model results are less consistent with independent lines of evidence, including measurements of temperature and salt (chloride) concentrations at depth within Yucca Mountain. However, the SNL procedure has a more complete representation of uncertainties associated with relevant physical parameters—a methodological advantage over the USGS approach.

• The SNL model does not include consideration of evapotranspiration—removal of water by evaporation and plant roots—from shallow buried layers of bedrock, a likely significant factor at Yucca Mountain.

• Rock properties in the USGS model were calibrated to infiltration measurements at Yucca Mountain. The SNL model was not calibrated to Yucca Mountain infiltration data, reducing the technical defensibility of the SNL model.

• The infiltration estimates are used as input to estimates of potential long-term repository performance at Yucca Mountain in a computer model known as Total System Performance Assessment, or TSPA. To make the SNL estimates compatible with observed site-specific data supporting related models in TSPA, DOE uses a statistical process that preferentially considers the lower end of the range of SNL infiltration estimates. As used by DOE, the statistical modification of the infiltration estimates does not have a strong technical basis.

• Although the effects on the regulatory process of QA infractions were not part of the Board's purview and therefore were not part of the Board's evaluation, the Board notes that compliance with QA procedures is an important part of the licensing process. However, even when scientific endeavors are not conducted in strict compliance with QA procedures, the fruits of those endeavors can have significant value. Likewise, strict observance of QA procedures is not by itself sufficient to guarantee sound technical and scientific analyses or data.

Recommendations

• DOE should use all available site-specific data in its estimation of infiltration. Relevant USGS data found to have transparency or traceability QA discrepancies should be re-qualified and used in estimates of infiltration.

• Because estimates of infiltration are necessarily imprecise, the Board recommends that DOE calibrate the infiltration model using all relevant site-specific data.

• Because plant uptake of water from bedrock fractures is likely to occur at Yucca Mountain, the Board recommends that DOE include parameterization—including associated uncertainty—that represents evapotranspiration from shallow buried bedrock in its model.

• The Board does not endorse the use of the statistically modified SNL infiltration estimates in TSPA.

Acknowledgement

This report benefitted from open and honest communication with involved scientists, all of whom demonstrated a strong personal commitment to developing a sound fundamental understanding of infiltration at Yucca Mountain. The Board appreciates their cooperation in this technical evaluation.

1. Introduction

The U.S. Nuclear Waste Technical Review Board was created by Congress in 1987 and was charged with performing an ongoing independent evaluation of the technical and scientific validity of the U.S. Department of Energy's (DOE) activities related to disposing of, packaging, and transporting high-level radioactive waste and spent nuclear fuel. A major focus of the Board's review is DOE's efforts to develop a proposed permanent repository for the wastes at Yucca Mountain in Nevada. The Board is required to report its findings and recommendations at least twice yearly to Congress and the Secretary of Energy.

This report is the Board's evaluation of the significance of new estimates of water infiltration developed by DOE for the proposed geologic repository for high-level radioactive waste and spent nuclear fuel at Yucca Mountain. The new estimates were developed in response to questions about the credibility of previous infiltration estimates for Yucca Mountain arising from apparent discrepancies in compliance with quality assurance (QA) protocols by U.S. Geological Survey (USGS) employees. The apparent QA discrepancies were identified in e-mail communications from 1998 to 2000 among some employees of the USGS engaged in long-term scientific investigations of present and future infiltration at Yucca Mountain. The estimates of present and future infiltration resulting from those investigations were used by DOE in previous assessments of Yucca Mountain as a geologic repository for isolating nuclear waste.

In the early 1980's, the USGS began a sustained series of field investigations to characterize infiltration, fluid flow, and solute transport in the unsaturated zone at Yucca Mountain. (For example, see Flint and Flint, 1995, and Flint et al., 2001.) The investigations included measurements of soil thickness and moisture content, infiltration tests, and field and laboratory tests of soil and rock hydraulic parameters. At a meeting of the Board's Postclosure Performance Panel held on March 14, 2007, in Berkeley, California, the USGS emphasized that because long periods can pass between years of higher precipitation, the sustained long-term nature of those investigations was key to developing a clear understanding of infiltration at Yucca Mountain.

In response to allegations that were made, the USGS conducted an internal scientific peer review of a later version of the numerical model used to estimate infiltration, known as INFIL. Independently, DOE contracted with scientists at Idaho National Laboratory (INL) who conducted a scientific peer review of an earlier version of the INFIL model. At the same time, DOE tasked scientists at Sandia National Laboratories (SNL) to develop a new model, called MASSIF, and a new set of infiltration estimates to be used in Total System Performance Assessment (TSPA) estimates of the waste isolation capability of the repository.[1] In addition, DOE QA reviewers evaluated the degree to which previous data and analyses complied with QA protocols.

The technical work plan for development of the replacement infiltration estimates by SNL stated that no new data would be collected (BSC, 2006a). However, the work plan allowed for new topographic elevation estimates to be derived from satellite data not previously used. In addition, scientists from the SNL model development team conducted field excursions to Yucca Mountain to collect data on soil thickness. During the excursions, they also observed the extent of caliche in-filling of fractures in shallow bedrock (SNL, 2007a).

The Board conducted the evaluation of infiltration estimates as part of its ongoing technical and scientific peer review and to fulfill a commitment made by Board Chairman B. John Garrick in testimony before the Subcommittee on the Federal Workforce and Agency Organization, Committee on Government Reform, U.S. House of Representatives, on April 5, 2005. In written remarks to the Subcommittee, Dr. Garrick stated, "The Board will follow progress of… [comprehensive investigations already under way at the Departments of Energy and Interior], and when they are concluded, the Board

[1] TSPA estimates are a significant component of a license application from DOE to the Nuclear Regulatory Commission to request authorization for constructing a repository for spent nuclear fuel and high-level radioactive waste at Yucca Mountain.

Table 1. Schedule of Board Interviews and Meetings

Date	Location	Activity	Topic
July 14, 2006	Albuquerque, New Mexico	Interview with SNL scientific and management personnel developing infiltration estimates for the Yucca Mountain Project.	Scientific approaches taken in SNL modeling of infiltration
August 7, 2006	Idaho Falls, Idaho	Interview with INL scientific and management personnel conducting review of USGS infiltration calculations for the Yucca Mountain Project.	Scientific approaches used in INFIL 2.2 and error checking of INFIL 2.0
August 25, 2006	Reston, Virginia	Interview with USGS scientific and management personnel conducting scientific review of the USGS infiltration estimate methodology.	Scientific evaluation of INFIL 3.0 version 5P
March 14, 2007	Berkeley, California	Public meeting of NWTRB Panel on Postclosure Performance.	Scientific and technical bases for DOE estimates of infiltration at Yucca Mountain, Nevada
April 27, 2007	Sacramento, California	Interview with USGS hydrologists Alan Flint, Lorraine Flint, and Joe Hevesi.	Scientific and technical bases for USGS estimates of infiltration at Yucca Mountain, Nevada

will evaluate the significance of the results for the DOE's technical and scientific work."[2, 3]

The Board's evaluation focused solely on the technical aspects of actions undertaken by the USGS and DOE in response to concerns raised by the e-mails and on the potential effects of those actions on the technical basis for DOE estimates of performance at Yucca Mountain. The Board evaluation consisted of technical review of the following: (1) the "old" USGS estimates of infiltration and their underlying technical bases; (2) the "new" SNL estimates of infiltration and their underlying technical bases; (3) the effects of the SNL estimates as used in performance assessment calculations; and (4) the value and credibility of existing data that could be used to support infiltration estimates.

2. Evaluation Procedure

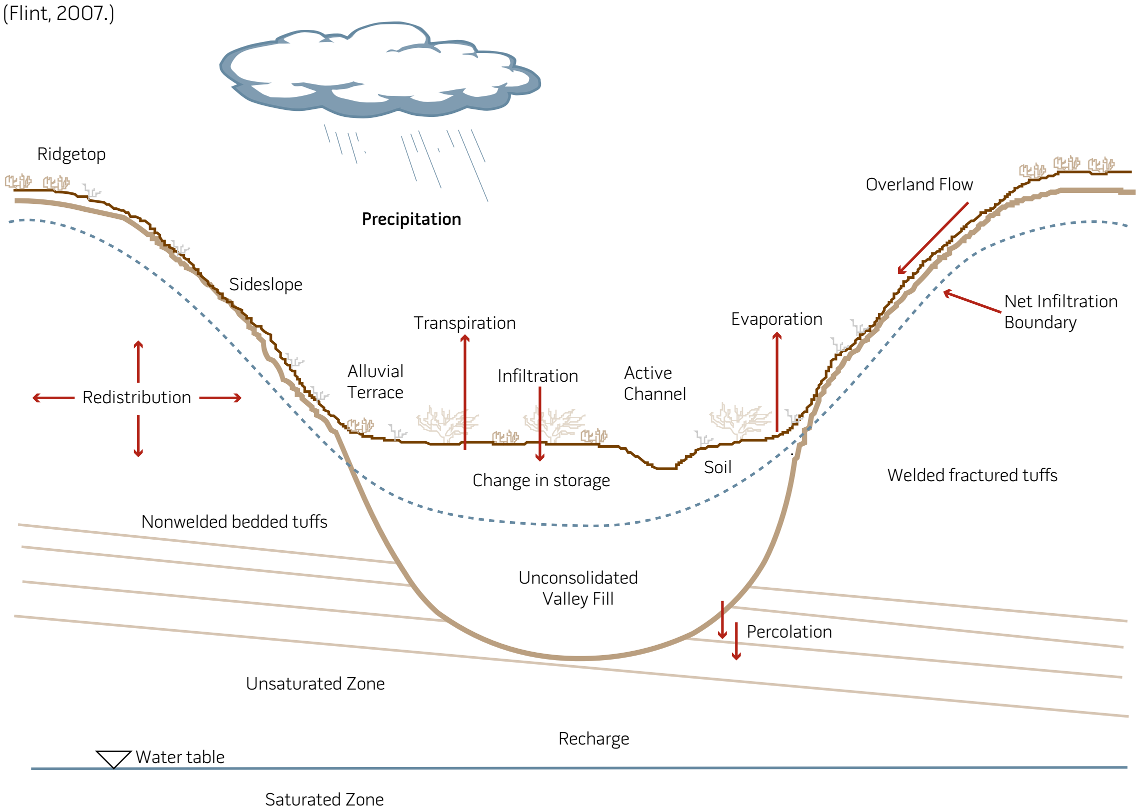
The Board's evaluation included review of relevant e-mail for technical content; review of nontechnical documents produced by DOE and the Department of Interior as part of their investigations; review of DOE and DOE contractor technical documents; and field interviews with scientists and engineers at SNL, INL, and USGS.

In addition, the Board Panel on Postclosure Performance held a one-day public meeting on March 14, 2007, in Berkeley, California, to examine the technical bases and effects of the new SNL estimates of infiltration. The individual scientists who made presentations at the Board's panel meeting demonstrated substantial dedication and scientific acumen in their areas of expertise. Board interviews and meetings are itemized in Table 1. A full transcript of the public meeting proceedings, including presentations, is available on the Board's Web site at *www.nwtrb.gov*. A list of questions posed to interviewees is included in Appendix B. Documents that were reviewed but not cited are listed in Appendix C.

[2] A full record of Chairman Garrick's oral and written testimony is in Appendix A.

[3] Freidman (2006) and U.S. Department of the Interior (2006) contain the findings of the inspectors general of DOE and the DOI, respectively. Neither investigation resulted in criminal charges. The DOE Office of Civilian Radioactive Waste Management (OCRWM) (OCRWM, 2006) conducted an initial evaluation of the technical effect of the issues raised by the e-mails on the Yucca Mountain Project's technical basis. That investigation found, "The [USGS] net infiltration rate estimates used in the total system performance assessment modeling for the Site Recommendation are consistent with and corroborated by several independent data sets."

Figure 1. Processes of the hydrologic cycle controlling infiltration at Yucca Mountain, Nevada. (Flint, 2007.)



3. Infiltration and Its Significance to Waste Isolation

In the Yucca Mountain performance assessment, the principal pathway for human radiological exposure is by radionuclide transport in flowing groundwater. Because infiltration below the zone where water is subject to evaporation and extraction by plants contributes to groundwater recharge and flow, infiltration is a significant controlling factor in the availability and rate of water movement and thus the transport of radionuclides from Yucca Mountain. At Yucca Mountain, infiltration is a small fraction of precipitation (see Table 2). Infiltration is determined using computer models that calculate the net amount of water remaining from precipitation after water has been lost to evaporation, transpiration by plants, and surface water (overland) flow. The models discretize the land surface into 30-meter-by-30-meter grid cells, and a hydrologic budget calculation is made for each cell.

Figure 1 shows the natural processes of the hydrologic cycle that control infiltration of water at Yucca Mountain (Flint, 2007). Infiltration estimates are calculated using computer models dependent on factors such as rainfall, soil depth, water extraction from soil and rocks by plants and evaporation, and a host of other parameters. Because precisely determining the magnitude of the relevant parameters is difficult, estimating infiltration in desert environments is a very challenging scientific undertaking.

4. Significant Factors Affecting Infiltration Estimates

Significant factors affecting current estimates of infiltration at Yucca Mountain are precipitation, evapotranspiration, soil depth, soil hydraulic conductivity, and rock hydraulic conductivity. Redistribution of surface water by overland flow was not found to be significant to estimates of total average infiltration at Yucca Mountain (SNL, 2007a). The significance of these factors and the technical validity of the estimates used by DOE are discussed below.

Precipitation is the principal source of water for infiltration at Yucca Mountain. As such, precipitation is an important factor in estimating infiltration. In the northern Mojave Desert, where Yucca Mountain is located, present-day precipitation is sparsely distributed and sporadic. Determining infiltration amounts over the period of repository performance requires estimating future precipitation. SNL and USGS estimates of precipitation cover 10,000 years—a time period corresponding to the previous Yucca Mountain standard and shorter than the new 1,000,000-year standard proposed by the U.S. Environmental Protection Agency. The SNL estimates are based on historical measurements from the region and on measurements from other sites used as analogs for future climate conditions at Yucca Mountain. The SNL analysis is not a weather forecast; it is a prediction of daily rainfall that is statistically consistent with average annual precipitation in present and postulated future climate conditions.

At present, Yucca Mountain is in an interglacial climate that is predicted by DOE to persist for another 400 to 600 years. Following the interglacial climate, a monsoonal climate is predicted for an additional 900 to 1,400 years. At the conclusion of that climate period, a glacial transition climate is predicted for the remainder of the 10,000-year period. Thus the glacial transition climate is the predominant climate for a 10,000-year repository performance assessment. Neither the SNL nor the USGS analyses explicitly include effects on precipitation or infiltration arising from the *el niño*-southern oscillation, the Pacific decadal oscillation, or anthropogenic climate change.

The USGS developed estimates of hourly and daily average precipitation and related weather parameters at Yucca Mountain that are based on site-specific measurements. Precipitation for individual model cells was adjusted using an empirical relationship that is based on the average elevation of the model cells. As is the case in the Mojave Desert region as a whole, at Yucca Mountain, higher elevations receive more precipitation. (BSC, 2004)

Replacement precipitation and related weather parameters were developed by SNL in accordance with the work plan for developing a replacement infiltration model in parallel with the quality review of the existing infiltration model (BSC, 2006a). SNL uses the approach of Woolhiser and Pegram (1979) to estimate 1,000-year (365,000-day) time series of mean annual precipitation for each climate state, based on statistical characteristics of measured precipitation data. The magnitude of any single day of calculated precipitation at Yucca Mountain is limited by the magnitude of the largest observed daily rainfall in the United States. SNL uses Latin hypercube sampling of process variables to incorporate uncertainty into their calculations, creating two replicates of twenty 1,000-year samples for each of the three climate states. The calculated 1,000-year samples are then ranked by amount of precipitation, averaged, and collected into ten unevenly-weighted statistical bins meant to capture representative years. Precipitation values used in the infiltration calculations are randomly selected from the ten probability-weighted statistical bins. The representation of uncertainty in precipitation calculations is a positive attribute of the SNL approach.

Evapotranspiration (ET) is the sum of water loss due to evaporation and water loss due to uptake by plants. ET is a function of a large number of parameters relating both to physical phenomena and to plant properties, including, among other things, solar radiation, surface albedo (the ability to reflect or absorb incoming solar radiation), temperature, wind speed, plant type, plant root depth, plant stomatal resistance, phase in growing season, and extent of plant canopy cover. ET consumes the largest fraction of precipitation at Yucca Mountain. Results of calculations presented by SNL at the March 14 Board panel meeting showed that ET consumed between 85 and 88 percent of precipitation at Yucca Mountain for all climate states.

The USGS determined ET using a standard technique known as Priestly-Taylor, modified by local site atmospheric and meteorological conditions (BSC, 2004). A positive attribute of the USGS implementation is that it includes the process of ET from upper layers of bedrock beneath shallow soil. The potential significance of ET from bedrock is suggested by field and computer modeling studies at Yucca Mountain. In one example, Stothoff et al. (1999) found that plants preferentially root within soil-filled fissures in the shallow bedrock and transpire water from the rock fractures during growing-season infiltration events.

The ET model forms the core of the SNL infiltration model. The computer implementation of the ET model is a major component of the DOE goal of developing a new infiltration model in parallel with the evaluation of the existing model of infiltration (BSC, 2006a). To calculate ET, SNL uses a method originally developed to determine crop irrigation needs known as FAO-56 (Allen, et al., 1998). The FAO-56 ET calculation begins with a reference value based on the rate of water consumption by well-watered grass trimmed to a specified height and subject to specified atmospheric conditions. That reference ET then is modified according to local crop and other conditions. Yucca Mountain vegetation models were based on studies of plant types and growth patterns from field ecological study plots in the vicinity of Yucca Mountain and from satellite images of Yucca Mountain. The predictive capability of the ET model as implemented by SNL was evaluated by comparing SNL model predictions with data collected from experimental studies. Results presented at the Board's March 14 panel meeting showed that the SNL model was able to reproduce with reasonable fidelity measurements of soil water storage from both bare-soil and vegetated-soil test plots. The measurements were taken as a part of weighing lysimeter experiments at the Nevada Test Site. The SNL ET model also was able to reproduce with reasonable fidelity field lysimeter experimental data collected at Reynolds Creek, Idaho (SNL, 2007a).

At the March 14 Board panel meeting, SNL reported that their model of infiltration did not account for the process of ET from the top layer of bedrock beneath soil-covered areas. Excluding the process of ET from the upper bedrock layer would tend to increase calculated infiltration estimates.

Soil depth has been shown to be an important parameter in infiltration calculations, partly because soil depth is related to the water-holding capacity of the soil zone. As used in this context, "soil" refers to unconsolidated sediment lying above bedrock. The thickness of unconsolidated sediment can reliably be measured directly or indirectly using known techniques and readily available technology. Over the infiltration model domain at Yucca Mountain, the thickness of unconsolidated sediment ranges from zero where bare rock is exposed to more than 50 meters in alluvial plains. In the infiltration models, soil depth is represented as an average value over a 900-m^2 model cell.[4] SNL models calculated that as much as 97 percent of predicted infiltration occurred in areas where soil is thin (0.1 m – 0.5 m) or absent, even though such areas occupy only 57 percent of the infiltration-model domain (BSC, 2006b). Thin soil occurs most commonly at higher elevations on ridge tops and ridge flanks, areas where the amount of precipitation is highest. SNL sensitivity studies presented at the March 14 Board panel meeting showed that aside from precipitation, infiltration estimates were most sensitive to the magnitude of soil thickness of the thinnest soil-depth class.

At the March 14 Board panel meeting, the USGS stated that soil depth was determined using a wide variety of independent direct and indirect measurement techniques, including geologic and soil maps, observations from outcrops, boreholes, hand-dug pits, and geophysical techniques. Soil depths were modified by empirical functions of topographic slope. In an interview conducted by the Board, USGS hydrologist Alan Flint stated that some soil depth data were collected before the existence and implementation of evolving Yucca Mountain QA policies and thus were not entered in the current database, nor were they used in subsequent work requiring compliance with QA protocols (Flint, personal communication, 2007).

[4] Because of natural variability, relating estimates from point measurements, such as boreholes, to averages over large domains is a common challenge in hydrologic models.

SNL developed a classification scheme for soil depth based on mapped soil type, similar to the classification scheme used by the USGS. Soil depths at Yucca Mountain are amenable to such classification because soil is commonly associated with distinct geomorphic settings, such as upland, valley bottom, and alluvial plain, each of which has a likely range of sediment thicknesses at Yucca Mountain. For each soil-depth class, SNL developed and used a statistical representation of the soil depths within that class derived from the subset of soil-depth data that were available and qualified for that class (BSC, 2006b). The SNL model was enhanced by some new soil-depth measurements (SNL, 2007a), but it does not incorporate all available soil-depth measurements obtained through geologic investigations of Yucca Mountain.

Soil hydraulic properties of hydraulic conductivity and porosity are factors that determine how readily water can flow through Yucca Mountain soil and the water-storage capacity of the soil, respectively. As such, soil hydraulic properties are important factors in estimating infiltration.

USGS reported that it determined hydraulic properties of soil at Yucca Mountain from a combination of field infiltration experiments, including double-ring infiltrometer studies, cone penetrometer tests, laboratory studies, and textural analyses. The soil type mapped in about two-thirds of the region where infiltration model estimates are used by downstream unsaturated-zone models in TSPA is called a *lithic haplocambid*. For the *lithic haplocambid* soil, USGS estimated saturated-soil hydraulic conductivity to be about $7 x 10^{-6}$ m/s and porosity to be about 33 percent (BSC, 2001).

SNL determined soil hydraulic properties using a pedotransfer function approach, matching textural characteristics of soils at Yucca Mountain with those of soils at Hanford, Washington, for which hydraulic property measurements exist. After grouping of the *lithic haplocambid* with two other soil units (to better support statistical analyses), the pedotransfer function-estimated values of hydraulic conductivity for this soil grouping are about one-tenth previous estimates, and the saturated water content (approximately equal to porosity) is about half of previous estimates (BSC, 2006c). Because of its significant areal extent with respect to the unsaturated-zone model domain, these differences may be significant to infiltration estimates. The SNL model does not incorporate all available soil hydraulic property measurements made by geologic investigations of Yucca Mountain.

Rock hydraulic conductivity describes the capability of water to flow in rock—water flows more readily in (saturated) rocks with higher hydraulic conductivity—and is therefore a significant parameter in the process of infiltration. At Yucca Mountain, rock hydraulic conductivity arises both from intergranular permeability and from fracture permeability. Where present, fracture permeability can increase bulk rock hydraulic conductivity by orders of magnitude. Secondary mineral filling of fractures, on the other hand, reduces the permeability of the fractures and thus the bulk rock hydraulic conductivity. Declining water saturation also dramatically reduces hydraulic conductivity, and so estimates of unsaturated hydraulic conductivity are based on both saturated hydraulic conductivity and on liquid (water) saturation.

At the March 14 Board panel meeting, the USGS stated that estimates of rock hydraulic conductivity were based on an extensive suite of field and laboratory measurements, as reported in Flint et al. (1996), Flint (1998), and BSC (2001). Bulk rock hydraulic conductivity at Yucca Mountain can be significantly altered by fracture permeability, which is itself a function of fracture density, fracture aperture, and the extent of fracture in-filling by secondary minerals. Average fracture density (that is, the number of fractures per unit area) for each rock unit was estimated from field observations and subsequently corroborated by data from boreholes (Flint et al., 1996; Altman, et al., 1996; BSC, 2001). The USGS infiltration model assumed filled 250-μm fractures, based partly on field observations, and measured the hydraulic conductivity of fracture-fill material in the laboratory (Flint et al., 1996). In an interview, it was reported that bulk rock hydraulic conductivity was estimated through independent computer-model simulations. The independent model simulated unsaturated flow in Yucca Mountain

Table 2. SNL and USGS Estimates of Infiltration at Yucca Mountain

Approximate Time Period (yr)	Climate State	SNL (2007a) Mean Annual Precipitation (mm/yr)	SNL (2007a) Mean Annual Infiltration (mm/yr)	BSC (2001) Mean Annual Precipitation (mm/yr)	BSC (2001) Mean Annual Infiltration (mm/yr)
0 – 600	Interglacial	174	14.3	189	3.6
601 – 2,000	Monsoon	275	25.5	301	8.6
2,001 – 10,000	Glacial Transition	283	30.0	316	13.4

rocks where change in moisture content had been measured over time. The best model fit or "calibration" was achieved with bulk hydraulic conductivity values that included the assumption of 250-µm filled fractures (Flint, personal communication, 2007). Accordingly, the USGS infiltration model used rock hydraulic conductivity values based on model calibration to the observed changes[5] in *in situ* moisture-content measurements arising from infiltration.

SNL assembled a new set of rock hydraulic conductivity values and used statistical distributions to describe hydraulic conductivity of rock units at Yucca Mountain (BSC, 2006d). SNL field observations revealed that, in general, some fraction of rock fractures was not completely mineral-filled. Therefore, the upper bound of rock hydraulic conductivity was calculated on the basis of the assumption of additional 200-µm open fractures. As an example of the effect of this assumption, the mean hydraulic conductivity of the lower lithophysal zone of the crystal-poor member of the Topopah Spring welded tuff (repository horizon rocks) increased three orders of magnitude over previous estimates reported by BSC (2001). Increased hydraulic conductivity enhances infiltration of available water.

5. Evaluation of SNL and USGS Model Results

Table 2 summarizes SNL and USGS estimates of present-day and future infiltration over the infiltration-model domain at Yucca Mountain (SNL, 2007a). The SNL estimate of 14.3 mm/yr median annual infiltration for the present-day interglacial climate is more than three times larger than previous USGS estimates of 3.6 mm/yr mean annual infiltration, shown for reference (BSC, 2001).

Model Calibration.
Model calibration is a common step in hydrogeologic model development and is appropriately performed before making predictive calculations. Typically, the calibration is performed to improve estimates of material properties, such as rock hydraulic conductivity, so that model calculation results are consistent with field observations. Although a calibrated model still can produce erroneous predictions of future conditions, scientists generally have greater confidence in models that are able to reproduce observed data while using a set of material property (parameter) values that are consistent with the rocks in the modeling domain. A poor fit of the model to data observations often indicates conceptual model error. At the March 14 Board panel meeting, SNL scientists stated that no calibration was performed for their model. As mentioned previously, the USGS infiltration-model parameters were based on a model calibration of rock properties to reproduce changes in observed *in situ* moisture-content measurements resulting from infiltration.

Multiple Lines of Evidence.
Beyond model calibration, confidence in model predictive estimates can be developed by testing and evaluating models and their components against multiple lines of evidence, including results of independent model estimates and data collected from monitoring programs and field experiments. The credibility of a model and its supporting conceptual and empirical bases are enhanced when that model can closely reproduce observed data. For example, as reported in the earlier discussion of ET, the SNL ET model

[5] Calibrating infiltration model properties on the basis of *change* in moisture content effectively minimized the influence of uncertainties regarding the absolute value of the measured moisture content.

was able to reproduce with a reasonable degree of fidelity the changes in stored water observed in lysimeter experiments run at the Nevada Test Site. As a result, the credibility of the ET model is enhanced for simulating the particular processes and plants tested in those experiments. (Note that it is *not* correct to infer that the credibility of the ET model also is demonstrated under a different set of conditions. Model credibility is demonstrated only for the particular set of conditions tested by the experiments.) In addition to the ET tests, SNL presented model comparisons showing that the results of the current model are generally within an order of magnitude of estimates from independent techniques, including chloride mass balance and Maxey-Eakin estimates (Maxey and Eakin, 1950).

Additional data sets available for model evaluation include historical records of surface-water flow within the model domain and measurements of temperature and salt (chloride) concentration within the unsaturated zone at Yucca Mountain. Flow of surface water as sheets or channelized flow in gullies, washes, and stream valleys at Yucca Mountain occurs in response to intense or prolonged rainfall and snowmelt events that overwhelm the local imbibition capacity of the soil and exposed rock. Both the SNL and the USGS infiltration models capture this behavior by incorporating a surface-water routing calculation that takes excess water from higher-elevation model grid cells and routes it to model grid cells at lower elevation. After losses due to ET and infiltration, only a small fraction of water flows over the land surface, and thus SNL scientists did not identify surface-water flow as a significant factor in average infiltration estimates. Nonetheless, presentations made at the March 14 Board panel meeting showed that by making minor adjustments in soil hydraulic conductivity, the SNL model was able to reproduce with reasonable fidelity the magnitude and timing of some observed surface-water runoff measurements in some watersheds of the model domain.

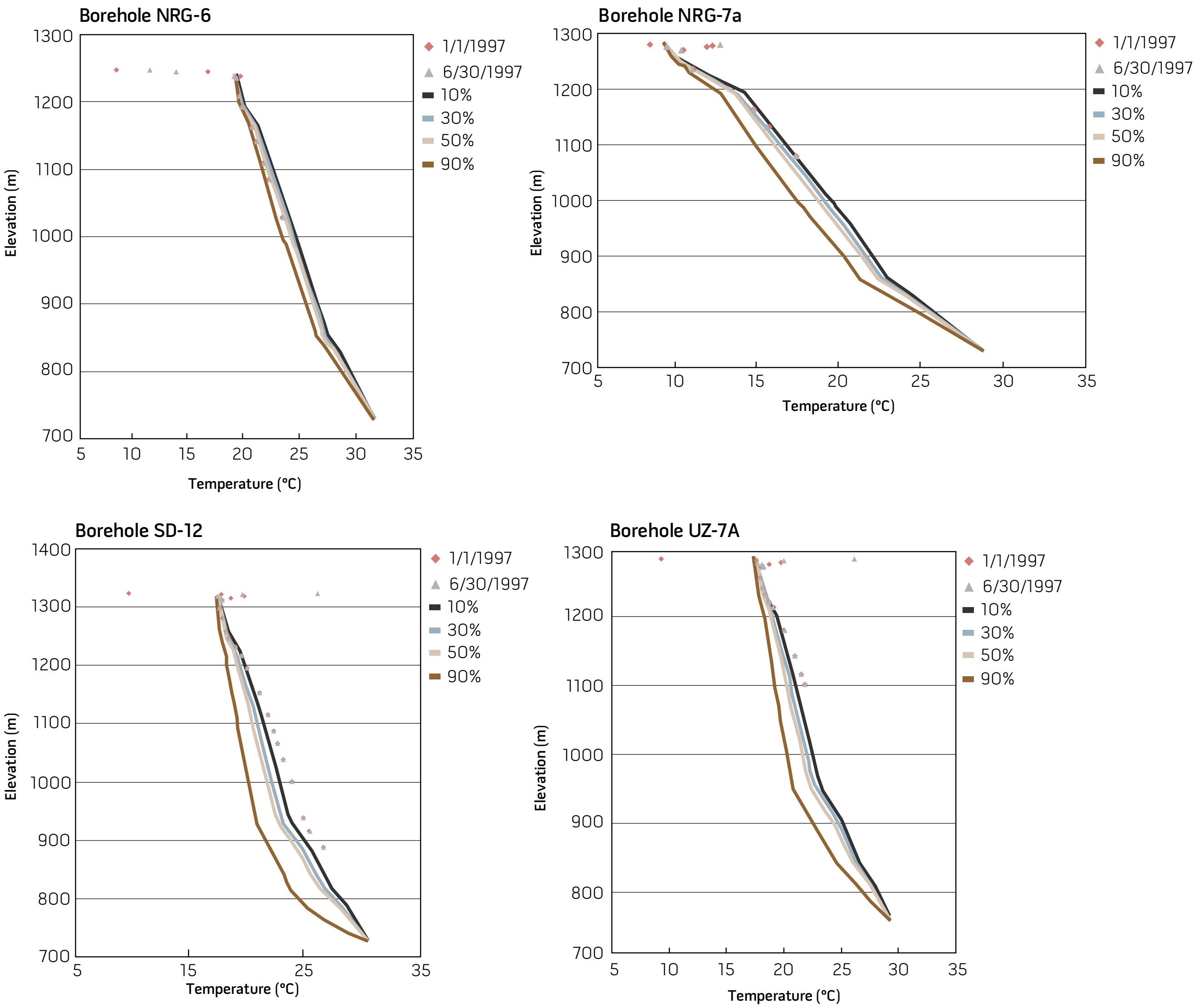
Subsurface temperature generally rises with depth below the land surface because of natural geothermal gradients. Water that infiltrates and percolates downward through the unsaturated zone tends to be relatively cool, and if fluxes in water percolation are sufficiently high, underground ambient temperatures can be reduced. Figure 2 shows unsaturated-zone model results presented at the Board's March 14 panel meeting comparing observed subsurface temperature distributions with those that would result from using infiltration rates from the SNL model predictions. Those models evaluated the following range of average infiltration estimates from SNL model predictions: 4.0 mm/yr, 10.1 mm/yr, 14.5 mm/yr, and 33.8 mm/yr, corresponding to the 10th, 30th, 50th, and 90th percentiles, respectively, of the infiltration estimates for the present-day climate. As shown in Figure 2, the model was able to reproduce the observed temperature values best when using the lower range of the infiltration estimates.

Chloride from salt is redistributed from the land surface to the subsurface by infiltrating and percolating water. At and near the land surface, the concentration of chloride in water is increased by evaporation, and thus lower infiltration rates encounter higher concentrations of chloride in the sources near the land surface. Using the same infiltration rates described in the previous paragraph, unsaturated-zone model tests presented at the March 14 Board panel meeting and shown in Figure 3 reproduced observed underground chloride concentrations best when using the lower range of the infiltration estimates. Higher values underestimated chloride concentration by approximately an order of magnitude.

Information presented at the Board's March 14 panel meeting made clear that USGS estimates of mean annual infiltration are based on an extensive suite of site-specific data and are consistent with multiple lines of physical and chemical evidence. The median annual infiltration estimates from the SNL model are not consistent with all available lines of evidence.

Model Comparisons.
SNL undertook a series of model comparisons of its newly developed model and the previous USGS model. The comparisons showed that when the parameterization of ET from the shallow bedrock is turned off in the USGS model and the remaining input

Figure 2. Comparison of measured subsurface temperature in four boreholes with calculated subsurface temperature using the 10th, 30th, 50th, and 90th percentiles of SNL infiltration estimates. In general, the lower SNL infiltration estimates produce the best overall fit to the measured data. (Houseworth, 2007.)

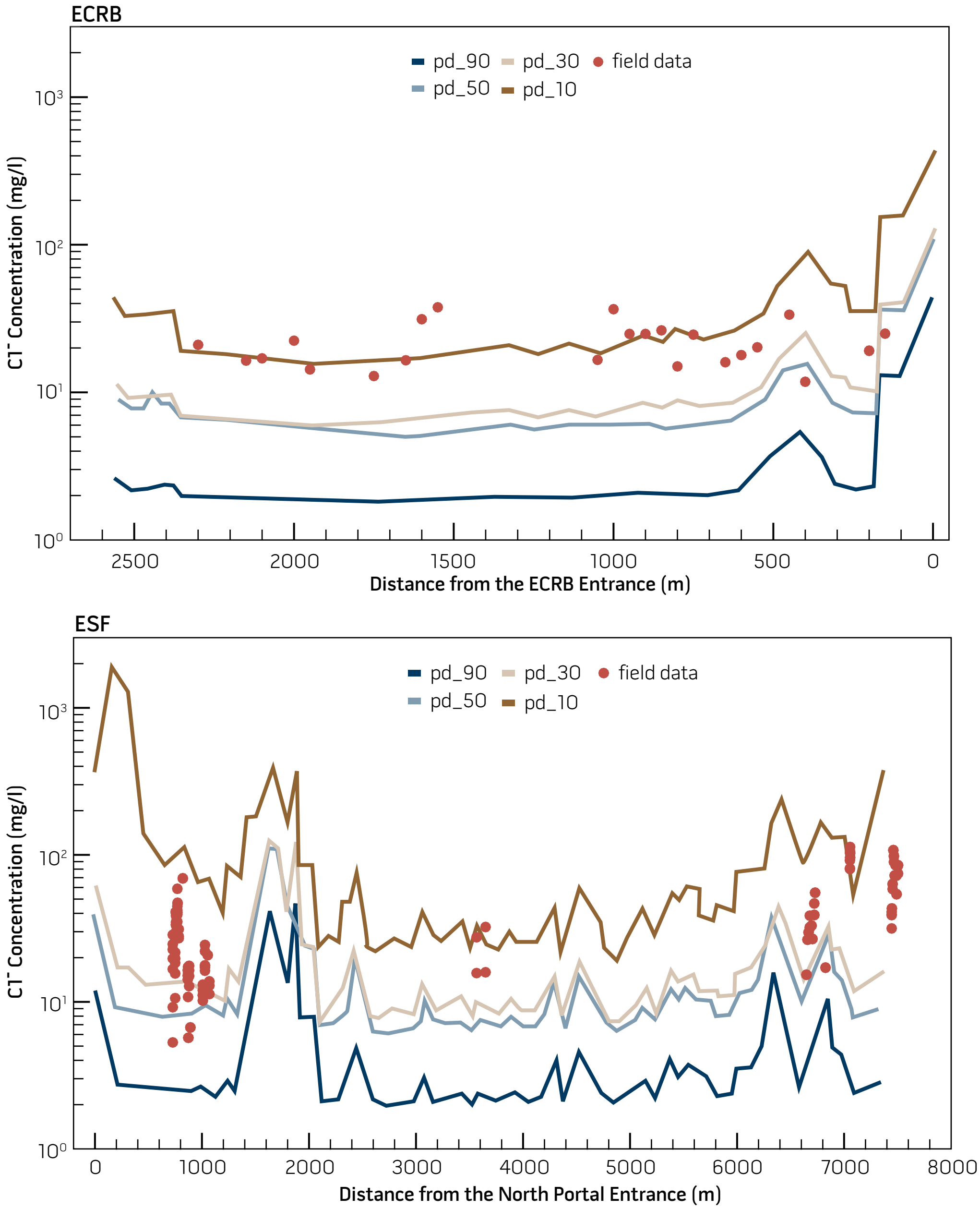


parameters are set to the same values, both models produce similar results for similar infiltration scenarios (Table 3). For example, SNL scientists conducted infiltration calculations for the Drill Hole Wash watershed using both SNL and USGS soil and rock properties. ET from bedrock, which is not simulated in the SNL model, was switched on and off in the USGS model. Precipitation was virtually identical in all cases. Because the model do-

Table 3. Comparison of SNL and USGS Model Calculations of Average Infiltration in the Drill Hole Wash Watershed for a Test Year.

		USGS Model (mm/yr)	
Model Parameters	SNL Model (mm/yr)	With shallow bedrock ET	Without shallow bedrock ET
SNL soil and rock properties	37	23	42
USGS soil and rock properties	14	8	12

Figure 3. Comparison of chloride concentration measured in the Exploratory Studies Facility (top) and Enhanced Characterization of the Repository Block (bottom) tunnels with chloride concentration calculated using the 10th, 30th, 50th, and 90th percentiles of SNL estimates of present-day (pd) infiltration. In general, the lower SNL infiltration estimates produce the best overall fit to the measured data. (Houseworth, 2007.)



mains use slightly different model grids, exact comparison of infiltration in each model grid cell is not possible. The values reported in Table 3 are watershed-wide averages.

Figures 4 and 5 show model test results for calculated infiltration over the Drill Hole Wash watershed, sorted by amount of water infiltrating into each model grid cell. In general, when the model parameters are the same, the calculated results are very similar for each model. In the case of the test using the SNL model parameter values, Figure 4 shows an abrupt

Figure 4. Comparison between SNL (MASSIF) and USGS (INFIL) model calculations of infiltration for the Drill Hole Wash watershed using SNL soil and rock properties (Levitt, 2007). ET from bedrock, not simulated in the SNL model, reduces the calculated infiltration in the USGS model (dark brown line).

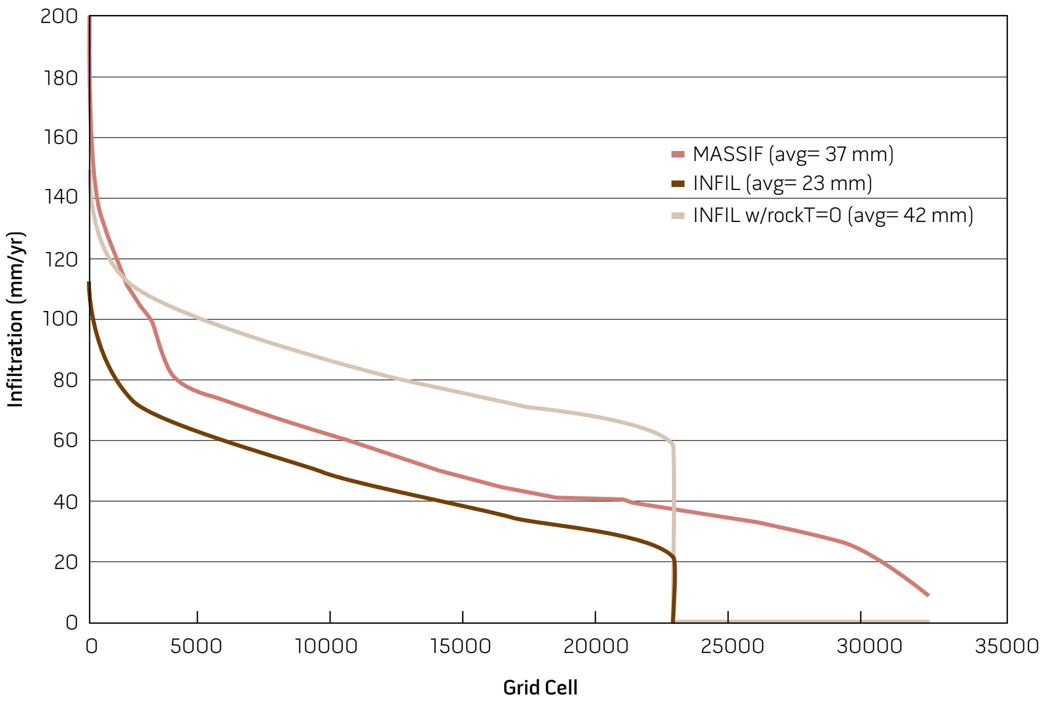
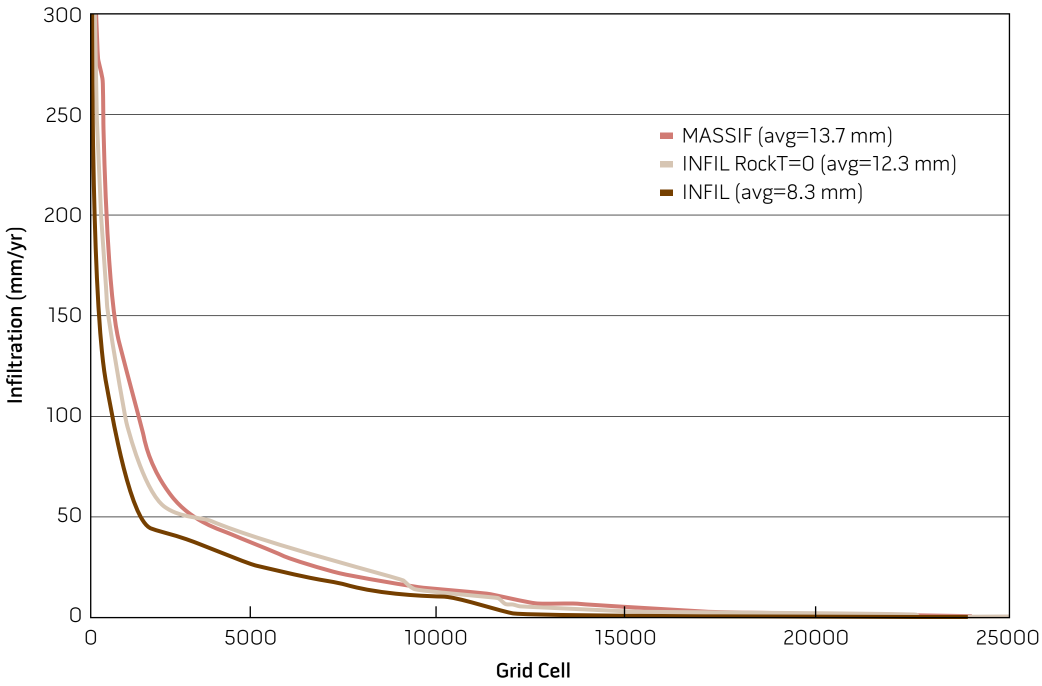


Figure 5. Comparison between SNL (MASSIF) and USGS (INFIL) model calculations of infiltration for the Drill Hole Wash watershed using USGS soil and rock properties (Levitt, 2007). ET from bedrock, not simulated in the SNL model, reduces the calculated infiltration in the USGS model (dark brown line).



cessation of calculated infiltration in the USGS model below a certain infiltration amount for cases both with and without bedrock ET. This suggests that a heuristic limitation in the USGS infiltration algorithm is encountered under the specified calculation conditions in the model. A similar condition is not seen in the SNL model in this case, nor is it seen in model simulations that use USGS model parameter values (Figure 5).

In summary, the SNL model does not include consideration of all available site-specific data used by USGS that are relevant to important infiltration factors, including soil depth and soil and rock hydraulic parameters, nor does it account for removal of water from upper layers of bedrock—a likely significant factor at Yucca Mountain. However, the SNL procedure has the benefit of a more complete statistical representation of uncertainties associated with relevant physical parameters.

Minor computational deficiencies in the USGS model were identified by DOE and USGS reviewers. For example, one reviewer reported identifying an error in computer coding that resulted in discrepancies on the order of 10^{-4} mm/yr (Levitt, personal communication, 2007). A similar magnitude of error in the USGS model resulted from a typographical error in a source text (Pollock, personal communication, 2007). Errors of this magnitude are not significant for long-term estimates of infiltration at Yucca Mountain.

SNL estimates of present-day infiltration at Yucca Mountain are approximately three times higher than USGS estimates. SNL estimates also are less consistent with independent lines of evidence, including measurements of temperature and salt (chloride) concentrations at depth in Yucca Mountain.

The Board found no significant errors in the computational approach used for infiltration estimates for either the USGS model or the SNL model. When the values of variables and the simulated natural processes are specified to be the same in the SNL and USGS models, the infiltration estimates from the two approaches are similar. The Board's opinion is that if all relevant available site-specific data at Yucca Mountain are used in both the USGS model and the SNL model, the repository performance estimates that are based on infiltration estimates from either model also should be essentially the same.

6. Evaluation of Use of SNL Model Results in Performance Estimates

Results of infiltration model calculations are used as input to the unsaturated-zone mountain-scale model and to the multiscale thermohydrologic model, among others, in the Yucca Mountain TSPA. As described at the March 14 Board panel meeting, to make estimates of present-day and future climate infiltration at Yucca Mountain more consistent with observed temperature and salt (chloride) measurements in the unsaturated zone, DOE preferentially assigned higher statistical probabilities to the lower range of the statistical distribution (10^{th} percentile) of SNL-estimated infiltration. The statistical probability weights were calculated using a procedure known as Generalized Likelihood Uncertainty Estimation (GLUE; K. Beven and A. Binley, 1992). As used by DOE, GLUE preferentially gives greater statistical weight to infiltration estimates that are more consistent with observed temperature and salt (chloride) measurements. Consistent with the recommendation of Beven and Binley (1992), in the DOE application of GLUE, the choice of the underlying statistical likelihood function is taken as arbitrary (SNL, 2007b). However, recent research has revealed that the likelihood function is not arbitrary and rather must describe the distribution of the model and data errors if a valid result is to be obtained (R. M. Vogel, R. Batchelder, and J. R. Stedinger, in review).

Furthermore, because the statistical fitting using the GLUE procedure is based on observed physical states and chemical conditions in Yucca Mountain that resulted from modern climate and infiltration, there is no technical basis for applying the identical statistical weighting scheme to infiltration estimates for future climates in TSPA.

As used by DOE, the GLUE statistical procedure does not have a strong technical basis. The Board is not aware of other instances in TSPA where statistical sampling of input data sets of a physical process is biased to yield desired outcomes of downstream processes (as opposed to statistical sampling that is based on the natural statistical distribution of the parameter or process). Because this application of the statistical procedure *ex post facto* in TSPA does not have a strong technical basis, the Board does not endorse the statistical modification of infiltration estimates made by DOE.

7. Quality Assurance

Although the effects on the regulatory process of QA infractions are not part of the Board's purview and therefore were not part of the Board's evaluation, the Board notes that compliance with QA procedures is an important part of the licensing process. In their assessment of the USGS infiltration estimates, DOE QA reviewers often reported that data or analyses failed to satisfy QA protocols because they were not transparent or traceable. DOE QA reviewers recommended replacing those data or analyses, as required.

DOE QA reviewers found that USGS estimates of soil depth were acceptable for use in previous infiltration calculations. However, DOE QA reviewers recommended against using those USGS soil-depth estimates in future infiltration calculations (BSC, 2006b). DOE QA reviewers found inconsistencies between point measurements of soil-depth data from boreholes and area-averaged values, as well as inadequate traceability and transparency of soil-depth estimates. At the Board's March 14 panel meeting, SNL reported that not all soil properties, such as soil hydraulic conductivity, used by USGS could be independently reproduced from available records. Furthermore, as a part of DOE's corrective action program, SNL found that bedrock saturated hydraulic conductivities used in previous USGS infiltration analyses (BSC, 2001) could not be traced to qualified data sources (BSC, 2006d).

As reported at the March 14 Board panel meeting, a consequence of QA review was to discard or disallow some USGS site-specific data. For example, a moisture-content data set documenting an infiltration event was not recognized as legitimate, in part because of insufficient documentation and in part because DOE QA reviewers were not permitted to communicate with scientists responsible for the work. In this instance, disallowing a rare and valuable data set of direct observations of a natural infiltration event at Yucca Mountain diminished the robustness of the empirical database supporting the new technical analysis.

DOE also conducted an independent QA audit of the new SNL infiltration model and accompanying report (DOE, 2007). That audit found that the infiltration model report ". . . is adequate for [the] intended purpose [and] meets established criteria for overall effectiveness in implementation, technical adequacy and product quality." Nonetheless, the auditors identified some specific technical areas in the model analysis that merited further attention, many of which are consistent with concerns expressed in this report. For example, among other findings, the independent auditors recommended that DOE do the following (DOE, 2007):

• List assumptions that bias infiltration calculations toward overestimation.

• Reduce uncertainty and biased spatial variability of [shallow] soil depth classification 4.

• Consider improving data spatial variability for soil, hill slopes and ridges, and hydraulic properties.

• Consider other available data sets and justify [the] pedotransfer method [used to determine soil hydraulic conductivity].

In summary, the Board's opinion is that the USGS program produced valuable results that are important to understanding the mountain hydrology and to building confidence in the estimated performance of the proposed repository, and that all available data should be used in evaluating the performance of the proposed repository. Relevant data that have been found to have transparency or traceability QA discrepancies should be requalified and used in estimates of infiltration. For example, moisture-content data measured by geophysical neutron logging can be recalibrated on the basis of laboratory analyses of rock core samples held in the DOE sample management facility.

8. Conclusions

The Board's review of DOE estimates of infiltration at Yucca Mountain was undertaken as part of the Board's ongoing technical and scientific peer review of DOE activities related to the Yucca Mountain repository program. It fulfills a commitment to Congress made by Board Chairman B. John Garrick in 2005. DOE elected to develop new estimates of infiltration at Yucca Mountain when allegations of QA violations by USGS infiltration investigators were inferred from USGS e-mail communications. Subsequent DOE technical reviews did not identify significant problems with the technical validity of USGS data or analyses. In fact, SNL found that USGS data and modeling were generally suitable for supporting previous DOE analyses and reports. However, largely because of multiple instances of inadequate transparency and traceability, SNL recommended that much of the USGS infiltration data and analyses should not be used to support analyses feeding into the license application (LA).

SNL developed a new infiltration model that is based on principles similar to those used by the USGS model. Components of the SNL model were tested and found to be robust in their ability to reproduce experimental observations. However, the SNL model differs from the USGS model in that the SNL model was not calibrated to observed site hydrogeologic data. Furthermore, because much of the USGS data were viewed as having QA deficiencies in terms of transparency and traceability, they were not used. The SNL model also neglected evapotranspiration—the removal of water by evaporation and plant consumption— from shallow buried bedrock. Probably as a result of all of these factors, the SNL model predicted approximately three-times greater infiltration at Yucca Mountain for the present-day climate than was predicted by the USGS model.

To reconcile the higher SNL infiltration results with independent hydrogeologic data collected at Yucca Mountain, DOE used a statistical approach known as GLUE for preferentially using the lower range of the infiltration estimates in TSPA. As implemented by DOE, the application of GLUE does not have a strong technical basis. The Board does not endorse the use of the statistically modified SNL infiltration estimates (which place greater statistical emphasis on the lower range of infiltration estimates) in TSPA.

The Board found no significant errors in the computational approach used for estimating infiltration by either the USGS or the SNL models, both of which reflect the substantial scientific acumen of the scientists who created the models. In fact, when the modeled processes and parameters were the same, both the SNL model and the USGS model produce similar results. However, the inconsistency between the SNL infiltration estimates and observed hydrogeologic data at Yucca Mountain is evidence of the need to incorporate all available site-specific data into infiltration models, even if some previous USGS data sets must be requalified to meet new QA standards. In addition, evapotranspiration from shallow buried bedrock at Yucca Mountain is likely to be significant and should be included in infiltration calculations.

Finally, the Board realizes that compliance with QA procedures is an important part of the licensing process and that evaluating regulatory aspects of DOE activities is not the Board's role. However, in this case, the QA program was cited by DOE in undertaking a very substantial technical effort that involved replacing previous USGS infiltration estimates with new SNL infiltration estimates. In addition, QA was a significant constraint on what data were and were not used in support of the new infiltration estimates. In the Board's view, even when scientific endeavors are not conducted in strict compliance with QA procedures, the fruits of those endeavors can be of significant value and merit. Likewise, strict observance of QA procedures is not by itself sufficient to guarantee sound technical and scientific analyses or data.

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† Although every effort has been made to ensure that references are available, not all references cited here have been released to the public by DOE. Furthermore, some of the cited references have undergone minor revision by DOE during the production of this document. The revisions are not expected to alter the conclusions presented here significantly.

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Appendix A. U.S. Nuclear Waste Technical Review Board Congressional Testimony

Statement of B. John Garrick

Mr. Garrick. Good morning, Mr. Chairman and members of the subcommittee.

I am John Garrick, chairman of the Nuclear Waste Technical Review Board. All 11 members of the Board are appointed by the President and serve on a part-time basis. In my case, I'm a private consultant specializing in the application of the risk sciences to complex technological systems in the space, defense, chemical, marine and nuclear fields.

As you know, Mr. Chairman, the board was created by Congress in 1987 to perform an ongoing, independent, technical and scientific evaluation of DOE's implementation of the nuclear Waste Policy Act. I am pleased to represent the board at this hearing. With your permission, Mr. Chairman, I will now briefly summarize my comments and ask that the full text of my written statement be entered into the hearing record.

According to the letter inviting the board to participate, today's hearing has two purposes: to address whether Federal employees falsified documents related to work at the Yucca Mountain; and to examine whether sound science exists for the proposed Yucca Mountain project.

Mr. Chairman, it would be inappropriate for the board to draw any conclusions at this time about the impact on DOE's technical work at Yucca Mountain from the group of redacted e-mails that were posted on the subcommittee's web site last Friday. As disturbing as it is to see such loosely framed discussions among scientists, the answers to important questions that might be raised by or about the e-mails or related documents should await the completion of comprehensive investigations already underway at the Departments of Energy and Interior.

The board will follow the progress of these investigations and when they are concluded, the board will evaluate the significance of the results to DOE's technical and scientific work. We will then report our findings to Congress and the Secretary of Energy.

In the meantime, the board will continue its ongoing peer review of DOE activities. The Nuclear Regulatory Commission is the appropriate agency to address questions about the effects on the regulatory process of possible infractions of QA procedures.

Mr. Chairman, let me close by saying that the board looks forward to continuing its congressionally established role of unbiased and independent technical and scientific information to Congress and the Secretary. As I mentioned earlier, we will be able to comment better on the significance of the activities that are the topic of this hearing when the full results of DOE and Interior investigations are known.

Thank you for the opportunity to present the board's views. I will be happy to respond to questions. [The prepared statement of Dr. Garrick follows.]

Statement of Dr. B. John Garrick, Chairman

U.S. Nuclear Waste Technical Review Board,

Before the Subcommittee on the Federal Workforce and Agency Organization

Committee on Government Reform

U.S. House of Representatives

April 5, 2005

Good morning, Mr. Chairman and members of the subcommittee. I am John Garrick, Chairman of the U.S. Nuclear Waste Technical Review Board. All eleven members of the Board are appointed by the President and serve on a part-time basis. In my case, I am a private consultant specializing in the application of the risk sciences to complex technological systems in the space, defense, chemical, marine, and nuclear fields.

As you know, Mr. Chairman, the Board was created by Congress in the Nuclear Waste Policy Amendments Act of 1987 to perform an ongoing independent evaluation of the technical and scientific validity of the Department of Energy's (DOE) efforts in implementing the Nuclear Waste Policy Act. The Board began its work in 1989 and has continuously reviewed the technical and scientific validity of DOE activities since that time. I am pleased to represent the Board at this hearing.

According to the letter inviting the Board to participate, today's hearing has two purposes. The first purpose is to question whether federal employees falsified documents related to work at the Yucca Mountain site. The second purpose identified in the letter is to examine whether sound science exists for the proposed project, in light of the allegations.

Mr. Chairman, it would be inappropriate for the Board to draw any conclusions at this time about the significance for the technical work at Yucca Mountain of the group of redacted e-mails that were posted on the subcommittee's web site on Friday afternoon. Answers to questions that might be raised by or about the e-mails should await the completion of comprehensive investigations already underway at the Departments of Energy and Interior. The Board will follow the progress of those investigations, and when they are concluded, the Board will evaluate the significance of the results for DOE's technical and scientific work. We will then report our findings to Congress and the Secretary of Energy. In the meantime, the Board will continue its ongoing technical and scientific peer review of DOE activities. The Nuclear Regulatory Commission (NRC) is the appropriate agency to address questions about the effects on the regulatory process of possible infractions of quality assurance procedures.

As you know, Mr. Chairman, reporting to Congress and the Secretary at least twice a year is an important part of the Board's mandate. In accordance with that mandate, in late 2004, the Board sent to Congress and the Secretary a report summarizing areas of progress in the Yucca Mountain program; issues that, in the Board's view, require additional attention; and the Board's priorities for 2005. Since the second purpose of this hearing touches on technical and scientific validity, I will now summarize some of the Board's findings from that letter report.

The Board believes that over the last year or so, DOE has made progress in several areas. For example, a key corrosion issue raised by the Board was addressed by DOE data and analyses, indicating that tunnel conditions during the thermal pulse will likely not lead to the initiation of localized corrosion of the waste packages due to deliquescence of calcium chloride. The Board also is encouraged by DOE efforts related to making earthquake ground-motion estimates more realistic and in completing an aeromagnetic survey that could shed light on igneous activity in the Yucca Mountain area. In addition, the DOE has made headway in developing a systematic approach to planning for the transportation of spent nuclear fuel and high-level radioactive waste.

Other issues require continued or additional attention, including an improved understanding and a clear explanation of the likely conditions inside repository tunnels during the thermal pulse; other corrosion issues related to the postclosure environment of the repository; the resolution of discrepancies among chlorine-36 studies; and improvements in the modeling of volcanic consequences. The Board also will follow with interest the work undertaken by the science and technology program established by Dr. Margaret Chu.

In addition to reviewing these important issues, the Board is establishing priorities for its technical and scientific review as the DOE prepares the information necessary to submit a license application to the NRC. In identifying its priorities, the Board considers (1) if the issue is important to the safe performance of the repository, (2) if the issue is important to public confidence, and (3) if the Board has special expertise and experience, which provide new and relevant perspectives on technical issues. In particular, the Board intends to review the DOE's technical and scientific work and analysis supporting total system performance assessment (TSPA). The Board will evaluate the extent to which the DOE has used TSPA as an integrative tool and how well the assumptions underlying TSPA results are supported by technical analysis and available evidence. Other Board priorities include an improved understanding of the performance of the hydrogeologic barriers, particularly regarding the magnitude and timing of the peak dose; how the DOE's thermal-loading strategy might affect trade-offs between preclosure and postclosure risk; issues affecting the waste-package lifetime; and the DOE's continued efforts to develop an integrated waste management system, including the handling, transportation, packaging, and disposal of spent nuclear fuel and high-level radioactive waste. The Board is especially interested in scientific work and analyses that may be undertaken by the DOE in response to likely changes in the regulatory compliance period for a Yucca Mountain repository.

Mr. Chairman, let me close by saying that the Board looks forward to continuing its congressionally established role of performing an independent evaluation of the DOE's technical and scientific activities related to the disposal, packaging, and transportation of the country's spent nuclear fuel and high-level radioactive waste and reporting to Congress and the Secretary. We will be in a much better position to comment on the topics of this hearing once we have reviewed the findings of the comprehensive investigations that are currently underway.

Thank you for the opportunity to present the Board's views. I will be happy to respond to questions from the subcommittee.

Appendix B. Questions Presented to Interviewees

1. How is the hydrologic cycle represented in your infiltration model?

2. Which components are represented explicitly?

3. Which components are not represented explicitly?

4. For processes, what algorithms are used?

5. For data, what empirical data are used?

6. What elements of the calculation are deterministic, what elements of the calculation are stochastic, and what elements of the calculation are probabilistic?

7. How does the numerical method implemented conserve volume or mass?

8. What residual is specified for convergence or for demonstration of an acceptable tolerance for a calculation?

9. What is the residual difference between the subject model's estimation of infiltration and the previous DOE estimates of infiltration for 190 mm/yr of precipitation and for 390 mm/yr of precipitation?

10. What is the sensitivity ranking of the independent parameters in terms of the dependent variable?

11. What are the first and second moments of the distributions of significant independent parameters?

12. What QA procedures were followed during the course of your technical work? To what extent did those procedures influence the technical approaches which you used?[†7]

[†] Although question 12 was not in the original list, the answer to this question emerged during the course of the onsite interviews. The question is added here for completeness.

Appendix C. Documents Reviewed but not Cited

In addition to the documents cited in the list of references, the U.S. Nuclear Waste Technical Review Board reviewed the technical documents identified in the table below.

BSC, 2006e. *Technical Evaluation and Review of Results, Technical Procedures and Calibration Methods Related to the Collection of Moisture Monitoring Data Using Neutron Probes in Shallow Boreholes*. TDR-NBS-HS-000019 REV 00

BSC, 2006f. *Data Analysis for Infiltration Modeling: Extracted Weather Station Data used to Represent Present and Potential Future Climate Conditions within the Vicinity of Yucca Mountain*. ANL-MGR-MD-000015

BSC, 2006g. *Data Qualification Report: Ground Cover Data for Ecological Study Plots at Yucca Mountain, Nevada*. TDR-NBS-GS-000030 REV 00

BSC, 2006h. *Data Qualification Report for Digital Surficial Deposits Mapping File for use on the Yucca Mountain Project*. TDR-NBS-GS-000029

BSC, 2006i. *Data Qualification Report for the Qualification of Yucca Mountain Site Precipitation Data for 1989 – 1992*. TDR-NBS-MD-000051

BSC, 2006j. *Data Qualification Report for the Qualification of Air Temperature Data from Meteorological Data Acquisition Station 24 for 1989 through 2004*. TDR-MGR-MD-000050 REV 00

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