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Overview

Since 1987, the U.S. Department of Energy (DOE) has spent more than $3 billion to characterize and evaluate Yucca Mountain, Nevada as a possible site for the world's first permanent facility to store high-level radioactive waste and spent fuel from commercial reactors.[1] In 1992, DOE completed the Early Site Suitability Evaluation (ESSE) and drew positive conclusions regarding the suitability of every site factor (volcanism, seismicity, human disruption, and so on).[2] Residents of the state of Nevada, however, disagree both with the conclusions of the DOE and with the notion that they can trust DOE to conduct reliable site studies. In fact, 80% of Nevadans are opposed to the proposed facility.[3]

Although many factors — political, economic, and geological — are responsible for the sharp disagreement between DOE and Nevadans, one important controversy concerns DOE assessors' use of expert judgment to estimate potential risks at Yucca Mountain. Indeed, even the U.S. Nuclear Regulatory Commission (NRC), in its review of DOE conclusions, warned that DOE "use of expert judgment... does not

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1 J.L. YOUNKER ET AL., U.S. DEPARTMENT OF ENERGY, REPORT OF EARLY SITE SUITABILITY EVALUATION OF THE POTENTIAL REPOSITORY SITE AT YUCCA MOUNTAIN, NEVADA 1–13 (1992).

2 *Id.*

3 P. Slovic et al., *Perceived Risk, Trust, and the Politics of Nuclear Waste*, 254 SCIENCE 1604 (1991).

generally conform to the 'good practices' discussed" in typical NRC documents; in particular, the NRC charged that many DOE analyses — such as those dealing with risks from volcanism — were inadequately conservative.[4] In this essay, we shall evaluate four classes of expert judgments used in Yucca Mountain risk assessments. Although none of these judgments was addressed by the NRC in its remarks, all of them represent potential problems at the proposed Nevada site. These expert judgments are (1) that short-term studies (a decade or less) provide an adequate basis for extrapolating to long-term risks (ca 10,000 years); (2) that models of site hydrogeology are reliable, even though they have not been confirmed in the field; (3) that simplifications of site hydrogeology do not misrepresent the actual situation; and (4) that sampling of site characteristics is extensive enough and representative enough to provide a basis for predicting future behavior at the site.

In this essay, we shall evaluate these classes of expert judgments used in Yucca Mountain risk assessments, in order to determine the extent to which, if any, the judgments may be responsible for erroneous risk estimates. We shall argue that, because judgments (2)-(4) are examples of faulty science, they do not necessarily show either that there is a specific problem with the Yucca Mountain site or that there is a general problem with geological disposal of radioactive waste. Rather, they argue for greater conservatism in the Yucca Mountain studies. Judgment (1), however, is so problematic that it appears to argue both against the Yucca Mountain site and against permanent geological disposal of high-level radioactive waste anywhere at present.

Our point in assessing these four classes of expert judgments is neither that our survey is exhaustive nor that all such judgments ought to be avoided. Some types of expert judgments are obviously unavoidable in both science and risk assessment. Hence, the problem is not expert judgments, as such, but the frequent absence of any ideas about the limits of error or uncertainty associated with them in many Yucca Mountain assessments, and the tendency of experts to be overconfident about the effects of their judgments.

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4 JOSEPH J. HOLONICK, REVIEW OF REPORT OF EARLY SITE SUITABILITY EVALUATION OF THE POTENTIAL REPOSITORY SITE AT YUCCA MOUNTAIN, NEVADA 3 (1992).

Judgments about Long-Term Risks

One of the most basic classes of expert judgments used in estimating the risk of radionuclide migration (at Yucca Mountain and at other proposed permanent sites) concerns extrapolations on the basis of short-term studies. Indeed, geologists who are asked to make predictions typically are forced to make expert judgments when they extrapolate either to the past or to the future on the basis of what they observe in the present. Often they use internal features, stratigraphy, and morphologic expressions of rocks, for example — or general principles describing dynamic geological processes operating through time — when they make inferences about past geologic events.[5] Frequently, for instance, geologists use the absence of certain phenomena in the past and present as evidence for denying the likelihood that a specific geologic process will occur in the future. Yet, such an inference is questionable, because one ought not simply assume from the absence of something that it was never there and that it will never be there. As Watson points out, "it is a non sequitur to argue from the absence of something [like given rock] in the past to the conclusion that it will not be present in the future."[6] There must also be other evidence, for example, for a process of rock removal, in order for the inference to be reasonable. Likewise, there must be "other evidence" when geologists extrapolate to the past or to the future on the basis of present data. Geologists know that, in general, the less we know about the processes and evidence supporting such inferences/extrapolations/judgments, the greater is the likelihood that we are wrong. Moreover, the smaller the empirical base used for such extrapolation, all things being equal, the greater the chance that it is not, or will not be, representative of past and future events and processes.

One problematic expert judgment made in many Yucca Mountain studies is that short-term tests, (for several years or less) provide adequate information for very precise predictions of long-term behavior, for example, isolation of the waste for 10,000 years and container

[5] *See* R. Watson, *Explanation and Prediction in Geology*, 77 J. GEOLOGY 488 (1969).

[6] R.A. Watson, *Absence as Evidence in Geology*, 30 J. GEOLOGICAL EDUC. 300–01 (1982).

integrity for 1,000 years.[7] This judgment — about the validity of a long-term inductive conclusion based on short-term data — is highly controversial, in part because the extended time horizon for any high-level repository is several times longer than recorded human history.[8] As Massachusetts Institute of Technology geologist, K.V. Hodges, a peer reviewer for the Yucca Mountain ESSE put it, the Congressional mandate for siting a high-level repository is for predictive information 10,000 years into the future. Geology, however, as he points out, is an explanatory and not a predictive science.[9] Or, as Dartmouth geologist N. Oreskes noted: "the extrapolation of short-term to long-term studies at Yucca Mountain flies in the face of 300 years of geological practice. The question is, how did they get away with that?"[10] "Predictive geology," according to Hodges, "is predicated on the assumption of a sort of inverse uniformitarianism: the past geologic record is the key to future geologic activity."[11] Yet, at least since the recent revolution in plate tectonics, uniformitarianism — in any precise, predictive sense — has been largely abandoned by geologists. As Hodges continues:[12]

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7 *See, e.g.*, J. BEAVERS & N. THOMPSON, ENVIRONMENTAL EFFECTS ON CORROSION IN THE TUFF REPOSITORY (1990) (Item 118 in DOE, DE91000566); W. Halsey, *Selection Criteria for Container Materials at the Proposed Yucca Mountain High Level Nuclear Waste Repository*, in NACE CORROSION '90 (1990) (Item 60 in DOE, DE91000566); J. Perry, A Linement Analysis of Yucca Mountain, Nevada: The Proposed High-Level Nuclear Waste Repository, in 6TH THEMATIC CONFERENCE ON REMOTE SENSING FOR EXPLORATION GEOLOGY: APPLICATIONS, TECHNOLOGY, ECONOMICS (1988) (Item 135 in DOE, DE91000566); D. Dobson et al., *Plans for Characterization of the Potential Geologic Repository Site at Yucca Mountain, Nevada*, in INTERNATIONAL CONFERENCE FOR HIGH-LEVEL RADIOACTIVE WASTE MANAGEMENT (1990) (Item 8 in DOE, DE91000566).

8 *See* G. SAWYER, REPORT OF THE STATE OF NEVADA'S COMMISSION ON NUCLEAR PROJECTS 73 (1990).

9 K.V. Hodges, *Comment*, in J.L. YOUNKER ET AL., REPORT OF THE PEER REVIEW PANEL ON THE EARLY SITE SUITABILITY EVALUATION OF THE POTENTIAL REPOSITORY SITE AT YUCCA MOUNTAIN, NEVADA 362 (1992).

10 N. Oreskes, Comments on Uncertainty, Expert Error, and Radioactive Waste 6 (unpublished remarks, Mar. 23, 1992).

11 Hodges, *supra* note 1, at 363.

12 *Id.*

> earthquake prediction is one of the most visible examples of predictive geology... but it remains a hit-or-miss proposition. Perhaps predictive geology will improve in the future... but DOE, the Congress, and the American people need to confront the fact that the earth science community does not have the tools necessary to generate models that will permit the prediction of future tectonic activity with a high degree of accuracy... tectonic predictions, when stripped of statistical sound and fury, are not much better than educated guesses.

Moreover, says Hodges, it is likewise "patently absurd" that we attempt to predict the probability of volcanic disruptions over 10,000 years. In asking for such predictions, claims Hodges, we are "asking the impossible."[13]

Indeed, the entire (14-person) DOE peer reviewer group for the Yucca Mountain ESSE confirmed Hodges' conclusions about the impossibility of reliable 10,000-year predictions for any waste repository site. They said:[14]

> many aspects of site suitability are not well suited for quantitative risk assessment. In particular are predictions involving future geological activity, future value of mineral deposits and mineral occurrence models. Any projections of the rates of tectonic activity and volcanism, as well as natural resource occurrence and value, will be fraught with substantial uncertainties that cannot be quantified using standard statistical methods.

If the Yucca Mountain peer reviewers are correct, then obviously making precise, long-term, geological predictions on the basis of short-term data is questionable.

Although long-term prediction is a problem in any area of science, the Yucca Mountain predictions are particularly problematic, as compared to those in other areas of science not only because they deal with thousands of years but also because the U.S. government regulations require the predictions to be very precise (see later sections of this essay for discussion of this point). They specify allowable levels of radionuclide releases over thousands of years. Hence, it is the

13 *Id.*, at 384.

14 YOUNKER ET AL., *supra* note 1, at B-2, (Consensus Position).

precision of the long-term predictions that make them more problematic at Yucca Mountain than in other applications of science. Moreover, in cases such as Yucca Mountain, precise, long-term predictions about safety are especially questionable because the potential dose commitments of radioactive isotopes (such as C-14, Pu-239 and I-129) — all with possibly serious health effects — extend from hundreds of thousands to millions of years.[15] In other words, long-term, precise predictions are more problematic in cases where their being wrong could lead to a human or environmental disaster. Such a disaster is especially worrisome because the U.S. Environmental Protection Agency (EPA) has explicitly warned that it is "impossible" to predict anything regarding the success of radioactive waste management beyond 100 years. The agency has noted that institutional controls are particularly problematic beyond a period of 100 years.[16] Indeed, when the state of Nevada did a review of the Yucca Mountain Site Characterization Plan in 1989, focusing on the hydrogeological pathways for possible radionuclide escape, one of its seven major "concerns" was using short-term studies as the basis for long-term site predictions.[17]

One of the main worries about making the judgment that a long-term repository risk is acceptable, given only short-term, incomplete data, is that some unforeseen catastrophic event could occur centuries from now that would compromise the integrity of the long-term facility. Yet the waste would be retrievable, according to U.S. regulations, for only 50 years after the repository is opened.[18] Because catastrophes have occurred in the past, there are grounds for similar worries about disruption of the waste-disposal facility. The U.S. landscape has a number of craters created by meteor hits, for instance, some of which (in Iowa and Arizona) are quite famous. Yet the annual probability of a

[15] D. HAWKINS, CONSIDERATIONS OF ENVIRONMENTAL PROTECTION CRITERIA FOR RADIOACTIVE WASTE (1978).

[16] U.S. ENVIRONMENTAL PROTECTION AGENCY, CONSIDERATIONS OF ENVIRONMENTAL PROTECTION CRITERIA FOR RADIOACTIVE WASTE 10 (1978).

[17] C.B. RALEIGH & THE PANEL ON COUPLED PROCESSES AT YUCCA MOUNTAIN, GROUND WATER AT YUCCA MOUNTAIN: HOW HIGH CAN IT RISE? (1992).

[18] *See* K.S. SHRADER-FRECHETTE, BURYING UNCERTAINTY: THE CASE AGAINST GEOLOGICAL DISPOSAL OF NUCLEAR WASTE, ch.2 (1993).

meteor strike is quite low, just as the probability of repository flooding is likely small.[19] When one is considering long-term predictions for something like the Yucca Mountain repository, however, even events likely having a low annual probability assume major proportions. In the case of volcanism or seismic activity, for example, it is not necessary to assume that the disruptive event would unearth the waste canisters. Rather, even a small seismic dislocation of some geological features might be sufficient to change the location and flow of groundwater that could flood the repository and leach the waste. Moreover, even if the per-year probability of dangerous seismic or volcanic activity is quite low, for example, 10-6, this figure means that during the lifetime of the repository such an event would be virtually certain. An annual probability of 10-6 converts to a 10-3 likelihood over 1,000 years. This is a quite high probability, and especially disconcerting when one considers the possible catastrophic consequences.

Obviously, it is questionable whether one can make an inductive prediction that guarantees the radwaste "permanent isolation from the biosphere" — as several risk assessors claimed — on the basis of inductive data obtained during only one or several decades.[20] Moreover, most of the Yucca Mountain experiments have been done and data obtained over periods of far less than a decade. Investigations of 304 days duration and 9 years duration, for instance, have both been called "long-term" studies.[21] However, data from 6-, 11-, and 18-month experiments, rather than multiple years, is more typical of Yucca

[19] NEVADA NWPO, 1 STATE OF NEVADA COMMENTS ON THE U.S. DEPARTMENT OF ENERGY CONSULTATION DRAFT SITE CHARACTERIZATION PLAN, YUCCA MOUNTAIN SITE, NEVADA (1989)) (Item 335 in DOE, DE90006793).

[20] 3 R. Stein & P. Collyer, *Pilot Research Projects for Underground Disposal of Radioactive Wastes in the United States of America*, in RADIOACTIVE WASTE MGMT. (1984) (Item 157 in DOE, DE89005394).

[21] K.G. KNAUSS ET AL., HYDROTHERMAL INTERACTION OF SOLID WAFERS OF TOPOPAH SPRING TUFF WITH J–13 WATER AT 90 AND 150/DEGREE/C USING ... LONG-TERM EXPERIMENTS (1987) (Item 18 in DOE, DE89005394); D. Hoffman et al., *Review of a Field Study of Radionuclide Migration from an Underground Nuclear Explosion at the Nevada Test Site*, in INTERNATIONAL CONFERENCE ON RADIOACTIVE WASTE MANAGEMENT (1983) (Item 140 in DOE, DE89005394).

Mountain investigations.[22] Tests on migration of spent fuel and groundwater transport of radionuclides, for example, are typically only months in duration, for example, 2, 6, and 12 months.[23] Even for tests as long as 3.5 years or 3 years duration, respectively, tests used to determine the degree and extent of spent-fuel migration or the integrity of the waste canisters,[24] researchers have been forced to extrapolate and make the expert judgment that behavior over 3.5 years will be representative of that over 10,000 or more years.

In the case of waste canisters, experiments of three years' duration are particularly problematic, because the future temperatures in the repository are expected to be as great as 200° C in the immediate vicinity of the waste,[25] causing changes in the surrounding rock.[26] Moreover,

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22 *See*, respectively, R. JACOBSON ET AL., A RECONNAISSANCE INVESTIGATION OF HYDROGEOCHEMISTRY AND HYDROLOGY OF RANIER MESA (1986) (Item 183 in DOE, DE89005394); KNAUSS ET AL., *supra* note 21; J. Bates & T. Gerding, *Performance of Actinide-Containing SRL 165 Type Glass in Unsaturated Conditions*, in SCIENTIFIC BASIS FOR NUCLEAR WASTE MANAGEMENT 11 (M. Apted & R. Westerman, eds. 1987(Item 14 in DOE, DE89005394)).

23 H.D. SMITH, ELECTROCHEMICAL CORROSION-SCOPING EXPERIMENTS: AN EVALUATION OF THE RESULTS (1988) (Item 151 in DOE, DE90006793); H.D. SMITH, INITIAL REPORT ON STRESS-CORROSION-CRACKING EXPERIMENTS USING ZIRCALOY-4 SPENT FUEL CLADDING C-RINGS (1988) (Item 153 in DOE, DE90006793).

24 J. Bates et al., *Identification of Secondary Phases Formed During Unsaturated Reaction of UO2 with EJ-13 Water*, in MATERIALS RESEARCH SOCIETY FALL MEETING (1989) (Item 102 in DOE, DE90006793); J. Bates et al., *Parametric Effects of Glass Reaction Under Unsaturated Conditions*, in MATERIALS RESEARCH SOCIETY FALL MEETING (1989) (Item 103 in DOE, DE90006793); MCRIGHT ET AL., PROGRESS REPORT IN THE RESULTS OF TESTING ADVANCED CONCEPTUAL DESIGN METAL BARRIER MATERIALS UNDER RELEVANT ENVIRONMENTAL CONDITIONS FOR A TUFF REPOSITORY (1987) (Item 114 in DOE, DE90006793); *see* R. WESTERMAN ET AL., CORROSION TESTING OF TYPE 304L STAINLESS STEEL IN TUFF GROUNDWATER EXPERIMENTS (1987) (Item 135 in DOE, DE90006793; H. WEISS ET AL., METALURGICAL ANALYSIS OF A 304L STAINLESS STEEL CANISTER FROM THE SPENT FUEL TESTING-CLIMAX (1985) (Item 119 in DOE, DE88004834).

25 C. HADLOCK, TECHNICAL SUPPORT OF STANDARDS FOR HIGH-LEVEL RADIOACTIVE WASTE MANAGEMENT, VOL. D: RELEASE MECHANISMS 49 (1980).

26 J. BLACIC ET AL., EFFECTS OF LONG-TERM EXPOSURE OF TUFFS TO HIGH-LEVEL NUCLEAR WASTE REPOSITORY CONDITIONS, FINAL REPORT (1986) (Item 67 in DOE, DE88004834).

in some experiments, all of the canisters made of the nuclear waste-package reference material have failed and showed stress-corrosion cracking when they were exposed to a one-year test in groundwater and tuff at the expected temperature of 200° C.[27] Nevertheless, DOE expects the canisters — presumably improved somehow — to last from 300 to 1,000 years. All of these problems suggest that long-term experiments are essential. The shorter the time of the experiment, all things being equal, the more questionable the value judgment that the data support precise predictions about repository behavior thousands of years in the future.

Loan companies find it difficult to predict mortgage rates for more than 30 or 40 years, given nearly a century of information. Yet, DOE risk assessors have predicted confidently that "meteorological conditions... for over 40 years" provide a firm basis for concluding "that any radiological emissions would be effectively dispersed before they reach highly populated areas" near a proposed permanent repository.[28] How could one know about dispersion 10,000 years hence? And how could one predict population centers so far into the future? Of course, once a repository were built, the location of such a facility might influence the place and growth of future cities. Nevertheless, Las Vegas, as it exists today, would have been unlikely 50 years ago, before the Hoover Dam, and the fastest growing cities a decade ago were not substantial even 100 years ago.[29] Yet, risk assessors, with far less inductive information, are attempting to predict precise phenomena associated with permanent repository behavior and its consequences for periods of time that are many orders of magnitude longer. Many of the radioactive isotopes that would be stored at sites like Yucca Mountain — such as I-129, Np-237, Cs-135, U-238, Zr-93

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[27] S. Pitman et al., *Corrosion and Slow-Strain-Rate Testing of Type 304L Stainless in Tuff Groundwater Environments,* in CORROSION '87 (1986) (Item 172 in DOE, DE88004834).

[28] U.S. DEPARTMENT OF ENERGY, 2 NUCLEAR WASTE POLICY ACT, ENVIRONMENTAL ASSESSMENT, REFERENCE REPOSITORY LOCATION, HANFORD SITE, WASHINGTON, at 6-24 and 6-25 (1986).

[29] P. O'BRIEN, TECHNICAL SUPPORT FOR HIGH-LEVEL RADIOACTIVE WASTE MANAGEMENT, TASK C REPORT: ASSESSMENT OF MIGRATION PATHWAYS 134 (1977).

— have half lives that are in the millions of years.[30] During such long time periods of radiotoxicity, changes in climate, groundwater, precipitation, and volcanic activity could occur.

Risk assessors, for example, need to predict precise phenomena associated with future climate, weather, mineralogy and water composition, even though climate and weather are the most variable and rapid natural processes influencing the repository, and even though mineral reactions are currently occurring there.[31] Even DOE researchers admit that "the climatic changes that are possible during the next 10,000 years of Yucca Mountain may cause changes in the hydraulic gradient.... The extent of these changes is uncertain."[32] Major variations in the climate of Nevada have occurred during the last 45,000 years, and the U.S. Geological Survey claims that future changes probably will occur within the time the waste materials are hazardous.[33] Precipitation patterns are likewise fluctuating, and assessors must be able to predict them in perpetuity. The data, however, covers only approximately the last 30 years,[34] yet 10,000-year precipitation predictions are crucial to the safety of Yucca Mountain because percolating water could infiltrate and transport radioactive leachate, once the containers have been breached. Hence, to assume that the 30-year precipitation data are adequate — for predicting the risks associated with a permanent repository — represents an expert judgment that is somewhat questionable, especially in light of the fact that both precipitation and its variability appear to have increased at the site.[35]

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30 *See* C. SMITH ET AL., POPULATION RISKS FROM DISPOSAL OF HIGH-LEVEL RADIOACTIVE WASTES IN GEOLOGIC REPOSITORIES 10, 51 (1982).

31 U.S. DEPARTMENT OF ENERGY, *Office of Scientific and Technical Information, Project History,* in YUCCA MOUNTAIN PROJECT BIBLIOGRAPHY, 1988–1989 *vii–xvii* (Supp. 2 1990).

32 U.S. DEPARTMENT OF ENERGY, 2 NUCLEAR WASTE POLICY ACT, ENVIRONMENTAL ASSESSMENT, YUCCA MOUNTAIN SITE, NEVADA RESEARCH AND DEVELOPMENT AREA, NEVADA, at 6-242 (1986).

33 U.S. GEOLOGICAL SURVEY, VEGETATION AND CLIMATES OF THE LAST 45,000 YEARS IN THE VICINITY OF THE NEVADA TEST SITE, SOUTH-CENTRAL NEVADA (1985) (Item 394 in DOE, DE88004834).

34 R. FRENCH, DAILY, SEASONAL, AND ANNUAL PRECIPITATION AT THE NEVADA TEST SITE, NEVADA (1986) (Item 186 in DOE, DE89005394).

Ultimately, judgments that short-term data provide an adequate basis for inferring extremely precise, long-term behavior rely on an inductive inference, on the assumption that the future will be like the past. This is the basic assumption of all historical geology. DOE has made exactly this judgment every time it has concluded, for example: "Yucca Mountain... would meet the U.S. Environmental Protection Agency standards... if present hydrologic, geologic, and geochemical conditions (as presently understood) persist for the next 10,000 years."[36] How could one guarantee, however, that such conditions will persist? Likewise, how could DOE justify its judgments that the future will be like the past? DOE has concluded, for example, regarding the Yucca Mountain site, that (1) "extreme weather phenomena are neither frequent enough nor severe enough to be expected to significantly affect the safety of repository operation." DOE has also claimed: (2) "no severe meteorological conditions have been recorded or are expected to occur in the region that would contribute to radionuclide releases." Even more surprisingly, DOE has affirmed: (3) "on the basis of the geologic record, no dissolution [of subsurface rock] is expected during the first 10,000 years after repository closure, or thereafter."[37] How could one affirm that there will never be rock dissolution at Yucca Mountain? Or that neither "extreme weather" nor "severe meteorological conditions" will occur at the site? Do DOE assessors have enough data to make these predictions? When the time periods at issue are so great, inductive judgments such as these are extremely questionable. Long-term judgments about the suitability of Yucca Mountain for a waste repository are especially questionable because of the existence of lakes in the Great Basin of Nevada during the Wisconsin period — 2 million years ago — and because moderate variations in climate are sufficient to

[35] *See* J. BRAITHWAITE & F. NIMICK, EFFECT OF HOST-ROCK DISSOLUTION AND PRECIPITATION ON PERMEABILITY IN A NUCLEAR WASTE REPOSITORY IN TUFF (1984) (Item D161 in DOE, NVO-96-24 (REV. 5)); R. FRENCH, EFFECTS OF THE LENGTH OF RECORD ON ESTIMATES OF ANNUAL AND SEASONAL PRECIPITATION AT THE NEVADA TEST SITE, NEVADA (1987) (Item 220 in DOE, DE89005394).

[36] U.S. DEPARTMENT OF ENERGY, *supra* note 32, at 6-298 to 6-299.

[37] *Id.*, The three quotes are, respectively, at 6-32, 6-32, and 6-257.

cause large changes in the hydrological budget of some of the closed basin systems in Nevada.[38] An evaluation of the Quaternary history of the Yucca Mountain area reveals that, like other locations proposed for radwaste sites, it has undergone geomorphic change in the last million years, and it may undergo catastrophic landslides in the future.[39] Other assessors have calculated the probability of a volcanic disruption hazard, given the natural historic seismicity of the Yucca Mountain region as 10-6 per year.[40]

Expert judgments about precise, long-term predictability at Yucca Mountain are also questionable in light of the fact that some assessors argue that the water table at Yucca Mountain could rise 130 meters if precipitation increased by 100%.[41] This is a significant and possible increase, since average precipitation levels, for a decade, often vary by two orders of magnitude.[42] At Yucca Mountain, for example, water tables stood at 926 meters (approximately 2,938 feet) only 14,000 years ago. High water tables were northeast of the Nevada Test Site (NTS) until only 7,000 years ago, and on the NTS 700,000 years ago.[43] On the other hand, some assessors claim that the water table at Yucca Mountain was never more than 200 feet above its present position,[44]

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38 L. Benson, *Effect of Paleoclimatic Fluctuations on the Transport of Radionuclides from Potential Waste Disposal Sites in the Great Basin of the Western United States*, 3 EARTH SCI. 7 (1980) (Item 90 in DOE, DE89005394).

39 S. MARA, ASSESSMENT OF EFFECTIVENESS OF GEOLOGIC ISOLATION SYSTEMS. GEOLOGIC FACTORS IN THE ISOLATION OF NUCLEAR WASTE: EVALUATION OF LONG-TERM GEOMORPHIC PROCESSES AND CATASTROPHIC EVENTS (1980) (Item 92 in DOE, DE89005394).

40 L. METCALF, PRELIMINARY REVIEW AND SUMMARY OF THE POTENTIAL FOR TECTONIC, SEISMIC, AND VOLCANIC ACTIVITY AT THE NEVADA TEST SITE DEFENSE WASTE DISPOSAL SITE (1983) (Item 142 in DOE, DE89005394); *See also* B. CROWE, VOLCANIC HAZARD ASSESSMENT FOR DISPOSAL OF HIGH-LEVEL RADIOACTIVE WASTE (1986).

41 J. Czarnecki, Characterization of the Subregional Groundwater Flow System of a Potential Site for a High-level Nuclear Waste Repository (Ph.D. dissertation, University of Minnesota, Minneapolis, 1988) (Item 278 in DOE, DE90006793).

42 T. DUNNE & L. LEOPOLD, WATER IN ENVIRONMENTAL PLANNING 52, 54, 70 (1978).

43 J. DAVIS, DESERT RESEARCH INSTITUTE, GEOLOGICAL RECONNAISSANCE AND CHRONOLOGIC STUDIES (1983) (Item 143 in DOE, DE89005394).

and that radwaste will be emplaced more than 650 feet below the surface and more than 600 feet above the water table.[45] The water table is currently between 728 and 775 feet above sea level.[46] Even if there were a significant climate change and a doubling of rainfall, a recent (1992) panel of the U.S. National Academy of Sciences (NAS) argued that the water table at Yucca Mountain would rise, at most, by 400 feet; although this is a significant rise, the panel concluded that the proposed repository would not be at risk of groundwater infiltration.[47] Such conclusions appear reassuring until one realizes that the same NAS panel warned that its modeling results involve very "large uncertainty," that there are few data to constrain the complex hydrologic system at Yucca Mountain, and that its predictions "depend heavily on expert judgment" because of the "unprecedented" exactitude required for 10,000-year predictions.[48] Because high-level radwaste requires essentially "permanent isolation from the biosphere,"[49] some geologists have said that any planned repository must be built under the assumption that groundwater will eventually come in contact with the high-level waste.[50] DOE, however, has continued to assume that, because the water table has been constant for several decades, therefore, it is likely to remain so in the future.

Making the expert judgment that short-term hydrogeological tests provide accurate predictions for long-term behavior has been one of the reasons for the erroneous underestimation of the potential for offsite

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44 U.S. DEPARTMENT OF ENERGY, *NNWSI History*, in BIBLIOGRAPHY OF THE PUBLISHED REPORTS, PAPERS, AND ARTICLES ON THE NEVADA NUCLEAR WASTE STORAGE INVESTIGATIONS 1–30 (1985).

45 H. MACDOUGALL ET AL., 3 SITE CHARACTERIZATION PLAN: CONCEPTUAL DESIGN REPORT, in NEVADA NUCLEAR WASTE STORAGE INVESTIGATIONS PROJECT, APP. A–E (1987) (Item 177 in DOE, DE90006793).

46 J. ROBINSON, WATER LEVELS IN PERIODICALLY MEASURED WELLS IN THE YUCCA MOUNTAIN AREA, NEVADA, 1981–1987 (1988) (Item 271 in DOE, DE90006793). *See also* RALEIGH, *supra* note 17.

47 RALEIGH, *supra* note 17.

48 *Id.* at 7, 122 & 135.

49 Stein & Collyer, *supra* note 20.

50 I. ROXBURGH, GEOLOGY OF HIGH-LEVEL NUCLEAR WASTE DISPOSAL 183 (1987).

radwaste migration at the low-level radioactive waste facility at Maxey Flats, Kentucky. Although the Maxey Flats site is disanalogous in many ways with the proposed Yucca Mountain site, several problematic risk-assessment methods appear to be similar at the two locations. The geologist (from the New Jersey Geological Survey) who did the original studies at the Kentucky location drilled and studied the wells for only 10 days. As a result, he concluded that they were dry, and that hydraulic conductivity was very low at the site.[51] On the basis of his analyses, the Kentucky facility was opened the year he did his studies. Other geologists and risk assessors, years later, observed the wells for a year and concluded that, because some of them were filled with water, therefore hydraulic conductivity was quite high.[52] Just as the longer-term studies gave the more accurate results — and a less optimistic picture of the Maxey Flats radioactive waste site — so also there is reason to question the expert judgment that short-term studies at proposed high-level sites, like Yucca Mountain, provide accurate data for precise, long-term predictions. Moreover, as we have already argued, given the longevity of the proposed Nevada site, the problems related to expert judgments about long-term predictions at other sites, and the difficulties with accurate geological predictions, there is reason to believe that this judgment is problematic. It poses a serious difficulty for any proposal to site a permanent geological repository either at Yucca Mountain or anywhere else, on grounds of the supposition that precise, long-term predictions about hydrogeology are reliable.

Judgments about Model Reliability

A more basic expert judgment is not only that one can predict long-term geological behavior on the basis of short-term data, but that one can model a geologically heterogeneous site, like Yucca Mountain, with "highly nonlinear" flow characteristics,[53] and that such models provide

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51 I. WALKER, GEOLOGIC AND HYDROGEOLOGIC EVALUATION OF A PROPOSED SITE.... 3 (1962).

52 S. PAPADOPULOS & I. WINOGRAD, STORAGE OF LOW-LEVEL RADIOACTIVE WASTES IN THE GROUND: HYDROGEOLOGIC AND HYDROCHEMICAL FACTORS 29–30 (1974).

53 N. Bixler & R. Eaton, *Modeling of Multiphase Flow in Permeable Media: (1)*

adequate and precise knowledge upon which to base future predictions about radwaste migration. Such judgments about the adequacy of modeling are questionable, both because the models cannot be validated in the field over the long term and because, if empirical data were available, one would not need to employ models in the first place. Admittedly, one can often determine that a given model is probably wrong, as does Watson when he criticizes the chronostratigraphic model on the grounds that it is false to Earth history, and that it gives rise to pseudo-problems of correlation and inclusion.[54] Typically, however, one does not have the data to confirm a long-term geological model. Assessors are forced to use models to evaluate all proposed repository sites, simply because they have inadequate data and theories to use in characterizing the area over the long term.[55] They do not know how the hydrology, geology, waste packages, and so on, will perform over centuries, and so they use models of the situation — Monte Carlo simulations, for example.[56]

One frequent rationale, for substituting modeling and simulations for actual empirical testing, is that modeling and simulations have been used before, in assessing the probability of nuclear accidents.[57] Probabilities related to nuclear accidents, however, are notoriously inaccurate. For example, all of the accident-frequency values obtained from operating experience in U.S. nuclear reactors fall outside the 90% confidence band of calculated expert probabilities in the best nuclear risk assessment ever performed (WASH 1400).[58] Different assessors'

Mathematical Model; (2) Analysis of Imbibation and Drying Experiments, in GORDAN RESEARCH CONFERENCE ON MODELING OF FLOW IN PERMEABLE MEDIA (1986) (Item 187 in DOE, DE90006793).

54 R. Watson, *A Critique of Chronostratigraphy*, 283 AM. J. SCI. 173 (1983); *see also* R. Watson & H. Wright, *The End of the Pleistocene: A General Critique of Chronostratigraphic Classification*, 9 BOREAS 153 (1980).

55 L. Ramspott, *Assessment of Engineered Barrier System and Design of Waste Packages*, in AM. NUCLEAR SOC'Y ANNUAL MEETING (1988) (Item 147 in DOE, DE90006793).

56 C. COOPER, NUMERICAL SIMULATION OF GAS FLOW THROUGH UNSATURATED FRACTURED ROCK AT YUCCA MOUNTAIN, NEVADA (1990).

57 C. SASTRE ET AL., WASTE PACKAGE RELIABILITY 22 (1986).

probability estimates associated with various reactor events typically vary by four orders of magnitude.[59] Hence, the use of nuclear-accident simulations does not necessarily provide a justification for the expert judgment that repository modelling is reliable. Indeed, speaking for the state, the Nevada Attorney General criticized DOE and its assessors for doing modeling of the Yucca Mountain site, modeling that depends on major untested assumptions, without validating the models in the field; spokespersons for the state of Nevada also warned that the uncertainty in the models (for possible radionuclide transport) was one of their seven major "concerns" about the reliability of Yucca Mountain studies.[60] Many risk assessors, however, typically assume that models alone are sufficient to demonstrate the acceptability of a particular repository site. They repeatedly affirm that such models, together with computer codes, "demonstrate the safety of a final storage site for nuclear wastes."[61]

Much of the problem with model uncertainty in the risk assessments of repository sites arises from the fact that all the laws and theories used to explain site characteristics and possible radwaste migration are based on highly idealized notions. Many assessors at Yucca Mountain, for example, use highly idealized continuum models (such as porous-media models) — that assume the underlying rock is solid and unfractured — rather than discontinuum models formulated to account for the effects of discrete fractures.[62] They do so because continuum models are simpler

58 U.S. NUCLEAR REGULATORY COMMISSION, REACTOR SAFETY STUDY, REPORT NO. (NUREG-75/014) WASH-1400 (1975).

59 *See* SHRADER-FRECHETTE, *supra* note 18, at ch. 6; and R. COOKE, SUBJECTIVE PROBABILITY AND EXPERT OPINION, ch. 9 (1991).

60 NEVADA NWPO, 1 STATE OF NEVADA COMMENTS ON THE U.S. DEPARTMENT OF ENERGY CONSULTATION DRAFT SITE CHARACTERIZATION PLAN, YUCCA MOUNTAIN SITE, NEVADA (1989) (Item 335 in DOE, DE90006793); 2 NEVADA NWPO, STATE OF NEVADA COMMENTS ON THE U.S. DEPARTMENT OF ENERGY CONSULTATION DRAFT SITE CHARACTERIZATION PLAN, YUCCA MOUNTAIN SITE, NEVADA (1989) (Item 336 in DOE, DE90006793).

61 *See, e.g.*, G. Bertozzi et al., *Long-Term Risk Assessment of Geological Disposal*, in RADIOACTIVE WASTE MANAGEMENT AND DISPOSAL 639, 647 (R. Simon, ed. 1986).

62 M. BOARD, EXAMINATION OF THE USE OF CONTINUUM VERSUS DISCONTINUUM

and more efficient to use, and because they have no superior alternatives.[63] Assessors also employ continuum models on the grounds that matrix flow predominates over fracture flow at Yucca Mountain, a highly questionable assumption.[64] Hence, there are a variety of reasons for believing that the idealized hydrogeological models at Yucca Mountain may not be accurate.[65] Indeed, external reviewers argue forcefully that, in general, the quality control on the Yucca Mountain modeling is poor.[66]

Another example of idealized, therefore questionable, judgments used in repository assessments are those that assume Darcy's Law is an accurate way to represent Yucca-Mountain site hydrogeology. Virtually all of the risk assessments that discuss transport time of groundwater at radwaste sites rely ultimately on variants of Darcy's Law.[67] It states that groundwater flow velocity is proportional to the hydraulic gradient.

MODELS FOR DESIGN AND PERFORMANCE ASSESSMENT FOR THE YUCCA MOUNTAIN SITE (1989); T. BRIKOWSKI, YUCCA MOUNTAIN PROGRAM SUMMARY OF RESEARCH, SITE MONITORING AND TECHNICAL REVIEW ACTIVITIES (JANUARY 1987–JUNE 1988) (1988); C. COOPER, *supra* note 56; *see* GEOTRANS INC., REVIEW OF MODELING EFFORTS ASSOCIATED WITH YUCCA MOUNTAIN, NEVADA 9 (1986).

63 *Id.* at 66.

64 *See* J. Lemons & D. Brown, *The Role of Science in the Decision to Site a High-Level Nuclear Waste Repository at Yucca Mountain, Nevada, USA*, 10 THE ENVIRONMENTALIST, 7 (1990).

65 T. BRIKOWSKI, YUCCA MOUNTAIN PROGRAM SUMMARY 75 (1988).

66 GEOTRANS INC., *supra* note 62, at 1.

67 *See, e.g.*, S. SINNOCK & T. LIN, PRELIMINARY BOUNDS ON THE EXPECTED POSTCLOSURE PERFORMANCE OF THE YUCCA MOUNTAIN REPOSITORY SITE, SOUTHERN NEVADA 8 (1984); SINNOCK ET AL., PRELIMINARY ESTIMATES OF GROUND WATER TRAVEL TIME AND RADIONUCLIDE TRANSPORT AT THE YUCCA MOUNTAIN REPOSITORY SITE 8 (1986); E. JACOBSON, INVESTIGATION OF SENSITIVITY AND UNCERTAINTY IN SOME HYDROLOGIC MODELS OF YUCCA MOUNTAIN AND VICINITY 5 (1984); F. THOMPSON ET AL., PRELIMINARY UPPER-BOUND CONSEQUENCE ANALYSIS FOR A WASTE REPOSITORY AT YUCCA MOUNTAIN, NEVADA *iii* (1984); N. HAYDEN, BENCHMARKING NNMSI FLOW AND TRANSPORT CODES: COVE 1 RESULTS 1–3 (1985); 1 A. DUDLEY ET AL., TOTAL SYSTEM PERFORMANCE ASSESSMENT CODE (TOSPAC0): PHYSICAL AND MATHEMATICAL BASES: YUCCA MOUNTAIN PROJECT 36–44 (1988) (Item 182 in DOE, DE90006793); C. SMITH ET AL., *supra* note 30, at 39; Y. LIN, SPARTON — A SIMPLE PERFORMANCE ASSESSMENT CODE FOR THE NEVADA NUCLEAR WASTE STORAGE INVESTIGATIONS PROJECT i (1985); BOARD, *supra note* 62, at 13,17.

This law, however, is an empirical, causal, and mathematical idealization.[68] Describing flow in porous media, Darcy's Law assumes that flow occurs through the entire cross section of the material, rather than through pores and between solids, as actually happens. The law further assumes that velocity is uniform and the path straight, and it relies on average values of hydraulic variables applicable to volume elements. Moreover, because the corrections in Darcy's Law, needed to make it applicable to a particular site, must be based on laboratory or field results and do not come from the fundamental law itself, it is not obvious that good scientific theory actually supports some of the generalizations in which Darcy's Law is employed. For example, its use at Yucca Mountain is particularly problematic, in part because the law is not suitable for conditions of fracture flow.[69]

Of course, hydrogeologists might argue, in most situations, that the idealizations and expert judgments central to models based on Darcy's Law are not significant, and that they could lead only to minor errors. However, the combined effect of numerous subjective judgments and small errors might be great, particularly in a situation of fracture flow. After all, siting a high-level radwaste repository requires long-term hydrogeological prediction, very slow groundwater migration time, and adequate information in the present. Such requirements mean that it is impossible to confirm that the Yucca-Mountain laboratory and field results used in connection with Darcy's Law are accurate. Hence the problem of idealization remains.[70] In his classic essay on methodology, Milton Friedman claimed that idealizations were a problem in science only to the degree that the predictions resulting from them could not be checked. Because predictions for sites like Yucca

68 *See* K. Shrader-Frechette, *Values and Hydrogeological Method: How Not to Site the World's Largest Nuclear Dump* in PLANNING FOR CHANGING ENERGY CONDITIONS, ENERGY POLICY STUDIES (J. Byrne and D. Rich, eds. 1988); K. Shrader-Frechette, *Idealized Laws, Antirealism, and Applied Science: A Case in Hydrogeology*, 81 SYNTHESE 329 (1989).

69 *See* 3 R. LOUX, COMMENTS ON THE U.S. DEPARTMENT OF ENERGY SITE CHARACTERIZATION PLAN, YUCCA MOUNTAIN SITE, NEVADA 6 (1989).

70 *See* N. CARTWRIGHT, HOW THE LAWS OF PHYSICS LIE 111 (1983); Shrader-Frechette, *supra* note 68.

Mountain cannot be checked over the long term, it is clear that they remain part of a classical scientific problem.[71]

The expert judgments about the adequacy of modeling proposed repository sites are also more questionable than those in many other areas of science because the site specifications to which the models must conform are sometimes very precise and therefore could be quite difficult to meet. For example, in the Yucca Mountain case, assessors are required to guarantee, by virtue of 10 CFR 60.113, "substantially complete containment" within the waste packages for 300 to 1,000 years and a controlled release rate from the engineered barrier system for 10,000 years of 1 part in 105 per year for radionuclides present in defined quantities 100 years after permanent closure.[72] Given such precise requirements for the Yucca Mountain repository, it is questionable whether a simulation, a model, of the site could provide information that is firm enough to meet such specific requirements. The more stringent the site specifications, the more accurate must be the information used to meet the specifications. Hence, the expert judgment about the accuracy of modeling is questionable because of the long time frame of the prediction, the specificity of the requirements, and the fact that the simulation or model cannot be checked. Despite these three problems, most risk assessors base their Yucca Mountain conclusions on a variety of sophisticated models.[73] Yet, only rarely do assessors

71 *See* M. Friedman, *The Methodology of Positive Economics*, in THE PHILOSOPHY OF ECONOMICS (D. Hausman, ed. 1984).

72 *See* A. Berusch & E. Gause, *DOE Progress in Assessing the Long Term Performance of Waste Materials*, in SCIENCE BASIS FOR NUCLEAR WASTE MANAGEMENT *x* (J. Bates and W. Seefeldt, eds. 1987) (Item 190 in DOE, DE89005394).

73 *See. e.g.*, D. Zyvoloski, *Simulation of Heat Transfer in the Unsaturated Zone*, in INTERNATIONAL CONFERENCE FOR HIGH-LEVEL RADIOACTIVE WASTE MANAGEMENT (1990) (Item 23 in DOE, DE91000566); K. Karasaki et al., *Building of a Conceptual Model at UE25-c Hole Complex*, in *id* (Item 35 in DOE, DE91000566); T. Wolery et al., *The EQ3/6 Software Package for Geochemical Modeling*, in AMERICAN CHEMICAL SOCIETY NATIONAL MEETING (1988) (Item 45 in DOE, DE91000566); A. RICHARDSON, YUCCA MOUNTAIN PROJECT: PRELIMINARY SHAFT LINER DESIGN CRITERIA AND METHODOLOGY GUIDE (1990) (Item 69 in DOE, DE91000566); J. KOTERAS, STUDIES OF COMPUTATIONAL MODELS FOR JOINTED MEDIA

openly admit that their models are uncertain by being based mainly on "conceptual designs."[74] Thus, expert judgments about the adequacy of modelling appear to have at least the potential to cause serious errors in QRA conclusions about Yucca Mountain and other proposed sites.

Judgments about Simplification of the Phenomena

Because real hydrogeological systems at proposed repository sites like Yucca Mountain are often quite complex, risk assessors frequently must make a further expert judgment that the simplifications of their models do not seriously misrepresent the situation they are attempting to understand and to predict. Indeed, risk assessors admit that simplifications of many hydrogeological phenomena are necessary in order to formulate analytic solutions to problems of hydraulic conductivity, infiltration, and so on.[75] According to the way that we are using the term "simplicity," one model or theory has more simplicity if it postulates fewer principles, laws, properties, or entities than another.[76] To render the real hydrogeological system at Yucca Mountain mathematically and scientifically tractable, for example, risk assessors have had to make partially subjective judgments about simplifying the situation.[77] These include simplifications such as that all radionuclides have identical transport retardation factors, or that all radionuclide releases are instantaneous.[78]

WITH ORTHOGONAL SETS OF JOINTS (1990) (Item 70 in DOE, DE91000566); L. Costin, *Application of Models for Jointed Rock to the Analysis of Prototype Testing for the Yucca Mountain Project,* in U.S. SYMPOSIUM ON ROCK MECHANICS (1990) (Item 81 in DOE, DE91000566); R. Glass, *Laboratory Research Program to Aid in Developing and Testing the Validity of Conceptual Models for Flow and Transport through Unsaturated Porous Media,* in GEOVAL '90 (1990) (Item 83 in DOE, DE91000566).

[74] For one such admission, *see* DEPARTMENT OF ENERGY, *supra* note 32, at 6-52 & 6-69.

[75] *See, e.g.,* 2 U.S. DEPARTMENT OF ENERGY, NUCLEAR WASTE POLICY ACT, ENVIRONMENTAL ASSESSMENT, DAVIS CANYON SITE, UTAH 6-120 (1986).

[76] *See* K. Shrader-Frechette, *Three Arguments Against Simplicity,* in AESTHETIC FACTORS IN NATURAL SCIENCE (N. Rescher, ed. 1990).

[77] *See, e.g.,* DUDLEY ET AL., *supra* note 67.

[78] F. Gelbard et al., *One-Dimensional Radionuclide Transport Under Time-Varying Conditions,* in INTERNATIONAL CONFERENCE FOR HIGH-LEVEL RADIOACTIVE

Other common simplifications in permanent-repository risk assessments are that water flow will be one-dimensional;[79] that percolation will be downward only through the unsaturated zone, but horizontal through the saturated zone;[80] that temperature and moisture are constant[81] or that there is a normal distribution of cumulative releases of radionuclides to the water table.[82] All of these partially subjective judgments about simplification have been made at Yucca Mountain, even though they are almost certainly counterfactual, and even though they have been criticized by external reviewers.[83]

Schedule constraints also often force a number of simplifications in risk studies.[84] Such simplifications obviously are not completely accurate representations of the real world but, in the case of Yucca Mountain, assessors make the partially subjective judgment that they are accurate enough to describe the phenomena. This judgment is problematic, of course, to the degree that the simplifications are likely to underemphasize the likelihood of radwaste migration. At least three

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WASTE MANAGEMENT (1989) (Item 123 in DOE, DE91000566); *see also, e.g.*, B. SAGAR & A. RUNCHAL, A MATHEMATICAL MODEL FOR FLUID FLOW, HEAT, AND MASS TRANSPORT IN VARIABLY SATURATED GEOLOGICAL MEDIA (1990) (Item 131 in DOE, DE91000566).

79 COOPER, *supra* note 56; DUDLEY ET AL., *supra* note 67, at 1; JACOBSON, *supra* note 67, at 12; B. TRAVIS ET AL., PRELIMINARY ESTIMATES OF WATER FLOW AND RADIONUCLIDE TRANSPORT IN YUCCA MOUNTAIN 3 (1984); R. PETERS, THE EFFECT OF PERCOLATION RATE ON WATER TRAVEL TIME IN DEEP, PARTIALLY SATURATED ZONES i (1986); SASTRE ET AL., *supra* note 57, at 24; LIN, *supra* note 67, at 1; SINNOCK, *supra* note 67, at 66.

80 SINNOCK, *supra* note 67, at 5 & 13.

81 L. MONDY ET AL., COMPARISON OF WASTE EMPLACEMENT CONFIGURATIONS FOR A NUCLEAR WASTE REPOSITORY IN TUFF: IV: THERMO-HYDROLOGICAL ANALYSIS 6 (1983).

82 SINNOCK ET AL, *supra* note 67, at 80.

83 GEOTRANS, *supra* note 62, at 11, 13; THOMPSON ENGINEERING COMPANY, REVIEW AND COMMENT ON THE U.S. DEPARTMENT OF ENERGY SITE CHARACTERIZATION PLAN CONCEPTUAL DESIGN REPORT 1–15 (1988) (Item 329 in DOE, DE90006793).

84 T. NELSON ET AL., YUCCA MOUNTAIN PROJECT WASTE PACKAGE DESIGN FOR MRS [MONITORED RETRIEVABLE STORAGE] SYSTEM STUDIES (1989) (Item 132 in DOE, DE90006793).

factors illustrate the underestimating effect of simplifications. Models that do not consider the growth of Ra-226 and other radionuclides in the long-lived decay chain stemming from the uranium and plutonium in the waste underestimate the health hazards of the waste.[85] Likewise, oversimplifying physical processes in the unsaturated zone and biological and chemical processes in the entire groundwater system may lead to underestimation of radionuclide transport and health hazards; if one assumes that adsorption of radionuclides reduces their public hazard, one may thereby forget that adsorbed radionuclides in the unsaturated zone may act as a very long-term contaminant source to the underlying saturated zone.[86]

A third example of simplification that causes an underestimation of risk has to do with synergism. Assessors typically assume that many hydrogeological variables — such as percolation flux, hydraulic conductivity, effective matrix porosity, and fracture porosity — are independent; they make this assumption of independence because they do not have data that enable them to correlate the variables.[87] Yet, obviously the combined effects of at least some of these factors could enhance the velocity of waste or water transport. Indeed, regarding Yucca Mountain, outside evaluators have argued that oversimplifications in the description of relevant hydrogeology compromise the scientific integrity of the site characterization plan.[88]

The expert judgment that phenomena and models may be simplified, in order to provide an acceptable description and explanation of the site, is problematic in part because simplicity is not always a good criterion for theory acceptability in science. It is not always a good criterion, because if two empirically underdetermined or vague theories were both equally able to account for certain empirical results, then scientists following a criterion of simplicity could be forced to choose a crude, suspect, single-factor theory, simply because it was the simpler of the

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85 SMITH ET AL., *supra* note 30, at 183.

86 E. REICHARD ET AL., GROUNDWATER CONTAMINATION RISK ASSESSMENT 180 (1990).

87 SINNOCK ET AL., *supra* not 67 at 79.

88 THOMPSON ENGINEERING COMPANY, *supra* note 83.

two. More generally, as Friedman has pointed out, using simplicity to choose among theories, all of which are consistent with the facts, is bound to lead to counterintuitive conclusions about the most acceptable scientific theory. This is because, for any such theory, there is a simpler one also consistent with the facts. Hence, because science strives for strong — not safe — hypotheses, using simplicity as a criterion for theory choice in science could lead to accepting theories that are weaker with respect to explanatory power.[89] Moreover, using simplicity as a criterion for theory choice in explaining characteristics of proposed repository sites is more problematic than in other areas of science. Given the inadequacy of the data and the heterogeneity of the Yucca Mountain site, for example, it is not clear that the simplified explanatory premises have a very high probability of being true.

In a highly applied risk-assessment situation, choosing a theory on the basis of simplicity, even though the empirical data are highly underdetermined, could lead to dangerous consequences. In such a case it might be better to admit that there is no adequate theory. For example, if one admitted that the simplified theories used to predict radwaste migration at Yucca Mountain might be inadequate, then this admission might have the virtue of preventing a questionable theory from being used as the basis for public policy that declares Yucca Mountain acceptable. The oversimplified models and theories used at Yucca Mountain bring to mind some of the scientific, health, and policy problems that arose when scientists and risk assessors made similar simplifications at the Maxey Flats low-level radwaste facility. Just as at Yucca Mountain, many of the Maxey Flats' scientists simplified the situation by assuming that there was only vertical movement of water above the water table. Yet, offsite migration at the Kentucky facility occurred in part through horizontal movement above the water table,[90] horizontal movement ruled out on the basis of an expert judgment.

[89] N. Goodman, *Safety, Strength, Simplicity*, 28 PHIL. SCI. 150 (1961); K. Friedman, *Empirical Simplicity as Testability*, 23 BRIT. J. PHIL. SCI. 25 (1972); Shrader-Frechette, *supra* note 76.

[90] K. WILSON & B. LYONS, GROUND-WATER LEVELS AND TRITIUM CONCENTRATIONS AT THE MAXEY-FLATS LOW-LEVEL RADIOACTIVE WASTE DISPOSAL SITE NEAR MOREHEAD, KENTUCKY, JUNE 1984 TO APRIL 1989 20 (1991).

Likewise, approximately 20 years ago, there was a conflict between two groups of geologists evaluating the groundwater-flow theories for the proposed radwaste site in Maxey Flats, Kentucky. The geologists from several universities (Georgia Tech and Auburn, among others) and from several consulting groups and industries (primarily EMCON and Nuclear Engineering Company, NECO) used an extremely simple, single-factor flow theory, premised completely on the low permeability of the shale on site. They concluded that the radwaste could not migrate offsite for centuries.[91] The geologists from several government agencies (USGS and EPA) rejected the simple flow theory of the academic and industry geologists and claimed that many factors — such as possible fissures, fractures, and hairline cracks between bedding planes — not merely the low permeability of the shale, had to be taken into account.[92] Offering a theory with less simplicity and more explanatory parameters and properties, they claimed that radwaste could well migrate offsite. Because groundwater flow on the Maxey Flats site was so slow and so difficult to monitor directly, both theories were empirically underdetermined and hence equally consistent with the facts. As a result, policy makers chose the theory with more simplicity, the low permeability theory of the industry and academic geologists. Their choice has proved dangerously wrong, because plutonium travelled offsite only several years after the facility was opened.[93] Maxey Flats became known as "the world's worst nuclear dump."[94] The moral of

[91] EMCON ASSOCIATES & J. MCCOLLOUGH, GEOTECHNICAL INVESTIGATION AND WASTE MANAGEMENT STUDIES, NUCLEAR WASTE DISPOSAL SITE, FLEMING COUNTY, KENTUCKY, PROJECT 108-5.2 (1975) (Unpublished report, available from EMCON, 326 Commercial Street, San Jose, California).

[92] D. Polluck & H. Zehner, *A Conceptual Analysis of the Ground-Water Flow System at the Maxey Flats Radioactive Waste Burial Site, Fleming County, Kentucky, U.S. Geological Survey Open-File Report*, in MODELING AND LOW-LEVEL WASTE MANAGEMENT (C. Little and L. Stratton, eds. 1981); E. WERNER, U.S. GEOLOGICAL SURVEY, JOINT INTENSITY SURVEY IN THE MOREHEAD KENTUCKY AREA (1980) (unpublished study).

[93] G. MEYER, MAXEY FLATS RADIOACTIVE WASTE BURIAL SITE: STATUS REPORT 9 (1975) (unpublished report).

[94] W. Naedele, *Nuclear Grave Is Haunting Kentucky*, Philadelphia Bulletin, May 17, 1979, at 1-3, in U.S. Geological Survey, Maxey Flats — Publicity, Vertical

the story is that the greater the empirical underdetermination of theories and models, the more dangerous it is to evaluate them in terms of the criterion of simplicity, alone, because the more likely it is that many "simple" theories are all consistent with the limited data. In the case of Yucca Mountain, the empirical underdetermination of the site is quite serious. Several DOE peer reviewers noted that modeling of flow at the site is "to a large extent based on simplifying assumptions which have not been fully verified by field observations."[95]

Judgments about the Reliability of Sampling

One of the expert judgments that is most crucial to the simplifications necessary to model any repository site is that sampling — via boreholes, wells, groundwater, or volcanic tuff cores — provides an adequate empirical base for predicting hydrogeological behavior at the location. At Yucca Mountain, DOE risk assessors have made a number of expert judgments about sampling. They made the judgments, for example, that hydraulic-conductivity values obtained from the southeastern part of the Yucca Mountain area "are representative of the values along the flow path."[96] In arriving at such judgments about the representativeness of their sampling, they subjected cores of tuff, for instance, to a variety of stresses in order to infer, inductively, how it might behave as a high-level waste repository. They also took samples of special glass and irradiated it for given periods in order to determine the leach rates of various radioactive elements.[97]

File, Louisville, KY Water Resources Div., U.S. Dept. Interior); F. Browning, *The Nuclear Wasteland*, 7 NEW TIMES 43 (1976).

95 YOUNKER ET AL., *supra* note 9, at 423 (D.K. Kreamer).

96 U.S. DEPARTMENT OF ENERGY, *supra* note 32, at 6-162.

97 For tuff sampling, *see, e.g.*, C. Voss & L. Shotwell, *An Investigation of the Mechanical and Hydrologic Behavior of Tuff Fractures Under Saturated Conditions*, in INTERNATIONAL CONFERENCE FOR HIGH-LEVEL RADIOACTIVE WASTE MANAGEMENT (1990) (Item 40 in DOE, DE91000566); *see also* R. PETERS ET AL., FRACTURE AND MATRIX HYDROLOGIC CHARACTERISTICS OF TUFFACEOUS MATERIALS FROM YUCCA MOUNTAIN, NYE COUNTY, NEVADA (1984) (Item D170 in DOE, NVO-96-24 (REV. 5)). For sampling of properties of glass *see, e.g.*, T. ABRAJANO ET AL., THE REACTION OF GLASS DURING GAMMA IRRADIATION IN A SATURATED TUFF ENVIRONMENT, Part 3, LONG-TERM EXPERIMENTS AT 1 X 104 RAD/HOUR (1988) (Item

Likewise, they subjected samples of spent fuel to tests, for thousands of hours, to determine the rate of oxidation.[98] In addition, they examined samples from two deep boreholes in order to draw conclusions about the nature of the aquifer.[99]

In all their sampling activities, Yucca Mountain researchers have typically made the expert judgment that a given number of boreholes or tuff samples, e.g., 2, 7, 20, 29, were sufficient and were representative enough to enable them to draw reliable inductive conclusions about site characteristics such as fracture transmissivity, permeability, and hydraulic conductivity.[100] However, the epistemological difficulty with relying on sampling in order to understand the hydrogeology of a site is that one never knows when the number of samples collected is enough, because one never knows if they are representative, or if the samples have captured the heterogeneities of the site. One often cannot adequately describe a site on the basis of several dozen boreholes; to attempt to do so would be like characterizing a large library on the basis of examining several dozen books.[101] It is well known, for example, that the host tuffs at Yucca Mountain are "highly variable."[102] Different

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23 in DOE, DE89005394).

98 R. EINZIGER & H. BUCHANAN, LONG-TERM, LOW-TEMPERATURE OXIDATION OF PWR SPENT FUEL: INTERIM TRANSITION REPORT (1988) (Item 26 in DOE, DE89005394).

99 S. Tyler, *Deep Installations of Monitoring in Unsaturated Welded Tuff*, in INTERNATIONAL CONGRESS ON HYDROLOGY OF ROCKS OF LOW PERMEABILITY (1985) (Item 173 in DOE, DE89005394); *see* L. Candy & N. Mao, *Nuclear Waste Repository Characterization: A Spatial Estimation/Identification Approach*, in EIGHTH TRIENNIAL WORLD CONGRESS-INTERNATIONAL FEDERATION OF AUTOMATIC CONTROL (1981) (Item 105 in DOE, DE89005394).

100 *See*, respectively, Y. CHUANG ET AL., LABORATORY ANALYSIS OF FLUID FLOW AND SOLUTE TRANSPORT THROUGH A VARIABLY SATURATED FRACTURE EMBEDDED IN POROUS TUFF (1990) (Item 120 in DOE, DE91000566); W. Lin & W. Daily, *Laboratory Study of Fracture Healing in Topopah Spring Tuff*, in NUCLEAR WASTE ISOLATION IN THE UNSATURATED ZONE (1989) (Item 47 in DOE, DE91000566); J. CONNOLLY & F. NIMICK, MINERALOGIC AND CHEMICAL DATA SUPPORTING HEAT CAPACITY DETERMINATION FOR TUFFACEOUS ROCKS (1990) (Item 66 in DOE, DE91000566).

101 L. CARTER, NUCLEAR IMPERATIVES AND PUBLIC TRUST 37 (1987).

102 D. Broxton, *Clinoptilolite Compositions in Diagenetically Altered Tuffs at a*

tuff samples react differently to the same environmental constraints. Often the samples are not representative of these differences, or it is not known whether they are representative, and hence whether geostatistical techniques give accurate estimates of variance. As late as 1988, for instance, assessors mentioned that they had just completed "the only hole drilled to date that penetrates the base of the tuff sequence and enters the underlying Paleozoic dolomite basement."[103]

Different samples used in adsorption studies appear to present a particular problem at Yucca Mountain. For example, when researchers used various samples of groundwater and tuff in order to study potential transport of radionuclides from a repository, they found that the adsorptive properties of the radionuclides on tuff were a function of time, temperature, and particle size, among other characteristics.[104] They also found that sorption values for various types of tuff differ, e.g., by at least four orders of magnitude.[105] Hence, representative adsorption samples are difficult to obtain, and conclusions about adsorption are dependent both on problematic samples and their representativeness, as well as on the models constructed from them.[106] Moreover, assessors are not able to check the representativeness of the samples used in adsorption studies, because much of the data and theory

Potential Nuclear Waste Repository, Yucca Mountain, Nevada, in INTERFACE SCIENCE AND ENGINEERING (P. Hofmann, ed. 1987) (Item 90 in DOE, DE90006793; *see* W. LINDERFELT, CHARACTERIZATION OF INFILTRATION INTO FRACTURED, WELDED TUFF USING SMALL BOREHOLE DATA COLLECTION TECHNIQUE (1986).

[103] D. BISH & S. CHIPERA, REVISED MINERALOGIC SUMMARY OF YUCCA MOUNTAIN, NEVADA, item 64 (1988) (Item 64 in DOE, DE90006793).

[104] S. Knight & K. Thomas, *Sorption of Radionuclides in Tuff Using Groundwaters of Various Compositions,* in 194TH NATIONAL MEETING OF THE AMERICAN CHEMICAL SOCIETY (1987) (Item 4 in DOE, DE89005394); K. THOMAS, SUMMARY OF SORPTION MEASUREMENTS PERFORMED WITH YUCCA MOUNTAIN, NEVADA, TUFF SAMPLES AND WATER FROM WELL J-13 (1987) (Item 6 in DOE, DE89005394); R. BECKMAN ET AL., PRELIMINARY REPORT ON THE STATISTICAL EVALUATION OF SORPTION DATA (1988) (Item 7 in DOE, DE89005394).

[105] U.S. NUCLEAR REGULATORY COMMISSION, IN THE MATTER OF PROPOSED RULEMAKING ON THE STORAGE AND DISPOSAL OF NUCLEAR WASTE (WASTE CONFIDENCE RULEMAKING) 44 F. R. 61372 (1980).

[106] H. FUENTES ET AL., PRELIMINARY REPORT ON SORPTION MODELING (1987).

underlying sorptive barriers are incomplete, unknown, or undeveloped.[107] In part because expert judgments about adsorption appear to have contributed to an underestimation of radionuclide transport at low-level radwaste sites like Maxey Flats and to a false belief that plutonium would not migrate rapidly,[108] there is reason to be cautious about any conclusions based on adsorption sampling.

Sampling methods used in repository risk assessments also often fail to be representative because researchers have sometimes modified the conditions under which they run experiments on samples. For example, in some Yucca Mountain cases, hydrogeologists used crushed-rock samples (not merely columns) to determine adsorptive values.[109] Yet, adsorption of radionuclides at Yucca Mountain, once

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[107] M. MORGENSTEIN, PHYSICS AND CHEMISTRY OF THE TRANSITION OF GLASS TO AUTHIGENIC MINERALS: STATE OF NEVADA, AGENCY OF NUCLEAR PROJECTS/NUCLEAR WASTE PROJECT OFFICE (1984) (Item 291 in DOE, DE90006793); BECHMAN ET AL., *supra* note 104; D. BISH & S. CHIPERA, REVISED MINERALOGIC SUMMARY OF YUCCA MOUNTAIN, NEVADA (1989) (Item 64 in DOE, DE90006793); *see also*, D. FINNEGAN & E. BRYANT, METHODS FOR OBTAINING SORPTION DATA FROM URANIUM-SERIES DISEQUILIBRIA (1987) (Item 55 in DOE, DE890006793); K. CAMPBELL, STATISTICAL GUIDELINES FOR PLANNING A LIMITED DRILLING PROGRAM (1988) (Item 60 in DOE, DE90006793).

[108] *See* K. Shrader-Frechette, *Scientific Progress and Models of Justification: A Case in Hydrogeology*, in SCIENCE, TECHNOLOGY AND SOCIAL PROGRESS (vol 2 RESEARCH IN TECHNOLOGY STUDIES, S. Goldman, ed. 1989) (Item 50 in DOE, DE890006793).

[109] *See, e.g.*, A. Meijer et al., *Sorption of Radionuclides on Yucca Mountain Tuffs*, in NUCLEAR WASTE ISOLATION IN THE UNSATURATED ZONE: FOCUS '89 (1989) (Item 82 in DOE, DE90006793); J. THOMPSON, LABORATORY AND FIELD STUDIES RELATED TO THE RADIONUCLIDE MIGRATION PROJECT: PROGRESS REPORT, OCTOBER 1, 1986-SEPTEMBER 30, 1987 (1988) (Item 358 in DOE, DE90006793); J. Thompson, *Actinide Behavior on Crushed Rock Columns*, 130 J. RADIOANAL. & NUC. CHEM. 353 (1989); W. DANIELS, LABORATORY AND FIELD STUDIES RELATED TO THE RADIONUCLIDE MIGRATION PROJECT PROGRESS REPORT, OCTOBER 1, 1980-SEPTEMBER 30, 1981 (1982) (Item 125 in DOE, DE89005394); C. Duffy & S. Al-Hassan, *Time and Frequency Domain Analysis of Tracer Migration in Crushed Tuff*, in WORKSHOP ON MODELING OF SOLUTE TRANSPORT IN THE UNSATURATED ZONE (1987) (Item 211 in DOE, DE89005394); R. Rundberg et al., *Observation of Time Dependent Dispersion in Laboratory Scale Experiments with Intact Tuff*, in SECOND INTERNATIONAL CONFERENCE ON CHEMISTRY AND MIGRATION BEHAVIOR OF ACTINIDES AND FISSION PRODUCTS IN THE GEOSPHERE (1989) (Item 19 in DOE, DE91000566).

containment has been breached, obviously will not occur in crushed rock but in fractured, intact rock. Moreover, the fractured, intact rock is less likely to adsorb radioactive materials (and retard migration) than is crushed rock.[110] Hence, use of crushed-rock samples probably contributes to an underestimation of the risk of migration.

Despite general methodological problems with sampling and particular difficulties with the representativeness of the Yucca Mountain samples, many DOE researchers remain confident that the adsorption values and radionuclide transport values "are being confirmed."[111] Obviously, however, by using different samples or different groundwaters or more extensive sampling or less crushed tuff, one could draw quite different conclusions about the adsorptive properties of the radionuclides or the transmissivity of the tuff; hence, one could draw different conclusions about the likelihood of radwaste migration offsite. Simply by considering the possibility that plutonium can form pseudo-colloids — that can facilitate transport — could reverse assessment conclusions about radwaste migration. It is conceivable, therefore, that for different samples under different conditions, for example, plutonium might not be adsorbed or captured as assessors predict.[112] And if sampling fails to provide accurate predictions, then expert judgments (about the types and numbers of sampling that ought to be done) may not provide a firm scientific basis for drawing general conclusions about site suitability.

When researchers sampled infiltration of precipitation at two Yucca Mountain sites, they found, e.g., hydrological activity at one location but not at the other.[113] Such results suggest that expert judgments about

[110] *See, Nuclear Waste Program: Hearings on the Current Status of the Department of Energy's Civilian Nuclear Waste Activities Before the Sen. Comm. on Energy & Natural Resources*, 100th Cong., 1st Sess. 204 (1987).

[111] A. Kelmers et al., *Evaluation of DOE Radionuclide Solubility Data and Selected Retardation Parameters: Description of Calculational and Confirmatory Experimental Activities*, in NRC RESEARCH ANNUAL REVIEW MEETING OF NUCLEAR WASTE MANAGEMENT RESEARCH ON GEOCHEMISTRY OF HLW DISPOSAL (1983) (Item 139 in DOE, DE89005394).

[112] U.S. DEPARTMENT OF ENERGY, *Project History*, in YUCCA MOUNTAIN PROJECT BIBLIOGRAPHY, 1988–1989 (1990).

interpolating or extrapolating regarding missing sample points could lead to difficulties, even if one employed geostatistics. Indeed, external reviewers have warned that many technical assumptions — expert judgments — about the site are not supported by field conditions and may be inappropriate to the Yucca Mountain system.[114] Of course, one obviously must make some types of expert judgments in hydrogeological situations, both about the quantity and representativeness of sample data. The problem is not the expert judgments about sampling as such, because they occur in all science and QRA. The real problem, in the repository case, is the frequent absence of any ideas about the limits of errors associated with such judgments. If one is ignorant about the limits of error, then the idealizations, extrapolations, interpolations, and simplifications could lead to false predictions, just as they did at Maxey Flats and at other nuclear-waste facilities. Moreover, in the case of the long time horizons associated with permanent repositories, it is impossible to know the limits of error, to any precise degree, because of the short-term data, the absence of long-term model confirmation, and the inductive inferences associated with both.

In risk assessments of Maxey Flats, sampling problems similar to those at Yucca Mountain caused serious difficulties and apparently contributed to the lack of knowledge about the facility's potential for radwaste migration. When industry geologists drilled wells at Maxey Flats, they found that they were dry, perhaps because their samples did not occur in areas where fractures happened to exist. When USGS geologists did other sampling, using well tests, however, they noted that some of the wells filled rather rapidly.[115] Because of difficulties associated with sampling, its representativeness, and its quantity, different scientists at Maxey Flats obtained contradictory empirical

[113] A. Norris et al., *Infiltration at Yucca Mountain, Nevada, Traced by 36Cl*, 29 NUCLEAR INSTRUMENTS AND METHODS IN PHYSICS RESEARCH, SECTION B: BEAM INTERACTIONS WITH MATERIALS AND ATOMS (NETHERLANDS) 376 (1987) (Item 92 in DOE, DE90006793).

[114] GEOTRANS, *supra* note 62, at 1.

[115] H. ZEHNER, U.S. GEOLOGICAL SURVEY, HYDROLOGIC INVESTIGATION OF THE MAXEY FLATS RADIOACTIVE WASTE BURIAL SITE, FLEMING COUNTY, KENTUCKY 110 (1981) (Open File Report).

results. For this reason, there are grounds for questioning repository risk data that are based on inadequate sampling. There are also grounds for questioning the expert judgment that Yucca Mountain sampling has already provided a reliable source of information about the site.

Admittedly, virtually all areas of science employ expert judgments about sampling. Much science would be impossible without sampling. Our point here is not that sampling is bad. The point, rather, is that in certain situations — characterized by heterogeneous phenomena and inadequate data to support very long-term predictions — the most reliable sampling is done in an extremely conservative, i.e., thorough, way. Because some Yucca Mountain sampling involved questionable judgments, for example, about factors such as using crushed rock, the sampling does not appear to have been done, in all cases, in a conservative way. Hence there are grounds, in cases like Yucca Mountain, for questioning some of the optimistic judgments of site suitability, given that they are based on limited sampling. There are also grounds for questioning the use of sampling as a basis for accurately assessing repository risk because the greater the number of boreholes drilled, for example, the more precisely we can characterize a proposed site. But such precision is bought at a price, since less drilling means less tendency to compromise site integrity, and more drilling (more accuracy) means a greater likelihood of compromising site integrity.[116] Hence, conclusions about site suitability need to reflect accurately the limits imposed by sampling.

Problems with Yucca Mountain versus Problems with Permanent Disposal

Several of the expert judgments (e.g., about the reliability of conclusions based on sampling) surveyed in this essay are widely used throughout science and risk assessment. Hence, the difficulty is not with using these judgments, as such, but with drawing stronger conclusions from them than are warranted by the existing scientific theories and inductive data. At Yucca Mountain, for example, we argued that some of the DOE site-suitability conclusions appeared to be stronger

116 CARTER, *supra* note 101, at 38.

than were warranted by the limited quantity and the questionable representativeness of the evidence. In general, however, there are no basic problems with employing expert judgments (such as those related to model reliability, simplification, and sampling) in science and risk assessment. Indeed, in many areas of science, there simply are no viable alternatives to making a variety of such judgments.

However, a number of the expert judgments used in the Yucca Mountain case do present difficulties. They appear to exemplify "bad science." They suggest that, were certain judgments — regarding risk estimation, for example — handled differently at Yucca Mountain, the scientific conclusions about the site might be somewhat different. Some of these examples of "bad science" include the expert judgments that models not validated and confirmed by field data are accurate, and that simplifying assumptions adequately represent the site, even though they have not been checked by actual observations.

Obviously, if "bad science" was responsible for all of the flawed expert judgments about risk estimation that we have criticized at Yucca Mountain, then these problems would argue only against repository sites chosen on the basis of flawed studies. "Bad science" would not argue generally against permanent, geological disposal of radwaste. But this raises the question whether the problems we have exposed in this essay represent difficulties that might be avoidable at other proposed repository sites or in other risk studies. Do these problems with expert judgments about risk estimation argue only against "bad science" and "bad risk assessment" or also against any permanent radwaste repositories?

At least one of the expert judgments criticized in this essay appears to present obstacles to any permanent, geological disposal of radwastes anywhere. This is the judgment that short-term data can be used to confirm precise conclusions about long-term (ca 10,000 years) site acceptability. If the arguments in this essay have been correct, then short-term scientific data militate against any precise, optimistic predictions regarding long-term (10,000 years) repository suitability and safety. Indeed, as we showed early in the essay, and as the Yucca

Mountain peer reviewers for DOE confirmed, there can be no reliable geological predictions regarding volcanism and seismicity, because geology is essentially an explanatory, rather than a precise, predictive science. As we also argued, and as the Yucca Mountain peer reviewers and various social scientists admitted, beyond 50 or 100 years, precise predictions about human and institutional errors and behavior are not reliable. This being so, use of only short-term geological data exacerbates the more general problem of accurate, long-term prediction.

U.S. regulations stipulate that precise, thousand-year predictions — regarding either geological factors like seismicity or social factors like repository intrusions aimed at securing natural resources — are required to guarantee the safety of a permanent repository.[117] If such accurate, long-term predictions are at present impossible, then a scientifically defensible siting of a permanent repository, at least at present in the U.S., likewise appears impossible.

[117] See K.S. SHRADER-FRECHETTE, *supra* note 18. *See also* A. Berusch & E. Gause, *supra* note 72.