STATE OF NEVADA

AGENCY FOR NUCLEAR PROJECTS/ NUCLEAR WASTE PROJECT OFFICE

NWPO-SE-054-92

EXPERT JUDGMENT IN ASSESSING RADWASTE RISKS:
WHAT NEVADANS SHOULD KNOW ABOUT YUCCA MOUNTAIN

BY

KRISTIN SHRADER-FRECHETTE, PH.D.
DISTINGUISHED RESEARCH PROFESSOR
UNIVERSITY OF SOUTH FLORIDA

BOB MILLER
Governor

ROBERT R. LOUX
Executive Director

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JUNE, 1992

THE NEVADA AGENCY FOR NUCLEAR PROJECTS/NUCLEAR WASTE PROJECT OFFICE (NWPO) WAS CREATED BY THE NEVADA LEGISLATURE TO OVERSEE FEDERAL HIGH-LEVEL NUCLEAR WASTE ACTIVITIES IN THE STATE. SINCE 1985, IT HAS DEALT LARGELY WITH THE U.S. DEPARTMENT OF ENERGY'S SITING OF A HIGH-LEVEL NUCLEAR WASTE REPOSITORY AT YUCCA MOUNTAIN IN SOUTHERN NEVADA. AS PART OF ITS OVERSIGHT ROLE, NWPO HAS CONTRACTED FOR STUDIES OF VARIOUS TECHNICAL AND SOCIOECONOMIC ISSUES ASSOCIATED WITH THE YUCCA MOUNTAIN PROJECT.

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Executive Summary

Expert Judgment in Assessing Radwaste Risks: What Nevadans Should Know about Yucca Mountain

For phenomena characterized by accurate and largely complete data, quantitative risk assessment (QRA) provides extraordinarily valuable and objective information. However, with phenomena for which the data, models, or probabilities are incomplete or uncertain, QRA may be less useful and more questionable, because its conclusions are typically empirically and theoretically underdetermined.

In the face of empirical or theoretical underdetermination, scientists often are forced to make a number of methodological value judgments and inferences about how to estimate and evaluate the associated risks. These value judgments and inferences concern factors such as model reliability, sampling, extrapolations, human error, credible worst cases, and so on. While not all methodological value judgments and inferences are avoidable in QRA, their reliability often can be assessed on the basis of the evidence for and against them. Both methodological value judgments and problematic inferences raise questions about the quality of expert judgment in risk assessment.

The purpose of this project is to evaluate instances of methodological value judgments and invalid or imprecise inferences that have occurred in the QRA done for the proposed Yucca Mountain high-level radioactive waste facility. We shall show (1) that questionable methodological value judgments and inferences have occurred in some Yucca Mountain QRA's; (2) that questionable judgments and inferences, similar to those in the Yucca Mountain studies, have occurred in previous QRA's done for other radiation-related facilities and have likely caused earlier QRA's to err in specific ways; and (3) that, because the value judgments and problems associated with some Yucca Mountain QRA's include repetitions of similar difficulties in earlier studies, therefore the QRA conclusions of some Yucca Mountain analyses are, at best, uncertain.

In order to improve the scientific methodology of the Yucca Mountain QRA's we recommend that assessors admit the methodological uncertainties in their work, and that they attempt to take account of probabilistic bias, human error, inappropriate use of probabilistic language, social amplification of risk, and the lack of public trust in the DOE. We also recommend that assessors employ null models to test their results; that they provide ranges of values (rather than averages) for parameters such as rates of radionuclide transport; that they analyze social impacts such as threats to due process, equal treatment, informed consent, full liability protection, and full compensation; that they obtain independent reviews of their work; and that they employ successful assessment procedures used in other nations.

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Chapter One

Introduction: Risk Assessment and Value Judgments

In 1962, scientists calculated the risks associated with a proposed US site for shallow land burial of transuranics and low-level radioactive wastes. Representatives from industry and academia praised the (Maxey Flats) Kentucky location and calculated that, if plutonium were buried there, it would take 24,000 years to migrate one-half inch. They said that "the possibility of subsurface migration offsite is nonexistent" (USGS 1962; Neel 1976, p. 258; see also Weiss and Columbo 1980, p. 5).

More conservative assessors and geologists claimed that it would take many hundreds of years for the radionuclides to migrate offsite (Montgomery and Blanchard 1979, p. 784; US Congress 1976, p. 28; Meyer 1976, p. x). Maxey Flats contains more plutonium (in curies) than any other commercial repository in the world (Zurer 1983), and it has the second-highest total radioactivity in curies of all low-level sites in the US (Kasperson and Abdollahzadeh 1988, p. 13). Yet, only ten years after opening the facility, plutonium and other radionuclides were discovered two miles offsite (USGS 1962; Meyer 1975, p. 9; Pacific Northwest Laboratory 1980, esp. pp. v, I-1, I-2, I-14, IV-6, IV-9, V-7ff.), causing the facility to be closed. The geological predictions were wrong by as much as six orders of magnitude.

1.1 What Can We Learn From Assessment Mistakes?

One of the many questions raised by this case is what we can learn about Yucca Mountain on the basis of our risk-assessment

mistakes at Maxey Flats and at other radwaste facilities. Although this analysis does not attempt to draw comparisons between two sites (like Maxey Flats and Yucca Mountain) with different physical attributes, missions, and types of radwastes, various sites can be compared with respect to their use of risk assessment. How risk assessors handle expert judgment, uncertainty, limited information, long time frames, and the process of evaluation at one site provides valuable comparative lessons that often can be applied to other sites. Can we do some Monday-morning quarterbacking about earlier assessments of radioactive waste facilities and thereby learn how to do a better job of assessment at Yucca Mountain?

One question to be addressed in this analysis is whether the Maxey Flats risk assessment, with its flawed hydrogeological predictions, was highly atypical. If it was, then perhaps Nevadans have little to fear. If it was not, then Yucca Mountain may also be a cause for concern. Are science, in general, and risk assessment, in particular, more reliable than the erroneous migration predictions at Maxey Flats suggest?

For phenomena for which the data, models, or probabilities are uncertain, experts reveal that uncertainties of six orders of magnitude are "not unusual" in risk assessment (Cox and Ricci 1989a, p. 1026). A famous study on the siting of LNG (liquefied natural gas) terminals in four countries showed that widely varying risk estimates for the same event are pervasive; in Oxnard, California, for instance, reputable hazard assessments (of the annual chance of dying in a liquefied natural gas accident)

differed by three orders of magnitude (Kunreuther et al. 1987, p. 261.). Likewise, current US-government predictions for the likelihood of a Three-Mile-Island-type accident differ by two orders of magnitude (Rasmussen 1981). Other cases are much the same; they suggest that scientific predictions and risk estimates are sometimes laden with enormous uncertainties. However, for phenomena characterized by accurate and more complete data, such as automobile accidents, quantitative risk assessment (QRA) involves fewer uncertainties. For this reason, QRA provides extraordinarily valuable and objective information.

1.2 Scientific Methodology, Value Judgments, and Inferences

Sometimes, however, QRA's are less valuable, objective, and scientific than they should be. As examples of scientific explanation and prediction, QRA's can go wrong in two main ways, with respect to their data or with respect to their methods. The focus of this analysis is QRA methods used at Yucca Mountain and how we may improve them. We can improve them in the same way that we strengthen science: by a persistent critique of the QRA arguments and by using tried canons of logic to assess the reliability of the QRA conclusions (see Nagel 1961, pp. 13-105).

According to the basic pattern of scientific explanation and prediction, we explain or predict some phenomenon by logically deducing the conclusion sentence (describing the phenomenon) from premise sentences (that account for the phenomenon). The premises of a scientific explanation/prediction are of two types: statements of specific, antecedent conditions and general

scientific laws. If the methods of a QRA or scientific explanation/prediction are problematic, it is typically because some aspect of the deductive move from the premises to the conclusion is questionable (see Hempel and Oppenheim 1948; see Nagel 1961, Braithwaite 1953).

Our methodological analysis of the arguments used in QRA focuses on two of the important ways in which the deductive move from scientific premises to conclusion can go wrong. Either the inferences used to justify the move from premises to conclusion may be suspect, or the methodological value judgments -- in terms of which we interpret the inferences, data, premises, and theories -- may be questionable. Inferences are the rules that we use in deriving conclusions from premises, and they may be valid or invalid. If we are given the premise, "A entails B," for example, we use an invalid inference if we draw the conclusion, "B entails A." Or, for instance, if we are given the premises, "A entails B," and "B entails C," then we use a valid inference -- transitivity -- if we draw the conclusion, "A entails C."

Methodological value judgments are interpretations of inferences, data, premises, or theories -- interpretations that rely on our commitment to a particular methodological value. For scientists, methodological values include simplicity, predictive power, explanatory fertility, external consistency, accuracy, and so on. Whenever we employ or apply inferences, data, or premises in the arguments of science or QRA, we must interpret them. Typically these interpretations take the form of methodological value

judgments. For example, someone committed to the methodological value of predictive power might make the methodological value judgment that, if models of some phenomenon had not been tested with actual field data, then they alone were an insufficient basis for drawing conclusions. Because of this methodological value judgment, such a person might discount the predictive value of computer models. Likewise, for instance, someone committed to the methodological value of external consistency -- rather than predictive power -- might make a quite different methodological value judgment. Such a person might judge that untested models of some phenomenon, provided that they were consistent with available data, were a sufficient basis for drawing conclusions about the phenomenon.

Because some interpretations or methodological value judgments are more plausible, logical, or defensible than others, it makes sense to assess them. Moreover, because methodological value judgments are interpretations of inferences, data, premises, or theories, they are somewhat subjective. They are also subjective because scientists may disagree about the relative importance of different methodological values in terms of which we make methodological value judgments. Of course, the value judgments that occur in science are not typically moral or ethical. We term methodological value judgments value judgments both because they are partially subjective and normative and because they are a function of methodological goals or values. Making some subjective value judgments is, of course, unavoidable even in science. The

point of this analysis is that often scientists are unaware of their subjective value judgments, and often they make judgments that are wrong.

When a scientific explanation/prediction or QRA relies on problematic inferences or value judgments, often those inferences or value judgments are problematic because they are based on erroneous or questionable assumptions, rather than on confirmed data or valid logic. Assumptions are propositions that are suppositions, that are taken for granted. Often they are taken for granted because it is impossible or impractical to confirm them. For example, one assumption underlying the Yucca Mountain work is that safe, geological storage of high-level radwaste is possible in perpetuity. Although there is evidence for this proposition, it cannot be confirmed, because of the long time period. Hence it is taken for granted; it is an assumption. Because methodological value judgments can be substantiated, but never fully confirmed, they are assumptions (about methodological values). Not all assumptions, however, are methodological value judgments; they might be judgments about things other than values. Generally, the more plausible methodological value judgments are based on more plausible assumptions. Likewise, all invalid inferences typically rely on some incorrect assumption or supposition, whereas valid inferences usually rely on correct assumptions or suppositions about the relationship between given premises and a conclusion.

Later, when we analyze some of the problematic methodological value judgments and inferences in Yucca Mountain QRA's, we shall

discuss the most problematic assumptions on which these value judgments and inferences rest. In some instances, we shall show that the QRA arguments fail to meet either the logical or the empirical conditions of adequacy for a scientific explanation in the strict sense. These conditions are (1) that each conclusion is a logical consequence of certain premises; (2) that the premises contain general laws that are required for deducing each conclusion; (3) that the premises have specific, empirical content capable of being tested; and (4) that the premises state propositions that are true (Hempel and Oppenheim 1948; Popper 1959). Typically, arguments that employ questionable methodological value judgments or invalid inferences, such as begging the question, violate one or more of these four conditions. Many areas of science, however, do not meet these four conditions for a scientific explanation in the strict sense. Hence, we shall argue that the main difficulty with many of the arguments in the DOE Yucca Mountain QRA's is not that they fail to meet one or more of these conditions for deductive scientific explanation. Their main deficiency is that, even at the level of inductive and retroductive science, there are typically inadequate reasons and incomplete data to support the conclusions of many QRA's.

1.3 Overview: Risk Estimation and Risk Evaluation

A QRA typically consists of three stages, risk identification, risk estimation, and risk evaluation. When assessors employ problematic inferences or questionable methodological value judgments in QRA, conclusions at two distinct stages of risk

assessment may be affected: conclusions that estimate a particular risk, or conclusions that evaluate a given risk. In risk estimation, stage two of QRA, one draws conclusions about the nature of the dose-response curve or the population at risk. In risk evaluation, stage three of QRA, one draws conclusions about the acceptability of a given risk.

In the remainder of this chapter, we shall describe risk estimation and risk evaluation in more detail. In chapters two and three, respectively, we shall assess some of the problematic methodological value judgments that occur at the risk estimation and the risk evaluation stages of QRA. In chapter four, we shall analyze some of the questionable logical inferences that occur at both the risk-estimation and the risk-evaluation stages of some Yucca Mountain QRA's. In the final chapter, we shall draw conclusions about the reliability of Yucca Mountain assessments and make recommendations about how to improve them.

1.4 Methodological Value Judgments Are Unavoidable in QRA

Many of the flaws that threaten the objectivity of risk assessments at radwaste sites occur in part because all science and all quantitative risk assessment (QRA) are laden with unavoidable methodological value judgments about how to estimate and evaluate the associated risks. Because such value judgments are unavoidable in science, our point is that often scientists and risk assessors are unaware of their value judgments, and often they make judgments that are wrong. These methodological value judgments concern factors such as model reliability, sampling, extrapolations, human

error, credible worst cases, and so on. While not all methodological value judgments are avoidable in QRA, the reliability of any particular value judgment often can be assessed on the basis of the evidence for and against it. Moreover, these value judgments occur at all three stages of risk assessment (identification, estimation, and evaluation), as well as in the risk management occurring after assessment. Such value judgments are particularly troublesome because they are often not recognized as such. Proponents of the "standard account" of risk assessment believe that it is more neutral and value free than it is. They typically believe that risk assessment is a largely scientific discipline to be perfected along hypothetical-deductive lines (see Rudner 1980, p. 236; Allen and Crump 1987, pp. 129-146), and that, if they merely discover the correct algorithms, then they will have the power to predict and assess risks in a wholly neutral way, much as Einstein and Bohm hoped for deterministic, predictive power for quantum mechanics. Proponents of the standard account of risk assessment also believe that it is possible to separate the allegedly purely technical steps of risk assessment from risk evaluation and risk management.

Critics of the standard account argue, however, that QRA, and especially its third stage, risk evaluation, is not merely a scientific investigation but also a political procedure to be negotiated among experts and the public (see Whipple 1989, pp. 1105-1120; US Nuclear Regulatory Commission 1975, p. 37; Starr and Whipple 1980, p. 1116; Cohen and Lee 1979, p. 707; Hafele 1979, p.

139; and M. Maxey 1979, pp. 410, 417; Cohen 1989, p. 575; Andrews 1988, pp. 85-97; Dreyfus 1982, p. 61; MacLean 1987, Part V; Clarke, 1989). They also argue that, because of the many unavoidable methodological value judgments involved in the process, risk assessment is not wholly objective (Ricci and Henderson 1988, pp. 285-293; Setlow 1988, pp. 1-5; Shrader-Frechette 1991a). Just as physicists do, assessors must make value judgments about which data to collect; how to simplify myriad facts into a workable model; how to extrapolate because of unknowns; how to choose statistical tests to be used; and how to select sample size. They must make value judgments in determining criteria for NOEL -- no-observed-effect level -- (Schneiderman 1987, pp. 107-128; Foulkes in Saxena 1989, pp. 31-47); in deciding where the burden of proof goes, which power function to use, what size test to run, and which exposure-response model to employ (Busch in Humber and Almeder 1987, pp. 9-55; see also Setlow 1988). Although such judgments are also assumptions, it is important to recognize that they are judgments about methodological values, values such as reliability, simplicity, predictive power, completeness, explanatory adequacy, and so on. Because such assumptions are value judgments, they can be wrong. They represent partially subjective aspects of allegedly objective risk estimates and evaluations.

Because risk assessors must continually make methodological value judgments, at every stage of their analysis, proponents of the standard account of risk assessment may encounter difficulty when they claim to be able to separate out some allegedly purely

technical aspect of risk assessment. They also run into problems when they claim that risk assessment can be separated from risk management. Because every part of assessment involves methodological value judgments, and because even scientific conclusions have implications for risk-management recommendations, therefore risk assessment is not always completely separable from risk management (see Reichard et al. 1990, p. 177). Perhaps the main goal of this analysis is to reveal the extent to which risk assessment in general and Yucca Mountain assessments in particular contain methodological value judgments that are questionable. Although no scientific enterprises are completely free of subjectivity, at least with respect to methodological value judgments, obviously the best science and risk assessment are the least subjective.

One of the best examples of the ways in which risk assessment is subjective is in the definition of risk as a compound measure of the probability and magnitude of adverse effect. This measure is often expressed in terms of average annual probability of fatality. Using this definition presupposes that one is justified in identifying/interpreting "risk" in terms of fatalities alone and in ignoring injuries, financial losses, social-political effects, and legal or constitutional harms, such as threats to due-process rights. Practitioners of the standard account of risk assessment often ignore such aspects of risk because of a narrow, evaluative definition of risk, and because the social and ethical aspects of risk are among the most difficult to handle. Thus, even at the

risk-identification stage, value judgments (about how to define risk) are unavoidable. Moreover, because of incomplete data and long years of testing, assessors are forced to interpret and to extrapolate from the information which they do have, and hence to make both pragmatic and epistemic value judgments about how to identify risks.

1.5 Value Judgments in Estimating Risks

In estimating risks, assessors may rely on methodological value judgments which, although not always erroneous, are sometimes question-begging and/or misleading. Every time one makes the methodological value judgment that a certain interpolation of missing data is acceptable, or that one ought to extrapolate from laboratory to field data, one is making a methodological value judgment about a factual situation, as all scientists do. To the degree that values are involved, the factual judgment could be incorrect. Obviously, however, value judgments about factual situations are never wholly avoidable, because data are rarely complete. Hence, assessors are forced to use value judgments to "fill in the gaps." The judgments focus on methodological values such as simplicity, heuristic power, completeness, explanatory adequacy, and so on.

At the second stage of risk assessment, risk estimation, one must make many value judgments about the validity of extrapolation from high to low doses, from animals to humans, and from one group of humans to another. The problems associated with such extrapolation are well known in science, as when health physicists

try to estimate a dose-response curve for low-level radiation exposure, given data points only for higher-level exposures. (A) Environmentalists, (B) industry representatives, and (C) members of health physics associations have each extrapolated, respectively, to a dose-response curve for radiation that is typically (a) logarithmic or supralinear, (b) quadratic, linear-quadratic, or linear with a large threshold, and (c) linear with no threshold. Subscribing to different value judgments about the low-dose end of the curve, they have claimed, respectively, that low-level radiation is very dangerous, not very dangerous, and moderately dangerous. To get some idea of the differences in the estimates produced by using different value judgments to support alternative models for radiation dose-response curves, consider the excess incidence of cancers predicted, other than leukemia and multiple myeloma. For a 10-rad exposure, the quadratic model predicts 560 excess cancers per million persons exposed, whereas the linear-quadratic predicts 4,732 excess cases, and the linear model predicts 10,630 excess cancers. Thus there is a 20-fold difference between the quadratic and the linear models! And there is an 86-fold difference between the predictions of the quadratic and the supra-linear models. However, the National Academy of Sciences' (NAS) Committee on Biological Effects of Ionizing Radiation claims that there is no reason to prefer one model over the other at low doses. Their position suggests that one value judgment about which curve to use is not always more objective than another (Longino 1986, pp. 3-11; BEIR IV, 1988; Shrader-Frechette 1983, pp. 25-27;

Paustenbach 1989; Saxena 1989; and Woodhead et al. 1988).

Estimating the population at risk and the dose received is just as problematic because estimators must assume that their theories provide a reasonable measure of exposure; that the exposure is related in some clear way to the administered dose; that the absorbed dose is a specific function of the administered dose; that phenotypic variation in populations does not inordinately affect dose received; that the critical organ dose is related precisely to the absorbed dose; and that the effect is a particular function of the critical organ dose. Because actual measurements of particular doses, e.g., of a chemical, cannot be made in all situations, a mathematical model of assumed exposure must be used, and assessors must make an epistemic value judgment as to its suitability. Sometimes these judgments differ radically; toxicologists, for example, typically view the notion of a safe threshold dose as controversial, whereas engineers, who sometimes equate dispersal with dilution, tend to assume some threshold below which a substance is no longer harmful. Neither group, however, typically addresses synergistic consequences (Longino 1986, p. 3; Purdham 1987, p. 9; Foulkes 1989, pp. 43ff.; BEIR IV 1988, pp. 442ff.; Woodhead et al. 1988), even though seemingly unimportant pathways of exposure can assume great significance owing, for example, to biomagnification or food-chain effects.

Moreover, it is rare that a substance is uniformly distributed across pathways and time. Numerous studies have shown that the target dose, pathway, and persistence of a toxic or hazardous

substance, for example, are difficult to predict. Predictive difficulties plagued epidemiologists tracing the distribution of radiation after the Chernobyl nuclear accident on April 25, 1986. Maps showing the areas of greatest radionuclide deposition look like Rorschach drawings; the distribution did not follow a predictable pattern based on prevailing wind direction and the rotation of the earth. Instead, numerous factors, such as rainfall patterns and the height of the radioactive plume, affected the highly irregular spread of radiation following the accident (von Hippel and Cochran 1986, pp. 18-24; Marshall 1986, pp. 814-815). Also, even if pathways of various toxins could be determined exactly, phenotypic variations among populations are such that one person could be 200 times more sensitive to a chemical or to radiation than another, even when both received equal doses (Nebert in Woodhead et al. 1988, p. 59). Given such situations, the assessor often is forced to make a number of highly interpretative, value-laden risk-estimation judgments.

1.6 Value Judgments in Evaluating Risks

Risk assessors also make methodological value judgments whenever they evaluate risks and compare one risk to another regarding acceptability. For example, whenever one claims -- that so long as the risk to the public from high-level radioactive waste is no greater than that arising from uranium ore, the risk is acceptable -- then one is making a value judgment about risk acceptability. Because such judgments involve values, they could be problematic with respect to ethical, political, or social norms.

They represent a second area in which risk assessment can go wrong.

Highly evaluative judgments characterize the third stage of hazard assessment, risk evaluation, because analysts typically use economic and psychometric methods to determine whether a risk is acceptable to society. In doing so, assessors are forced to make a number of highly evaluative judgments, such as whether monetary-term parameters can adequately represent the real cost or benefit of a thing; whether the magnitude of risks, costs, and benefits is more important than their distribution (Cox and Ricci 1989a, pp. 1038ff.; Samuels in Woodhead et al. 1988, pp. 113-120; Shrader-Frechette 1985, esp. chapters 2, 5, 6, and 7); whether past societal risk levels reveal desirable risk levels for the present; whether past hazards ought to have been accepted; whether the preferences people express via instruments such as surveys provide reliable indicators as to acceptable risks; and so on.

All the assumptions, extrapolations, and erroneous inferences that may be present during the three stages of hazard assessment arise in large part because nearly all situations of risk identification, estimation, or evaluation -- like many situations in science -- are empirically underdetermined. Because they are empirically underdetermined, risk assessors are forced to make some methodological value judgments, so as to interpret the data available to them. At root, these assumptions and inferences often reduce to the problem of getting a grip on causality. This is difficult, since causes are not seen; they are inferred on the basis of their effects. Cancers, for example, do not wear tags,

saying they were caused by their subject's smoking, or by use of oral contraceptives, or by diet drinks, or by breathing the emissions of the chemical plant next door. Moreover, we know statistically how much of one agent causes cancer in general, but we can never determine whether a substance caused a particular cancer. We can only make a methodological value judgment to support inferences about what caused a certain cancer.

Risk victims everywhere are typically able to show a statistically significant increase in certain types of injuries/deaths, a correlation between increased dose and increased response, but no cause of particular cancers, for example. Without proof of causality, they can claim no benefits. In the absence of proof and complete data, they are forced, like risk assessors everywhere, to rely on methodological value judgments, on inference, extrapolation, and simplification (see Bond 1986, pp. 24-43).

1.7 Conclusion

In summary, methodological value judgments in risk assessment -- as in all science -- typically fall into a number of categories. They are, for example, value judgments about the acceptability of

- a given definition of risk
- a given simplification of the situation
- a given way of selecting data leading to explanatory fertility
- a given aggregation of the data
- a given sample size and the accuracy of conclusions based on it
- a given statistical test and its predictive power
- a given model for exposure
- a given dose-response model and its external consistency
- a given extrapolation from the data
- a given price/value for risk avoidance.

Each of these and other methodological value judgments enables us

to respond to a situation that is empirically undetermined. Yet, because our response involves a value judgment, it could be wrong. It could lead to serious problems in the risk assessment. Because of this, we need to explicitly take account of all the relevant methodological value judgments on which our scientific conclusions depend. We need to determine whether the evidence tends to substantiate these value judgments or to call them into question. By using more reliable methodological value judgments in QRA, and by becoming more aware of the value judgments we do make, we shall provide better QRA and, as a result, better public policy.

Chapter Two

Methodological Value Judgments in Estimating Radwaste Risks

One of the most useful measures of the degree of reliability of a scientific conclusion is the extent to which it is sensitive to particular assumptions and methodological value judgments. If a conclusion is extremely sensitive to such a judgment, then it is important to know how plausible the assumption or value judgment is. Otherwise one could place misguided confidence in a highly unreliable conclusion.

Probabilistic risk-assessment conclusions about the Yucca Mountain site, while typically optimistic about site suitability, are also highly sensitive to a number of assumptions or methodological value judgments. For example, most site assessors have concluded that, as US regulations require, no radionuclides are likely to reach the water table at Yucca Mountain in less than 1,000 years. Other assessors, particularly those from the state of Nevada, have concluded that groundwater travel time from the disturbed environment to the accessible environment could be as short as 978 years, and that, as a result, Yucca Mountain would not meet government standards for a repository (see, for example, Bryan 1985, vol. 1, pp. I-42 and I-43; Peters 1986, p. 32; see Sawyer in US Congress 1987a, pp. 709, 712). Conclusions about groundwater travel time, however, are highly sensitive to a number of assumptions about the rate of fracture flow and infiltration, e.g., 0.01 mm/year (Barnard and Dockery 1991). Conclusions about radionuclide migration are also highly sensitive to a number of

value judgments about the reliability of the simulations used, the validity of a variety of extrapolations and interpolations, the lack of need for more site-specific data, and so on. If different value judgments and assumptions were used, then quite different conclusions about radionuclide migration and repository containment could very likely be drawn. As one group of assessors put it, for example: "the use of a low net infiltration rate for this problem made it not unexpected that there was no predicted radionuclide release to the water table....Other...rates...would probably result in considerably different transport results" (Barnard and Dockery 1991, p. 5-6).

Numerous value judgments arise in a quantitative risk assessment (QRA) of storing high-level radwaste. In studies of the Yucca Mountain site, there are a number of characteristic methodological value judgments made in estimating the magnitude and distribution of the potential radiological risk. In fact, in a review of the Yucca Mountain Site Characterization Plan, evaluators criticized the fact that much of the report is comprised of designs based on large assumptions that lead to inconclusiveness in terms of technical integrity. As a result, claimed the evaluators, the likely success of the designs proposed within the report is highly questionable from a technical point of view. Further, the evaluators charged that the questionable designs were based on technical errors and on oversimplifications. As a result, many of the concepts within the Yucca Mountain plan have not been developed to the degree necessary to insure scientific integrity (Thompson

Engineering Company 1988). The purpose of this analysis is to examine several examples of the ways in which the Yucca Mountain risk assessments -- despite the areas in which they are technically successful -- may have gone wrong, either through problematic reasoning or through questionable methodological value judgments.

The forthcoming analysis of questionable methodological value judgments (chapters two and three) and inferences (chapter four), however, is neither mutually exclusive nor exhaustive. Value judgments about model reliability, for example, often intersect with other value judgments about the plausibility of certain simplifications in the treatment of site phenomena. Likewise, there are a number of value judgments that are not even mentioned in this analysis. Specific transportation-related judgments, for instance, are not included, both because assessors and decisionmakers appear to be aware of many of the shortcomings in this area and because a number of contracts have already been offered for studies to assess transportation impacts associated with Yucca Mountain.

2.1 Value Judgments about Long-Term Risks

One of the most basic methodological value judgments used in estimating the risk of radionuclide migration at Yucca Mountain is the judgment that short-term tests, for several decades or less, provide adequate information for predicting long-term behavior -- for example, isolation of the waste for 10,000 years and container integrity for 1,000 years (see, for example, Beavers and Thompson 1990; Halsey 1989; Perry 1988; Dobson et al. 1990). This methodological value judgment, about the validity of a long-term

inductive conclusion based on short-term data, is highly controversial. For one thing, the conclusion (about long-term risks) does not follow logically from the premises (about short-term data). Hence, this value judgment fails to meet the first logical condition for an adequate scientific explanation/prediction in the strict sense (see section 1.2 earlier; Hempel and Oppenheim 1948; Popper 1959). Even as an inductive or probabilistic explanation this value judgment is highly questionable. The extended time horizon for the Yucca Mountain repository is several times longer than recorded human history (see Sawyer 1990, p. 73). Egyptians have been unable to protect the tombs of the Pharaohs for less than four thousand years, and some of the them were looted within centuries. Italians have been unable to protect Renaissance art treasures for less than one thousand years, yet we in this generation have to be able to guarantee the isolation of nuclear wastes for tens of thousands to millions of years.

Although long-term prediction is a problem in any area of science, the Yucca Mountain predictions are particularly problematic not only because they deal with thousands of years but also because the government regulations require the predictions to be very precise (see section 2.9 of this report). They specify allowable levels of radionuclide releases over thousands of years. Hence, it is the precision of the long-term predictions that make them more problematic at Yucca Mountain than in other applications of science.

The methodological value judgment that short-term studies

provide adequate and precise predictions of very long-term behavior is also questionable, in the Yucca Mountain case, because an environmental and health catastrophe could result from faulty predictions. The potential dose commitments of some of the isotopes (such as C-14, Pu-239, and I-129) in the waste extend from hundreds of thousands to millions of years (Hawkins 1978). Moreover, the US Environmental Protection Agency (EPA) has explicitly warned that it is "impossible" to predict anything regarding the success of radioactive waste management beyond 100 years, and that institutional controls are particularly problematic beyond a period of 100 years (US EPA 1978, pp. 10, 26). The institutional factor also illustrates why Yucca Mountain long-term predictions are more problematic than in other areas of science.

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 the time limitations for conducting the necessary studies (NWPO 1989, vol. 1). At the center of problems with time limitations is the fact that, as one Yucca Mountain peer reviewer (K. V. Hodges) for the DOE put it, siting activities require a predictive science, but geology is an explanatory science with only limited predictive power (Younker, Albrecht, et al. 1992, p. 362). Indeed, the Yucca Mountain peer reviewers for the DOE were so worried about long-term predictability that they issued the following statement about site suitability:

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...will be fraught with substantial uncertainties (Younker, Albrecht, et al. 1992, p. B-2).

The main worry about making the value judgment that a long-term risk at Yucca Mountain 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 repository. Since such catastrophes, over the long term, have occurred in the past, there are grounds for such worries. The US 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 meteor strike is quite low. When one is considering long-term predictions for something like the Yucca Mountain repository, even events such as volcanism or seismic activity, events likely having a low annual probability, assume greater proportion. 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 the local geology might be sufficient to change the location and flow of groundwater that could possibly flood the repository and leach the waste. Although no mechanism (currently known) appears capable of raising the water table to the

repository level, nevertheless such a rise remains a possibility (Raleigh 1992). 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 is virtually certain. An annual probability of 10^{-6} converts to a 10^{-3} probability over 1,000 years. This is a quite high probability, 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" (Stein and Collyer 1983) on the basis of data obtained during only one or several decades. Moreover, most of the Yucca Mountain experiments and data are from periods of far less than a decade. Investigations of 304 days duration and 9 years duration, for instance, are both called "long-term" studies (Knauss et al. 1987; Hoffman et al. 1983). However, data from 6-, 11-, and 18-month experiments, rather than multiple years, is more typical of Yucca Mountain investigations (see, respectively, Jacobson et al. 1986; Knauss et al. 1987; Bates and Gerding 1987). 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 (Smith 1988). Even for tests as long as 3.5 years or 3 years duration, respectively, in order to determine the degree and extent of spent-fuel migration or the integrity of the waste canisters (Bates et al. 1989; McCright et al. 1987; see Westerman et al. 1987; Weiss et al. 1985), researchers are forced to

extrapolate and make the value judgment that behavior over 3.5 years will be representative of that over 10,000 or more years.

In the case of the waste canisters, experiments of three years' duration are particularly problematic, because the future temperatures are expected to be as great as 200 degrees C. in the immediate vicinity of the waste (Hadlock, p. 49), causing changes in the surrounding rock (Blacic et al. 1986). Moreover, in some experiments, all of the experimental 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 degrees C. (Pitman et al. 1986), even though the US Department of Energy (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 inductive value judgment that the data support 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. 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 (O'Brien 1977, p. 134). Yet, risk assessors, with far less inductive information, are attempting to predict repository behavior for periods of time that are many orders of magnitude longer. Many of the radioactive

isotopes that will be stored at Yucca Mountain -- such as I-129, Np-237, Cs-135, U-238, Zr-93 -- have half lives that are in the millions of years (see Smith et al. 1982a, pp. 10, 51). During such long time periods of radiotoxicity, changes in climate, groundwater, precipitation, and volcanic activity could occur.

Yucca Mountain risk assessors, for example, need to predict 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 (Project History in US DOE 1990b). Major changes in the climate of Nevada have occurred in the last 45,000 years, and the US Geological Survey claims that future climatic changes probably will occur within the time the waste materials are hazardous (USGS 1985). Precipitation patterns are likewise changing, and assessors must be able to predict them in perpetuity. The precipitation data for Yucca Mountain, however, covers only approximately the last 30 years (French 1986), 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 (see also Braithwaite and Nimick 1984). Hence, to assume that the 30-year precipitation data are adequate represents a methodological value judgment that is somewhat questionable, especially in the light of the fact that both precipitation and its variability appear to have increased at the Nevada test site (French 1987).

Ultimately, value judgments that short-term data provide an adequate basis for inferring extremely long-term behavior rely on an inductive inference, on the assumption that the future will be like the past. For sciences like physics and chemistry, such value judgments about future predictions often are not problematic. They are especially questionable in geology, however, because scientists no longer accept uniformitarianism. Hence, to predict the distant future, geologists would need to employ a questionable version of "reverse uniformitarianism." Moreover, when the time periods at issue are so great, when the predictions must be so precise, and when the consequences of faulty predictions are so grave, inductive value judgments about long-term predictions become more questionable than in other areas of science. Long-term judgments about the suitability of Yucca Mountain for a waste repository are also questionable because of the existence of lakes in the Great Basin of Nevada during the Wisconsin period -- 2 million years ago -- and because moderate changes in climate are sufficient to cause large changes in the hydrological budget of some of the closed basin systems in Nevada (Benson 1980). An evaluation of the Quaternary history of the Yucca Mountain area reveals that it has undergone geomorphic change in the last million years (Mara 1980). 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 (Crowe 1986).

Value judgments about long-term predictability at Yucca Mountain are also questionable in the light of the fact that some

assessors have concluded that the water table at Yucca Mountain could rise 130 meters if precipitation increased by 100 percent (Czarnecki 1988; see also Raleigh 1992). This is a significant and possible increase, since average precipitation levels, for a decade, often vary by two orders of magnitude. (Dunne and Leopold 1978, pp. 52, 54, 70). At Yucca Mountain, water tables stood at 926 meters only 14,000 years ago. High water tables may have been northeast of the Nevada Test Site (NTS) until only 7,000 years ago, and on the NTS 700,000 years ago (Davis 1983). Of course, some assessors claim that the water table at Yucca Mountain was never more than 200 feet above its present position (NNWSI History in US DOE 1985a), and that radwaste will be emplaced more than 650 feet below the surface and more than 600 feet above the water table (MacDougall 1987; Raleigh 1992, p. 1). The water table is currently between 728 and 775 feet above sea level (Robinson 1988). Such numbers appear obviously acceptable (see Raleigh 1992) until one recalls that some radwaste requires essentially "permanent isolation from the biosphere" (Stein and Collyer 1983), and that there is no way to guarantee such permanence.

Making the value judgment that short-term hydrogeological tests provide accurate predictions for long-term behavior is one of the reasons for the underestimation of the potential for offsite radwaste migration at the low-level radioactive facility at Maxey Flats, Kentucky. The geologist who did the original studies at the Kentucky site 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 (Walker 1962, p. 3). On the basis of his analysis, 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 (Papadopoulos and Winograd 1974, pp. 29-30). Just as the longer term studies gave the more accurate results, and just as the longer term studies gave a less optimistic picture of the Maxey Flats radioactive waste site, so also there is reason to question the methodological value judgment that short-term studies at Yucca Mountain provide accurate long-term data.

2.2 Value Judgments about Water in Fractured, Unsaturated Media

Another methodological value judgment central to assessment of Yucca Mountain risks is that despite the discontinuous, nonhomogeneous nature of the fractures in the tuff, it is nevertheless possible to predict, with reasonable accuracy, the probability of radioactive migration through the fractured tuff after the containment of the canisters has been breached. This value judgment -- about a particular interpretation of simplicity and explanatory power -- is especially problematic for the unsaturated zone at Yucca Mountain, because much less is known about it. Also, the tuff itself is quite heterogeneous, with eight orders of magnitude of variation sometimes occurring in the saturated hydraulic conductivities (Peters et al. 1984, p. i). Nevertheless, risk assessors claim to have demonstrated that "methodologies are available for characterizing fracture flow"

through saturated fractures (Evans et al. 1987). They say that such methods are "suitable" for determining fracture flow, or "adequate" and "valid" (Daily and Ramirez 1986; Pruess and Narasimhan 1988; see Majer et al. 1989). Such value judgments are especially questionable in the light of DOE peer reviewers' comments that fracture flow and consequent groundwater transport time are the biggest conceptual issues regarding site suitability (Younker, Andrews, et al. 1992, pp. 214, 2-13). Moreover, even the DOE admits that unsaturated flow in fractured media is uncertain, in part because the dominant processes influencing the flow are uncertain (Younker, Albrecht, et al. 1992, p. 188).

An alternative methodological value judgment, one to which representatives of the state of Nevada appear to subscribe, is that, given the discontinuities and heterogeneities in the fractures, such characterizations are impossible because the flow is likely to be random and unpredictable. Indeed, recognizing that travel time through fractures is faster than through any rock matrix (Klavetter et al. 1989), representatives of the state of Nevada have warned that the great uncertainties regarding flow through heterogenous, fractured material is one of their seven major hydrogeological "concerns" about Yucca Mountain (NWPO 1989, vol. 1; Malone 1989b, p. 1453; 1990b; State of Nevada 1989c, vol. 3, p. 6).

At Yucca Mountain, risk assessors are attempting to model the site and to predict possible releases of radionuclides through the fractures (see Karasaki 1990; Yow 1990; Costin 1990; Tillerson

1989; Zimmerman and Bodvarsson 1990; Lee et al. 1990; Pyrak-Nolte and Cook 1990). Because they have inadequate empirical data (Greenwade and Cederberg 1987), and because behavior of heterogeneous, partially saturated or saturated sites is not at present mathematically tractable, they use models that assume a more homogeneous hydrogeological situation. The models assume, for example, uniformly spaced or parallel fractures (see, for example, Buscheck and Nitao 1988; Erickson et al. 1986; see Cuderman 1981), or use single-flow equations (see, for example, Peters and Klavetter 1988). Often they ignore the fact that drying is more or less rapid along different fractures (see, for example, Ramirez and Daily 1987). Yet, all these heterogeneities could be enough to change the predicted rates of radionuclide migration at Yucca Mountain. Moreover, there do not appear to be any general laws about fracture flow in a heterogeneous environment. And if not, then this methodological value judgment violates the second logical condition for an adequate scientific explanation/prediction in the strict sense (see section 1.2 earlier; Hempel and Oppenheim 1948; Popper 1959).

One of the major difficulties associated with hydrogeologically modeling a heterogeneous site has to do with rate of infiltration. Infiltration of water into the site is largely a function of precipitation which, as we mentioned already, is highly variable. Infiltration, in turn, is highly variable from one spot to another at Yucca Mountain because of differences in the underlying hydrogeology, especially the presence of fractures. In

some Yucca Mountain studies, for example, researchers showed that rainwater on site evaporated and had no influence at depth, yet they cautioned, for example, that five feet of water entered boreholes via fractures at one of their sampling spots (Project History in US DOE 1990b, p. xiii; see Norris et al. 1987). This sort of heterogeneity, with no infiltration at depth anywhere, except for one place where five feet of water accumulated, is exactly the sort of nonuniformity that could play havoc with value judgments about our ability to predict radwaste migration.

Infiltration is particularly important at Yucca Mountain because, although less than three percent of precipitation onsite likely infiltrates deeply enough to recharge the saturated zone, nevertheless concentrations of infiltration in time or space, according to some assessors, could supply enough flux to cause fracture flow on site (Sinnock and Lin 1984, pp. 14-15). Assessors have warned that the rock at Yucca Mountain can act as a sink for infiltrating water, and that "significant winter recharge could occur...due to snow melt" (Linderfelt 1986). Climate change to wetter conditions could also cause more infiltration and enhanced fracture flow (Sinnock and Lin 1984, p. 17). Given the possibility of fracturing because of the heat of the waste (Sinnock and Lin 1984, p. 24), and given the possibility of intense rainfall at a particular location, assessors' claiming that fracture flow is "unlikely" or "not credible" (Sinnock and Lin 1984, pp. 41, 16) is a questionable methodological value judgment. It is questionable, in part, because fracture flow is so sensitive to a relatively

small change in the percolation rate. If the percolation rate increases by only one order of magnitude above conservative values, this might be enough to initiate fracture flow. Fracture flow, in turn, would significantly reduce the travel time of water between the repository and the water table (Peters 1986, p. i; Travis et al. 1984, pp. 4).

A few assessors have warned about the reliability of the models for fractured media (Pruess et al. 1988), cautioning that the hydraulic parameters are "poorly known" and basic issues are "unresolved" (Evans et al. 1987; Rulon et al. 1986; see Rasmussen and Evans 1987; Thompson 1987). Such worries are likely part of the reason why the state of Nevada claimed, responding to the conceptual design of the Site Characterization Plan, that "one of the most disturbing aspects is the lack of attention given to the geohydrologic setting and its performance at the Yucca Mountain site" (Thompson Engineering Company 1988, p. 13). Many researchers, however, appear to believe that the models can be "verified" or are "valid" (Pruess and Narasimhan 1988). (We discuss verification problems later, in section 4.9 of chapter four.)

Another difficulty with methodological value judgments about predictability of fracture flow is that past judgments about flow through fractures, at other radioactive radwaste sites, have been overly optimistic about radioactive containment, and they have resulted in serious error. Indeed the methodological value judgment at the Maxey Flats radwaste facility, that no flow through fractures was likely, was one of the key mistakes that led to

offsite release of radionuclides, including transuranics, less than a decade after the facility was opened (Blanchard et al. 1978, pp. 1, 29; see Shrader-Frechette 1990).

Although the Maxey Flats, Kentucky site is quite different from the proposed Nevada site in both its physical characteristics and the type of waste it is supposed to handle, the sites are similar in that both are plagued by fractures in the underlying rock. The Maxey Flats situation is, however, relevant to that at Yucca Mountain by virtue of the ways that risk assessment has been applied and misapplied at both places.

At Maxey Flats, the radioactive releases occurred within nine years, although they were predicted to occur after centuries, or even after thousands of years (Neel 1976, p. 258; see also Weiss and Columbo 1980, p. 5; Meyer 1975, p. 9). Scientists employed by promoters of the Maxey Flats site presented simple, low-permeability models for the shale on site, and policymakers concluded that the possibility of offsite migration was "essentially nonexistent" (Neel 1976, p. 258; EMCON 1975). The USGS Project Director, however, explicitly said that any simple, quantitative model for the site was impossible because Maxey Flats is a poorly permeable, fractured, geological system. Any prediction of flow paths would be impossible, he said, because of the highly irregular hairline fractures and the fracture intensities (Zehner 1981, pp. 35, 40; Werner 1980, p. 45; see Wilson and Lyons 1991; Shrader-Frechette 1988, 1989a, 1990).

Because prediction of fracture flow at Maxey Flats would

require detailed information about the spatial distribution and hydraulic properties of each of many hairline fractures in a variety of successive strata (e.g., Nancy Shale, Henley Shale, Ohio Shale, and so on), the US Geological Survey (USGS) Project Director concluded that groundwater flow at Maxey Flats could not be predicted (Zehner 1981, p. 3). Any model, he said, would presuppose conditions for its accuracy that were not met at Maxey Flats, conditions such as "uniform transmission of water through the rocks" (Zehner 1981, p. 132). In sum, although his warnings were ignored by state promoters of the site, he concluded that "hydraulic conditions do not meet the requirements for the method of analysis" (Zehner 1981, p. 134). His argument, years earlier, about the Maxey Flats site, is quite similar to current claims, by Yucca Mountain assessment reviewers, that the untested Yucca Mountain models are not appropriate for the complex site hydrogeology (State of Nevada 1989c, vol. 2, p. 2). In both cases risk assessors were/are using untested models that may not account adequately for fracture flow.

Because of the irregularly fractured tuff, the heterogeneity of the hydrogeological site, and the incomplete information about the long term future, it is questionable whether the hydraulic and geological conditions at Yucca Mountain meet the requirements of the methods used there. At Maxey Flats, scientists concluded that their predictions went wrong because site conditions did not meet the idealized methods of analysis that presuppose uniformities. The same could be true at Yucca Mountain. If the site conditions, like

the fractured tuff, do not meet the conditions for analysis, then it could be quite dangerous to make the value judgment that one can accurately predict radwaste migration in the heterogeneous, fractured media at Yucca Mountain. This value judgment could represent one of the most serious deficiencies in some QRA's of Yucca Mountain.

2.3 Value Judgments about Model Reliability

A more basic methodological value judgment is not only that one can predict fracture flow, but that one can model a geologically heterogeneous site with "highly nonlinear" flow characteristics (Bixler 1986), and that such models provide adequate knowledge upon which to base future predictions about radwaste migration. Such judgments about the adequacy of modeling are questionable, because the models cannot be validated in the field over the long term. Hence, they appear to violate the third logical condition for an adequate scientific explanation in the strict sense: the empirical content of the explanatory premises is capable of being tested (see section 1.2 earlier; see also Hempel and Oppenheim 1948; Popper 1959). Also, if empirical data were available, one would not need to employ models in the first place. Assessors use models simply because they have inadequate data and theories to use in characterizing the site over the long term (Ramspott 1988). They do not know how the hydrology, geology, waste packages, and so on, will perform over centuries, for example, and so they use simulations of the situation -- Monte Carlo simulations, for example (Cooper 1990). Their 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 (Sastre et al. 1986, pp. 22-24). Probabilities related to nuclear accidents, however, are notoriously inaccurate. For example, all of the probability values obtained from operating experience in US nuclear reactors fell outside the 90 percent confidence band of calculated expert probabilities in the best nuclear risk assessment ever performed (WASH 1400), and probability estimates associated with various events typically varied by four orders of magnitude (see section 4.10 of chapter four and Cooke 1991, chapter 9). Hence, the use of nuclear-accident simulations does not necessarily provide a justification for the value judgment that Yucca Mountain modeling is reliable. Indeed, the state of Nevada criticized the US Department of Energy (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 (NWPO 1989, vol. 2). The state also warned that the uncertainty in the models of possible radionuclide transport were one of seven major "concerns" about the reliability of Yucca Mountain studies (NWPO 1989, vol. 1).

Much of the problem with model uncertainty at Yucca Mountain 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, for example, use highly idealized continuum models (such as porous media models) -- models

that assume that the rock is solid and unfractured -- rather than discontinuum models formulated to account for the effects of discrete fractures (Board 1989; Brikowski 1988; Cooper 1990; see GeoTrans 1986, p. 9). They do so because the continuum models are simpler and more efficient to use, and because they have no superior alternatives (Board 1989, p. 66). Assessors also use the continuum models because they claim that matrix flow predominates over fracture flow at Yucca Mountain. As we argued earlier in section 2.2 (see also Lemons and Brown 1990, p. 7), however, this assumption is questionable. Hence, there are a variety of reasons for believing that the idealized hydrogeological models at Yucca Mountain may not be accurate (Brikowski et al. 1988, p. 75). Indeed, external reviewers have argued forcefully that, in general, the quality control on the Yucca Mountain modeling is poor (GeoTrans 1986, p. 1).

Another example of idealized, therefore value-laden and questionable, methodological judgments are those that assume that 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 on site rely ultimately on variants of Darcy's Law (see, for example, Sinnock and Lin 1984, p. 8; Sinnock et al. 1986, p. 8; Jacobson 1984, p. 5; Thompson et al. 1984, p. iii; Hayden 1985, p. 3-1; Dudley 1988, pp. 36-44; Smith et al. 1982a, p. 39; Lin 1985, p. i; see GeoTrans 1986, pp. 13, 17). According to this law, groundwater flow velocity is proportional to the hydraulic gradient. This law, however, is an empirical, causal,

and mathematical idealization (see Shrader-Frechette 1988, 1989a). 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 generalizations in which Darcy's Law is employed. Its use at Yucca Mountain is particularly problematic, in part because the law is not suitable for conditions of fracture flow (see State of Nevada 1989c, vol. 3, p. 6).

Of course, hydrogeologists might argue that, in most situations, the idealizations and value 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 allegedly small errors might be quite great, particularly in a situation of fracture flow. After all, in dealing with a case (like Yucca Mountain) requiring long-term hydrogeological prediction, very slow migration time, and adequate information in the present, 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 (see Cartwright 1983, p. 111 and Shrader-Frechette 1988, 1989a).

Milton Friedman claimed that idealizations were a problem in science only to the degree that the predictions resulting from them could not be checked. Since the Yucca Mountain predictions cannot be checked, over the long term, it is clear that they remain part of a classical scientific problem (see Friedman 1984).

The value judgments about the adequacy of modeling are also questionable because the specifications to which the models must conform are quite 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 10^5 per year for radionuclides present in defined quantities 100 years after permanent closure (see Berusch and Gause 1987).

Given such precise requirements for the Yucca Mountain repository, it could be questionable whether it is reasonable to make the value judgment that a simulation, a model, of the site will provide information that is firm enough to meet such requirements. The more stringent the site specifications, the more accurate must be the information used to meet the specifications. The value judgment about the accuracy of modeling is questionable because of the length of the prediction, the specificity of the requirements, and the fact that the simulation or model cannot be checked. Despite these problems with value judgments associated with the adequacy and accuracy of modeling, however, a number of

risk assessors are basing their Yucca Mountain conclusions on a variety of sophisticated models (see, for example, Zyvoloski 1990; Karasaki 1990; Wolery et al. 1988; Richardson 1990; Koteras 1990; Costin 1990; Glass 1990). Nevertheless, the value judgment about modeling appears to have the potential to cause serious errors in QRA conclusions about Yucca Mountain.

2.4 Value Judgments about Simplification of the Phenomena

Because the real hydrogeological system at Yucca Mountain is quite complex, the risk assessors must make a further methodological value judgment that the simplifications of their models do not seriously misrepresent the situation that they are attempting to understand and to predict. Indeed, simplifications of the phenomena are necessary in order to formulate analytic solutions to problems of hydraulic conductivity, infiltration, and so on. 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 (see Shrader-Frechette 1990). In order to render the real hydrogeological system at Yucca Mountain mathematically and scientifically tractable, risk assessors must make certain methodological value judgments about simplifying the situation (see, for example, Dudley et al. 1988), simplifications such as that all radionuclides have identical transport retardation factors, or that all radionuclide releases are instantaneous (Gelbard 1989; see also, for example, Sagar and Runchal 1990).

Other common Yucca Mountain simplifications of assessors are

that water flow will be one-dimensional (Cooper 1990; Dudley et al. 1988, p. 1; Jacobson 1984, p. 12; Travis et al. 1984, p. 3; Peters 1986, p. i; Sastre et al. 1986, p. 24; Lin 1985, p. 1; Sinnock et al. 1986, p. 66); that percolation will be downward only through the unsaturated zone, but horizontal through the saturated zone (Sinnock et al. 1986, pp. 5, 13); that temperature and moisture are constant (Mondy et al. 1983, p. 6); or that there is a normal distribution of cumulative releases of radionuclides to the water table (Sinnock et al. 1986, p. 80). All of these value judgments about simplification of the Yucca Mountain situation are potentially counterfactual, and they have been criticized by external reviewers of the Yucca Mountain assessments (GeoTrans 1986, esp. pp. 11, 13; Thompson Engineering Company 1988, esp. pp. 1-15). Because these value judgments simplify the phenomena, it appears that they violate the fourth condition for the adequacy of a scientific explanation/prediction in the strict sense: that the explanatory premises state propositions that are true (see section 1.2; see also Hempel and Oppenheim 1948; Popper 1959). Moreover, given the inadequacy of the data and the heterogeneity of the Yucca Mountain site, it is not clear that the explanatory premises of this argument have a high probability of being true.

Schedule constraints are partially responsible for a number of simplifications in the Yucca Mountain studies (Nelson et al. 1989). Such simplifications obviously are not completely accurate representations of the real world, but many Yucca Mountain assessors make the methodological value judgment that they are

accurate enough to describe the phenomena. This value judgment is problematic, of course, to the degree that the simplifications are likely to underemphasize the likelihood of radwaste migration. Three examples of the underestimating effect of simplifications will suffice. 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 (Smith et al. 1982a, p. 183). Likewise, oversimplifying the physical processes in the unsaturated zone and the 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 hazard to the public, 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 (Reichard et al. 1990, p. 180).

A third example of simplification that underestimates risk has to do with synergism. Assessors, including those at Yucca Mountain, 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 (Sinnock et al. 1986, p. 79). Yet, obviously the combined effects of at least some of these factors could enhance the velocity of waste or water transport. As a consequence of methodological value judgments about the

acceptability of simplifications of the phenomena, evaluators have argued that oversimplifications in the characterization of the site hydrogeology have compromised the scientific integrity of the site characterization plan (Thompson Engineering Company 1988).

The value judgment that Yucca Mountain 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 two. More generally, as Friedman (1972) has pointed out, using simplicity to choose from 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 could lead to accepting theories that are weaker or less acceptable than others, in terms of explanatory power (Goodman 1961; Shrader-Frechette 1990).

In a highly applied situation, like Yucca Mountain, choosing a theory on the basis of simplicity, even though the empirical data are highly underdetermined, could lead to dangerous consequences.

In such a situation, it might be better to admit that there is no adequate theory. Such an admission would have the virtue of preventing simplified, perhaps false, theories to be used as a basis for public policy. 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.

Because of the way that oversimplified models and theories have been used at Yucca Mountain, it brings 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. This is not to argue that Yucca Mountain and Maxey Flats have similar or comparable hydrogeology, only that the process of simplification used at Maxey Flats resulted in miscalculating important risk components, which in turn led to problematic policy decisions. 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 (Wilson and Lyons 1991, p. 20), horizontal movement that was ruled out, on the basis of a methodological value judgment.

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 (EMCON 1975). 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 and fractures, and hairline cracks between bedding planes, not merely the low permeability of the shale, had to be taken into account (Polluck and Zehner 1981; Werner 1980). 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, policymakers chose the theory with more simplicity, the low permeability theory of the industry and academic geologists. Their choice has proved dangerously wrong, however, as we noted earlier, because plutonium travelled offsite only several years after the facility was opened (Meyer 1975, p. 9). It became known as "the world's worst nuclear dump" (see Naedele 1979, pp. 1-3; Browning 1976, p. 43). The moral of the Maxey Flats story, for Yucca Mountain, is that the greater the empirical underdetermination of theories and models, the more

dangerous it is to evaluate them and formulate them in terms of the criterion of simplicity. Similar problems with value judgments about simplification might lead to dangerous consequences at Yucca Mountain.

2.5 Value Judgments about the Reliability of Sampling

One of the methodological value judgments that is most crucial to the simplifications necessary to model the Yucca Mountain site is that sampling -- via boreholes, wells, groundwater, or volcanic tuff cores -- provides an adequate empirical base for predicting hydrogeological behavior at the site. Risk assessors subjected cores of tuff, for example, to a variety of stresses in order to infer, inductively, how the tuff might behave as a high-level waste repository (Voss and Shotwell 1990; see also Peters et al. 1984). They also took samples of special glass and irradiated it for given periods in order to determine the leach rates of various radioactive elements (Abrajano et al. 1988). Likewise they subjected samples of spent fuel to tests, for thousands of hours, to determine the rate of oxidation (Einziger and Buchanan 1988). In addition, they examined samples from 2 deep boreholes in order to draw conclusions about the nature of the aquifer (Tyler 1985; see Candy and Mao 1981).

In all their sampling activities, Yucca Mountain researchers have typically made the value 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 (see, respectively, Chuang et al. 1990; Lin and Daily 1989; Connolly and Nimick 1990; Nimick 1990). However, the epistemological difficulty with relying on sampling in order to understand the hydrogeology of the Yucca Mountain 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. It is well known that the host tuffs at Yucca Mountain are "highly variable" (Broxton 1987; see Linderfelt 1986). Different tuff samples react differently to the same environmental constraints, and 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 example, 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" (Chipera and Bish 1988).

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 partially a function of time, temperature, and particle size, among other characteristics (Knight and Thomas 1987; Thomas 1987; Beckman et al. 1988). They also found that sorption values for various types of tuff differ, for example, by at least four

orders of magnitude (US NRC 1980, p. B-60). 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 (Fuentes et al. 1987). Moreover, assessors are not able to check the accuracy or the representativeness of the samples used in adsorption studies, because much of the data and theory underlying sorptive barriers are incomplete, unknown, or undeveloped (Morgenstein 1984; Bechman et al. 1988; Chipera and Bish 1989; see also Finnegan 1987; Campbell 1988). In part because value judgments about adsorption appear to have contributed to an underestimation of radionuclide transport at Maxey Flats radwaste site and to a false belief that plutonium would not migrate rapidly (see Shrader-Frechette 1989c), there is reason to be cautious about the conclusions drawn regarding radionuclide adsorption at Yucca Mountain.

Other Yucca Mountain samples failed to be representative in the sense that the researchers modified the conditions under which they ran experiments on them. For example, in some cases, hydrogeologists used crushed rock samples (not merely columns) to determine adsorptive values (see, for example, Meijer et al. 1989; Thompson 1988, 1989; Daniels 1982; Duffy and Al-Hassan 1987; Rundberg et al. 1989), even though migration of radionuclides at Yucca Mountain, once containment has been breached, obviously will not be in crushed rock but in fractured, intact rock that is less likely to adsorb radioactive materials (and retard migration) than

is crushed rock (see US Congress 1987a, p. 204).

Despite all the disanalogies and uncertainties in the sampling, many researchers remain confident that the adsorption values and radionuclide transport values "are being confirmed" (Kelmers et al. 1983). Obviously, however, 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, and hence 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 change assessment conclusions about radwaste migration. Hence, it is conceivable that for different samples under different conditions, for example, plutonium might not be adsorbed or captured as assessors predict (Project History in US DOE 1990b). And if sampling interferes with such predictions, then it is not clear that general conclusions about site characteristics can be drawn from premises about particular samples. And if not, then the first logical condition for an empirically adequate scientific explanation/prediction in the strict sense may not be met: the conclusions are not logical consequences of the premises (see section 1.3; Hempel and Oppenheim 1948; Popper 1959). Even in a probabilistic or inductive sense, QRA value judgments about sampling are questionable given the limited data for Yucca Mountain and the site heterogeneity. Hence, the value judgments about the types and numbers of sampling that are done are absolutely crucial

to the conclusions about site suitability.

Likewise, when researchers studied infiltration of precipitation at two Yucca Mountain sites, for example, they found hydrological activity at one location but not at the other (Norris et al. 1987). Such results suggest that value judgments about interpolating or extrapolating about missing sample points, on the basis of existing ones, could lead to invalid or misleading conclusions, even if one employed geostatistics. Indeed, external reviewers of the Yucca Mountain assessments have warned that many technical assumptions about the site are not supported by field conditions and may be inappropriate to the Yucca Mountain system (GeoTrans 1986, p. 1). Nevertheless, in hydrogeological situations, one must always make methodological value judgments both about the quantity and the representativeness of the sample data. Without some articulation of the limits associated with such value judgments, however, the idealizations, extrapolations, interpolations, and simplifications could lead to invalid conclusions, just as they did at Maxey Flats and at other nuclear waste facilities.

In risk assessments of the Maxey Flats site, sampling problems similar to those at Yucca Mountain apparently contributed to the lack of knowledge about the site's potential for radwaste migration. When industry geologists drilled wells on the Maxey Flats site, 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 (Zehner 1981, p. 110). Because difficulties associated with sampling, its representativeness, and its quantity can cause contradictory empirical results, there is reason to question the methodological value judgment that Yucca Mountain sampling has already provided a reliable source of information about the site. Admittedly, however, virtually all areas of science employ methodological value judgments about sampling. Much science would be impossible without sampling. Hence, 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 sampling involved questionable methodological value 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 the Yucca Mountain case, for questioning some of the optimistic judgments about site suitability, given that they are based on limited sampling.

2.6 Value Judgments about Laboratory Prediction of Field Behavior

In assuming that sampling has provided an accurate picture of Yucca Mountain hydrogeology, risk assessors have also made the additional methodological value judgment that laboratory analyses of samples provide an adequate basis for conclusions about field behavior (Fuentes et al. 1988; see Triay 1989; Rundberg et al. 1989; Voegele 1985; Oversby and McCright 1985). Rather than doing

a sufficient number of experiments in the field, for example, hydrologists and geologists at Yucca Mountain do laboratory experiments on cores of tuff taken from the field (see, for example, Weeks and Wilson 1984). Using laboratory data about site geochemistry, about behavior of crushed (not solid) tuff, about sorption, and about retardation of radionuclide transport, for example, assessors extrapolate to draw conclusions about all these factors on site (see State of Nevada 1988a, vol. 1, pp. I-9, I-10, II-2, II-3). Because the assessors' premisses concern laboratory (and only limited site) data, whereas their conclusions are about the site, their methodological value judgment apparently causes them to violate the first logical condition for an adequate scientific explanation in the strict sense: that the conclusion follow deductively from the premises (see section 1.2 earlier; Hempel and Oppenheim 1948; Popper 1959). Even as a probabilistic account, it is not clear that good reasons support the inference from laboratory to field behavior.

One of the things assessors wish to determine in their laboratory studies is whether "fracture healing" (in which fractured rock samples become sealed when water flows through them at elevated temperatures) can prevent leakage of radionuclides (Project History in US DOE 1990b). Obviously there are many disanalogies between laboratory and field behavior of a core of tuff, any one of which could account for erroneous estimates of future radionuclide transport at Yucca Mountain. Admittedly, some assessors have been sensitive to these disanalogies and have

emphasized the importance of field studies to check models and samples (see, for example, Heuze 1982). Nevertheless, the very use of samples itself, samples investigated in a laboratory setting, requires one to make untested methodological value judgments about the degree of fit between the laboratory conclusions and those of the field. Like value judgments about sampling, judgments about the accuracy of using laboratory data to describe field conditions occur in many areas of science. The problem is not with the value judgment that one can use data in this way, but with some Yucca Mountain studies that have failed to test this value judgment as completely as possible by experiments in the field. In other words, the problem is not with laboratory data and associated value judgments, but with their application at Yucca Mountain. This application appears lacking in scientific conservatism and field confirmation.

2.7 Value Judgments That Interpolations Are Acceptable

Still another major methodological value judgment in many of the Yucca Mountain studies is that accurate interpolation of sparse and irregularly spaced data is possible. A number of assessors make this assumption (see Williams 1988 and Campbell 1986, for example), even though the data are not uniform, even though infiltration, for example, occurs at some locations but not at others (Norris et al. 1987), and even though low groundwater flow rates are guaranteed only for unsaturated conditions where infiltration has not compromised the repository site (Glassley 1989; see Aines 1986). Heterogeneities in the hydrology and geology onsite indicate that

curve-fitting techniques could fail to provide an accurate picture of hydrogeology at Yucca Mountain. This may be why, for example, the state of Nevada listed uncertainties regarding infiltration and groundwater travel time as among its seven major "concerns" regarding site hydrogeology (NWPO 1989, vol. 1). Of course, the problem here is not with value judgments about interpolation, since many scientists must make them. The problem is that the use of value judgments about interpolation at Yucca Mountain appears insufficiently careful and conservative.

2.8 Value Judgments That Human Error Is Not Significant

Another problematic methodological value judgment that is implicit in a number of Yucca Mountain risk assessments is the presupposition that human error is not a significant contributor to risk at the site. In one of the official DOE documents, this value judgment is made quite clear: "Because of the plans to mark the site and to use other passive means to prevent human intrusion into the repository, and because of the intention to ensure that the site will have little value in unique resources, large-scale human activities that would inadvertently affect the repository are not likely to take place at the site. Accordingly, the only scenarios currently considered for this case are those involving occasional random, exploratory drilling at the site" (US DOE 1990a, p. 3-18). Such omissions in the DOE methodology appear especially questionable in the light of consensus statements, by the DOE peer reviewers, that credible projections are possible only 5 or 10 years into the future, and that "natural resource occurrence" (and

subsequent mining in the future) are fraught with "substantial uncertainties" (Younker, Albrecht, et al. 1992, p. B-2).

As the policy position of the DOE makes clear, the DOE discounts not only large-scale human error and inadvertent activities causing intrusion into Yucca Mountain, but also organized sabotage and terrorism. Indeed most of the DOE research on Yucca Mountain, as revealed in its own Program Assessment, is on physical-science topics related to the risk. There is almost nothing on the socioeconomic risk or on human aspects of risk, such as transportation (US DOE 1990a). All of these value judgments may be highly questionable, as we shall argue shortly.

Typical Yucca Mountain risk assessments also make the same controversial methodological value judgment that human error at Yucca Mountain will be insignificant. For example, assessors assume that risk managers will have to deal only with radioactive "releases that would be expected from the repository under undisturbed conditions," that is, conditions where human accident, error, or sabotage does not disturb the site (Thompson et al. 1984, p. i). After explicitly ignoring human error and accident and other disruptive features, the same assessors conclude that "even for the highest credible flux...releases of radioactivity to the accessible environment in 10,000 years after closure are significantly less than the limits imposed in the draft standards (40 CFR 191) for environmental radiation protection" (Thompson et al. 1984, p.i). After ignoring such human disruptions of the site, risk assessors typically conclude that Yucca Mountain will meet government

environmental requirements; indeed, they typically put a quite precise figure on the risk involved. For example, they say that the site will cause "less than one health effect every 1,400 years" (Thompson et al. 1984, pp. vi-vi). Such confident and optimistic predictions seem questionable in the face of assessors' tendency to ignore an important class of risk factors, namely, human causes of repository failures.

Because the vast majority of the DOE-funded Yucca Mountain studies deal with purely physical, non-human processes, it appears that DOE policymakers and assessors presuppose either that human error is unimportant at Yucca Mountain, or that poorly understood risks (like human error) can be ignored in favor of what is better understood (physical transport mechanisms for radwaste). Either value judgment about Yucca Mountain is inconsistent with previous inductive evidence about estimates of human error at other facilities as well as evidence about likely human error at Yucca Mountain. For example, several risk assessors calculated the probability of human disruption onsite after the first century. They said that the probability of disruption through drilling at Yucca Mountain could be as high as 5×10^{-2} to 2×10^{-3} per year (Smith et al. 1982a, p. 222). If the estimates of some assessors about the probability of human disruption at Yucca mountain are so high, it is questionable how assessors can simply ignore this human factor, and then conclude that the risk at Yucca Mountain is quite low. Given that there is an active gold mine within 15 miles of Yucca Mountain, and several inactive mines within 10 miles (US

Congress 1987a, p. 195), it does seem reasonable to believe that future drilling might occur nearby.

Moreover, the methodological value judgment that one can ignore the human-caused risks at Yucca Mountain is all the more questionable, given the fact that human behavior far into the future is not predictable (Goble et al. 1988, p. 40). If it is not predictable, it is unclear how Yucca Mountain conclusions can meet the first logical requirement for an adequate scientific explanation/prediction in the strict sense, that the conclusion be a logical consequence of certain premises (see section 1.2 earlier; Hempel and Oppenheim 1948; Popper 1959). Moreover, even in a probabilistic sense, it is not clear that good reasons support this value judgment. After all, the human contribution of technological accidents could be as high as 90 percent in the case of the airlines and the chemical industry (Emel et al. 1987, p. 44; Golding and White 1990, p. 5). The US Office of Technology Assessment has said that more than 60 percent of accidents involving hazardous materials are the result of human error (Golding and White 1990, pp. 5-8; see also Tuler et al. 1988, p. 91). Indeed, some reviewers of the Yucca Mountain assessments have explicitly criticized the DOE failure to give sufficient attention to human error at Yucca Mountain (Emel et al. 1987, pp. 108, 110; Emel et al. 1988a, p. 9; Golding and White 1990, pp. 2, 28; Burns et al. 1990, p. ii; Tuler et al. 1988; see Petterson 1988; Peters and Hennen 1988).

Human error or misjudgment is one of the major contributors to

risk in the cases where government radioactive waste facilities have caused large-scale contamination and threats to welfare. At the Maxey Flats site, for example, the facility was closed, only a decade after it was opened in 1962. Offsite migration of radionuclides caused the closure, and the site received much government attention and adverse publicity. Yet, more than 15 years after its well documented problems of poor containment, the government has failed to oversee and clean up the site effectively. Indeed, social and human factors compounded the problem, even after it was brought to public attention. As late as 1987, wells to monitor contamination on site revealed that tritium levels in the Maxey Flats groundwater exceeded the Environmental Protection Agency limit by 6 orders of magnitude (Lyverse 1987, pp. 15-16). The Maxey Flats situation suggests that not only do humans cause a significant amount of the risk from radioactive waste management but that, even once failures are brought to light, humans often amplify, rather than correct, the risk.

The question raised by the Maxey Flats case is why one should believe that humans at Yucca Mountain will not contribute through error or mismanagement to the radwaste risk, given that they have done so at Maxey Flats, at Fernald (Ohio), at Hanford, at Savannah River, at Oak Ridge, at Rocky Flats, at Idaho Falls, and at Lawrence Livermore. Indeed, many corrections for safety and environmental problems were not made adequately at these places, and the risk was exacerbated in large part because the government did not wish to bear the cost (US Congress 1989b, p. 28). The DOE

has admitted that it caused soil and water contamination at all these places, that it violated its own regulations, failed to tell employees when they were working with plutonium, and used retaliation against workers who were whistleblowers (US Congress 1987b, pp. 2ff., 9ff.).

The US General Accounting Office (US GAO) pointed out, for example, that Savannah River, Rocky Flats, Hanford, Idaho Falls, Maxey Flats, West Valley, all have extensive onsite contamination. Presumably the existence and continuation of contamination at these major DOE facilities indicates that no hazardous facility is free from problems caused by human error (US Congress 1989b, p. 36). Indeed, the US GAO said that contamination at DOE facilities is so extreme that the government knows neither the extent of it nor what is needed to clean it up; government experts also testified that the complacency at the DOE is similar to that existing at Chernobyl before the accident (Fultz in US Congress 1989b, pp. 36, 41-45; Emel et al. 1988a, pp. 68-74).

At the nuclear feed materials plant at Fernald, Ohio, for example, the company (under DOE supervision and instruction) repeatedly ignored environmental regulations, contaminated the site, and illegally stored radioactive materials. In this DOE plant, workers even processed plutonium for 22 years without wearing respirators (US Congress 1987b, pp. 143-146), and the DOE gave the plant repeated permission to break its own regulations and to make regular discharges of uranium in nearby rivers, permission that was given from the very beginning of the operation of the

plant (US Congress 1989b, pp. 52, 27-28). In-house recommendations for correcting safety problems and reducing risks were ignored, even when workers died (US Congress 1989b, p. 54). At the Fernald facility, the DOE made "no attempt" to monitor releases or to "take corrective measures" once problems had occurred (US Congress 1989b, p. 67). Indeed, the DOE even shipped 2500 tons of thorium sludge in corroding steel containers to Fernald, to be stored there, even though Fernald had no use for the waste (US Congress 1989b, p. 134).

At the Maxey Flats facility, the government-supervised company (Nuclear Engineering Company, NECO, later called "US Ecology") illegally dumped radioactive materials offsite and refused to admit investigators to the site, once offsite radioactivity had become a problem (Shrader-Frechette, 1988, p. 127). For the government even to allow Maxey Flats to dump 950 pounds of special nuclear materials (plutonium, uranium-233, and enriched uranium 235), in an area with average annual rainfall of 48 inches, in shallow soil trenches 25 feet deep (Carey et al. 1990, p. 1) suggests human error or ignorance. Moreover, given DOE's previous problems with violating environmental regulations and with secrecy, as illustrated by problems such as those at the Fernald facility, it is clear that assessors need to pay more attention to the problem of human error at Yucca Mountain. Discounting human error at Yucca Mountain is extremely problematic because external reviewers have already criticized the DOE for its lack of coordination at the Yucca Mountain site (GeoTrans 1986, p. 1), for its ignoring the

social contributors to risk (see, for example, Malone 1990a, p. 171), and for allegedly using Yucca Mountain as a justification for its own self- and pre-determined policies (Lemons, Malone, and Piasecki 1988, p. 31; Winsor and Malone 1990, pp. 197, 205; Golding and White 1990).

Representatives from the Hanford Nuclear facility and from Yakima nation, near Hanford, likewise have criticized "DOE's reckless environmental and safety practices at Hanford" (US Congress 1987a, p. 271). Texans have testified before Congressional committees that DOE's handling of the proposed radwaste site in their state caused them to have "no confidence" in the DOE's technical ability and responsiveness to legitimate public concerns (US Congress 1986, p. 325; US Congress 1987a, p. 245). Residents of Mississippi accused the DOE of not sharing data about their state's possible radwaste site with them (US Congress 1986, p. 625), and numerous state geologists have accused the DOE of technical deficiencies caused by its own political agenda (US Congress 1986, p. 736). Nevadans have charged DOE with secrecy in the face of Yucca Mountain studies, with not consulting with them, and with failure to fund Nevada requests for research about the site (US Congress 1987a, pp. 216, 70ff.). Indeed, Nevada had to sue the DOE to get funding for independent technical studies of the Yucca Mountain site (US Congress 1987a, p. 726). As a result, the GAO concluded that the DOE has not allowed the states and Indian tribes to participate in the high-level waste siting program to the extent intended by the Nuclear Waste Policy Act of 1982 (US Congress

1987a, p. 923). All these problems suggest not only that human error is likely to occur at Yucca Mountain, contrary to what many government risk assessors claim, but also that the error may arise in part through the bias, mismanagement, and lack of concern of the very government agencies that ought to be protecting the public interest.

One common denominator among many of the problems of human error may be the institutional shortcomings of agencies such as the DOE. To the degree that the difficulties are institutional, then the human-error and risk-amplification problem may be even greater than we have suggested so far. Hence, making the methodological value judgment that human error will not be a significant contributor to the Yucca Mountain risk seems highly questionable. The value judgment seems capable of compromising QRA conclusions about repository safety.

2.9 Judgments That Risk Assessment Is Adequate for Regulation

Given all the value judgments made in Yucca Mountain risk assessments, as well as the knowledge that similar judgments (and the processes by which those judgments were made) appear to have contributed to problems at other radioactive waste facilities, like Maxey Flats, Fernald, Savannah River, Hanford, Idaho Falls, and Rocky Flats, an obvious question is whether the Yucca Mountain site itself is "knowable" to the degree necessary to guarantee long-term isolation of radionuclides and compliance with government regulations. Do the available data and site characteristics lead one to believe that QRA of Yucca Mountain can be done with

sensitivity and precision adequate to insure credible regulation and long-term safety? As we mentioned earlier (section 2.1), one of the main problems with the science and QRA at Yucca mountain is that regulations for siting a repository require accurate predictions, whereas the science of geology can give us mainly explanations, not predictions (K. V. Hodges in Younker, Albrecht, et al. 1992, p. 362).

Many risk assessors believe that the data and the site are adequate to insure excellent regulation and safety. They say that Yucca Mountain would comply with the regulations (Sinnock et al. 1986, p. i). This value judgment, however, is quite controversial if one considers all the ways in which incomplete data, inadequate theory, uncertainty, and site heterogeneity threaten accurate knowledge of Yucca Mountain. Because of all the questionable assumptions and value judgments, including incompleteness in the Yucca Mountain assessments, perhaps one of the most significant value judgments of assessors is that their information is adequate for regulation and for decisions about the site -- or that it will be adequate even after the site characterization work proposed by DOE.

One of the main reasons why the value judgment -- that site knowledge is adequate for regulation and for safety -- is questionable is that the numbers of the DOE may be too close for comfort, given the numerous questionable assumptions and value judgments used by assessors (see Hamilton et al. 1986, p. 9-12). Changes of only one order of magnitude in some of the critical

parameters dealing with fracture flow, infiltration, precipitation, or volcanic and seismic activity could initiate disastrous changes in the Yucca Mountain repository. For example, increasing the alleged percolation rate by only one order of magnitude could initiate fracture flow and speed groundwater travel time (Peters et al. 1985). Such sensitive numbers, together with the two to six orders of uncertainty characterizing risk assessments of phenomena like those at Yucca Mountain (see chapter one), suggest that the margin for error at Yucca Mountain may be too slim to insure adequate government regulation and safety. In other words, adequate scientific explanation/prediction, in the strict sense, requires that the explanatory premises state true propositions (see section 1.2 earlier; Hempel and Oppenheim 1948; Popper 1959). Yet, because of all the uncertainties in the Yucca Mountain data, it is not clear that the premises are true or even probable.

As we already mentioned in the second section of this chapter, fracture flow, for example, could enhance transport of water and radioactive leachate, above the flux at Yucca Mountain, by as much as 5 orders of magnitude (Dudley et al. 1988, p. 92), and porous flow alone would mean leachate could reach the water table in 10,000 to 20,000 years (Travis et al. 1984, pp. 3-4). Since assessors have confirmed that "fractures do exist of sufficient width to allow significant water flow in the unsaturated region" (Travis et al. 1984, p. 16), and that with a large fracture flow rate, ^{99}C , ^{238}U , and ^{237}Np could get through to the water table in less than 10,000 years (Travis et al. 1984, p. 25; Sinnock et al.

1986, p. i), knowledge of fracture flow is a crucial determinant of site safety. Yet, knowledge of fractured zones, particularly for unsaturated regions, is very limited, and the seismicity at Yucca Mountain, prior to 1960, is virtually unknown even though seismic failure is possible (Science Applications International Corporation 1985; Emel et al. 1988b, pp. 23-32). Indeed, one wonders how a fractured site, even in an arid climate like Yucca Mountain, could be acceptable if the absence of water could not be guaranteed for the life of the repository (O'Brien 1977, p. 68). At Yucca Mountain, there is no such guarantee.

A person who makes the value judgment that site knowledge is sufficient for regulation and for safety is in the questionable position of knowing significant problems could occur with fracture flow, seismicity, and volcanism, yet not being able to predict any of them accurately -- because of all the problems with modeling, sampling, extrapolation, and so on, already discussed. Even the Nuclear Regulatory Commission (NRC) recognized some of these problems when it commented that the Yucca Mountain risk assessments fail to recognize adequately the uncertainty in the data (NRC Staff Comments in US Congress 1987a, p. 204). Indeed, the NRC said that the environmental assessments of the DOE for its proposed radwaste facilities are, in general, "overly optimistic" (Rusche in US Congress 1987a, p. 917). For example, at Yucca Mountain, "in most cases, hydraulic data are insufficient for performing geostatistical analyses" (Sinnock et al. 1986, p. 58), and "traditional flow path chemical evaluation does not directly apply

to tuffaceous volcanic environments" (Raker and Jacobson 1987, p. 72).

Likewise, there is "no known mechanical model that describes nonuniform corrosion well enough to use in performance assessment" of the waste canisters (Stephens et al. 1986, pp. xvi, 8-2). In areas of hydrology, geology, canister security, climate, volcanism, and seismicity, no techniques exist, at the present time, for removing the uncertainties at Yucca Mountain or even for quantifying them (Malone 1990b, p. 381; Brown and Lemons 1991, p. 319). Basic questions concerning the reliability of the studies remain unanswered (Lemons and Brown 1990, p. 10). Indeed, how could significant uncertainties be removed if one required precise predictive power and regulatory guarantees regarding the site for 10,000 years?

The long time period of storage is one reason that other reviewers have claimed that "compliance with US [radiation dose] limits cannot be shown objectively by PRA [probabilistic risk assessment] methods" (Emel et al. 1990, p. 5). One reason for this problem is that the precise, probabilistic standards of the Environmental Protection Agency (EPA) for the management of spent fuel and high-level and transuranic radioactive wastes cannot be confirmed with current data. The standards set limits for releases when events have more than a 1 in 10 chance of occurring over the 10,000 years (Hunter and Mann 1989, p. 1). Such precise probabilistic standards cannot be guaranteed for so long a time, however. As one reviewer put it: "no assurance can be given that

all significant factors have been examined here" (Hunter and Mann 1989, p. 2). Other reviewers maintained that it is doubtful whether we can model or predict information about the site at all, given the heterogeneities and uncertainties at the site (Thompson Engineering Company 1988, p. 13). Still other reviewers, including those from the utility industry and from the National Academy of Sciences, proclaimed that the limits of environmental science have been exceeded by the goals set by the nation's radioactive waste program (Malone 1989b, p. 1453).

Because of all the uncertainties in the Yucca Mountain data and methods, assessors typically are not able to determine the degree of accuracy in their models (Thompson Engineering Company 1988, p. 5). They are able, for example, merely to say that there is a "high level of probability" that groundwater travel time to the water table will exceed 10,000 years (Sinnock et al. 1986, p. 57). In other words, the degree of uncertainty regarding groundwater travel time is very great, the margin of safety necessary to prevent significant problems, such as fracture flow, is quite slim and yet, despite this narrow "window," some persons appear to believe that Yucca Mountain will be predictably safe or in compliance with government regulations requiring a groundwater travel time greater than 1,000 years (Sinnock et al. 1986, p. i).

There is also only a "narrow window" or slim margin preventing fracture flow because, as we mentioned previously, if the percolation rate increases by only a factor of 10, then fracture flow will increase, and the travel time of leachate from the waste

will increase significantly (Peters 1986, p. i). In the world of groundwater flow, where risk assessments "are highly uncertain" (Reichard et al. 1990, p. 101), a factor of 10 as a window of safety is quite small. Indeed, in some of the simulated cases, water travel time from the repository to the water table is less than 1,000 years (Bryan 1985, vol. 1, pp. I-42 and I-43; Peters 1986, p. 32; see Sawyer in US Congress 1987a, pp. 709, 712). Hence, the value judgment that current and near-future knowledge about Yucca Mountain can guarantee safety and compliance with government regulations -- for example, requiring groundwater travel time of more than 1,000 years -- appears questionable.

The value judgment about travel time is not only factually questionable but also inconsistent. One well known group of assessors, for example, found that, according to their models, some calculated groundwater travel times are less than 10,000 years. They also admit that hydraulic data are insufficient and that there was not enough time to estimate cumulative radioactive releases (Sinnock et al. 1986, pp. 58, 75). Nevertheless they conclude that the "evidence indicates that the Yucca Mountain repository site would be in compliance with regulatory requirements" (Sinnock et al. 1986, pp. i-ii), and that "no radioactivity from the repository will migrate even to the water table immediately beneath the repository for about 30,000 years" (Sinnock and Lin 1984, p. 41).

How do some migration values of less than 10,000 years translate to a migration time of "about" 30,000 years? How can the same assessors claim that the repository will be in compliance with

government regulations (Sinnock and Lin 1984, p. 37), when they also assert that low flux "will probably limit flow velocities to the extent that no water will reach the water table for tens to hundreds of thousand of years" (Sinnock and Lin 1984, p. 53). Such poorly grounded "probable" knowledge of something that may occur within tens to hundreds of thousands of years (a wide range) is hardly consistent with precise claims about safety and regulatory compliance. Likewise, how can the same DOE assessors conclude, with confidence, that no radioactivity could migrate to the water table for at least 30,000 years (Sinnock and Lin 1984, p. 41), and yet claim: "Because data and understanding about water flow and contaminant transport in deep unsaturated fractured environments are just beginning to emerge, complete dismissal of the rapid-release scenarios is not possible at this time" (Sinnock and Lin 1984, p. 53)? How is the 30,000-year claim consistent with the assertion about not dismissing the rapid-release scenarios?

Assessors investigating the uncertainties in the Yucca Mountain hydrogeological data also have admitted that, for the unsaturated zone, uncertainties in groundwater velocities may be as much as 100 percent above or below the mean value (Jacobson 1985, p. 90). They likewise claim that a change in percolation of a factor of only 10 is sufficient to initiate fracture flow, that groundwater travel time is extremely sensitive to fracture flow (Sinnock and Lin 1984, p. 29), and that heat from the waste could cause fractures (Sinnock and Lin 1984, p. 24; Smith et al. 1982a, p. 91). Given such caveats, how can the same assessors consistently

claim that fracture flow is not a credible process (Sinnock and Lin 1984, p. 16) and that groundwater flow will be "well within the limits set by the NRC" (Sinnock and Lin 1984, p. 37)?

Similar inconsistencies appear, when the same assessors, after acknowledging (1) that they have incomplete data (Sinnock et al. 1986, p. 58), (2) that they have no time to estimate cumulative radioactive releases (Sinnock et al. 1986, p.75), and (3) that they may "have underestimated the cumulative releases of all nuclides during 100,000 years, by an amount that is unknown" (Sinnock et al. 1986, p. 77), nevertheless draw a contradictory conclusion. They conclude that only one ten-millionth of allowable releases of radionuclides will reach the water table (Sinnock et al. 1986, p. 80).

Likewise, assessors admit that solubility limits and retardation factors are site- and (radioactive) species-dependent (Smith et al. 1982a, p. 49). They also claim that they may have underestimated radioactive releases (Smith et al. 1982a, p. 183). If the same DOE assessors do not know the degree to which they may have underestimated radioactive releases (Sinnock et al. 1986, p. 77), how do they know so precisely that only one ten-millionth of allowable releases will be released? Similar inconsistencies and unsupported extrapolations occur throughout the Yucca Mountain analyses with DOE assessors confidently affirming that there will be "less than one health effect every 1,400 years" (Thompson et al. 1984, pp. v-vi). A more consistent appraisal, given the problems with the data and models at Yucca Mountain, might be that of the

assessors who concluded: "Even though we have tried to use the best data and models available at this time, we make no claims that these results have any value in the performance assessment of the Yucca Mountain repository site" (Dudley et al. 1988, p. 56). If such claims are plausible, then knowledge of the site may not be adequate for confident regulation.

Previous experiences at the Maxey Flats radwaste facility suggest that similar problems with value judgments about hydrogeological accuracy may have occurred there. The Environmental Protection Agency (EPA) believed that the knowledge of the Maxey Flats site was adequate to insure containment, credible regulation, and safety, largely because "the general soil characteristics" at the facility are "very impermeable" (EPA 1973, p. 133). Yet, such general assurances failed to address the problem of migration with sufficient precision and accuracy. Other hydrogeologists noted that accurate determination of hydraulic conductivity is impossible at a site, like Maxey Flats, with fractures (Papadopoulos and Winograd 1974, pp. 29, 33). US Geological Survey (USGS) scientists claimed that the Maxey Flats hydrogeology, because of the fractures, was "too complex for accurate quantitative description" (Zehner 1979, pp. 48-52). Because of the complexity and uncertainty associated with much information about Yucca Mountain, there is reason to believe that optimistic value judgments, about the accuracy of site studies, may lead to misleading or inappropriate conclusions, just as they did at Maxey Flats.

Chapter Three

Methodological Value Judgments in Evaluating Radwaste Risks

In late 1987, Congress passed an amendment to the Nuclear Waste Policy Act of 1982. This amendment directed that Yucca Mountain, Nevada was the only remaining potential site for the nation's first high-level radioactive waste repository (see Carter 1989 and Lemons et al. 1989). If Yucca Mountain is found to be unsuitable, the Department of Energy (DOE) is required to make recommendations to Congress within 6 months.

3.1 Value Judgments about the Reliability of Single-Site Studies

One methodological value judgment underlying all the Yucca Mountain evaluations is that suitability of a site for high-level radwaste can be determined by assessing only one site (Yucca Mountain), rather than by comparative assessments of a number of sites. This value judgment is particularly problematic because it allows assessors and policymakers to decide upon a "suitable" rather than an "optimal" site (Lemons, Malone, and Piasecki 1988, p. 38). Moreover, a number of researchers have charged that the Yucca Mountain site was chosen for evaluation, from the 9 original sites (Foreword in US DOE 1985a), because of political- economic expediency and manipulation, rather than because of demonstrated geological superiority (Jacob 1988; Davis 1988; Karkut 1988; Bryan 1987a; see Carter 1977; US Congress 1990, pp. 213-214; US Congress 1987a, p. 210; US Congress 1986, p. 45; Kunreuther et al. 1990, p. 470; Winsor and Malone 1990, p. 197). At the very least, this methodological value judgment requires one to assume that an

adequate risk assessment can be accomplished, even if there is no alternative for comparison. It requires one to assume that the political situation surrounding the one-site choice does not breed an undesirable consensus (see Emel et al. 1988b, p. 20). It could be, as R. R. Loux, Director of the Nuclear Waste Project Office for the state of Nevada put it: choosing only one site, Nevada, "sets the stage for a railroad job" (US Congress 1986, p. 235). Other observers say explicitly that the facility is being "forced" on the state of Nevada (Sawyer 1990, p. 2).

Performing an adequate risk assessment, in the absence of alternative sites, is particularly problematic because there is no perfect site; because perfect containment of the waste, in perpetuity, is impossible; and because long-term predictions are quite uncertain. Hence, in the absence of perfect containment and certain predictions, conservative and comparative assessments are surely required. Following similar reasoning, members of the European nuclear community have viewed the one-site strategy of the US and the Federal Republic of Germany as "highly vulnerable" (Emel et al. 1990, p. 5). Without comparative analysis of other sites, some assessors have maintained that there is a declining confidence that geological facilities for high-level radwaste will become available anytime in the near future, since there are many problems associated with Yucca Mountain, even though it is the only site (State of Nevada 1989b, 1989c).

Moreover, to study only one site appears to beg the question of site suitability and to "put the cart (the site decision) before

the horse (the site evaluation)." If one begs the question of site suitability, then one cannot provide an adequate scientific explanation, in the strict sense of having explanatory premises that deductively lead to a positive conclusion about site suitability (see section 1.2 earlier; Hempel and Oppenheim 1948; Popper 1959). Even in a less strict sense there are not good scientific reasons for inferring that single-site studies are sufficiently reliable. As evaluators from the state of Nevada pointed out, assessing only one site appears to put the evaluation process backwards: selecting a site for nongeological reasons then making the geological evaluations appear favorable (NWPO 1985, vol. 2). Indeed, given the inadequate analysis of proposed sites (see Keeney 1987), it is arguable that the question has already been begged. (For further discussion of begging the question, in a different context, see section 4.2 of chapter four).

In a one-site political environment, it seems extraordinarily difficult to believe that assessors could discover that the site is not fit for a repository and then return to Congress for further instructions (see Marshall 1988). One reason why the assessors are unlikely to do so is that they will be able to define what is fit, and they will not be forced to answer the question, "more fit than what other sites and more fit in what other respects?" (For discussion of the single-site choice, see Russell, et al. 1989; US GAO 1988; US GAO 1989). Hence the single-site assessment appears to be based on a methodological value judgment -- and perhaps a political judgment -- with questionable scientific and political

assumptions and consequences.

Moreover, there is some evidence, in the Maxey Flats case, that once assessors get into the business of evaluating a single site -- rather than doing comparative evaluation of several sites, in order to determine which is best -- the assessment becomes more susceptible to bias or misuse by vested political interests. The fractured, heterogenous Kentucky site was chosen for political reasons (see Zettwock 1985; Shrader-Frechette 1988, pp. 126ff.), in part because there was no open competition among competitor sites. It is arguable that the offsite migration might have been prevented, and another site chosen, were the Maxey Flats competition open to alternative sites. The same conclusion could hold true for the nation's first high-level radwaste facility. It too ought to be open to extensive study of a number of candidate sites.

3.2 Value Judgments That a Given Magnitude of Risk is Acceptable

All risk evaluations, at Yucca Mountain and elsewhere, also rely on the methodological value judgment that predicting events having a certain probability of occurrence is sufficient to provide a guarantee of repository safety. Obviously, however, no particular level of probable safety is ever known to be enough. No premises about some magnitude of safety deductively lead to a conclusion about site acceptability, because site acceptability is not a logical consequence of particular empirical claims. Hence, the value judgment about magnitude of risk appears to violate one of the conditions for a scientifically adequate explanation (see

section 1.2; Hempel and Oppenheim 1948; Popper 1959). One risk assessor, studying ground motion at Yucca Mountain, based his "conservative estimates" on the value judgment that predicting ground motion that had a one-in-ten chance of occurring was a sound basis for seismic design of the repository (King 1990). However, one could just as easily argue that one ought to design for a one-in-a-hundred or a one-in-a-thousand chance of ground motion occurring.

Other groups of risk assessors concluded that there had been no "significant" fault-related movement on the Yucca Mountain Site in the last 500,000 years (NNWSI History in US DOE 1985a), and that moderate earthquakes would likely occur at Yucca Mountain at recurrence intervals of tens of thousands of years (King et al. 1989). The obvious question this raises, however, is whether 500,000 years of no "significant" fault-related movement or 10,000 years of no moderate earthquakes is enough. Should there have been 5,000,000 years of no such significant movement? Or more or less? The level of designed safety is obviously a value judgment.

Likewise, some risk assessors calculated the probability of a volcanic disruption hazard at Yucca Mountain as 10^{-6} per year (Crowe 1986), while others have calculated this risk as between 10^{-8} and 10^{-9} per year (Metcalf 1983), with the probability of volcanism exceeding 10^{-4} over 10,000 years (Emel et al. 1988a, p. 10). Not only do these numbers cover a wide range, but there is no certain way to be sure that the possibility of volcanism is ever gone; volcanism at an individual center may last 500,000 years, contrary

to what many Yucca Mountain assessors have assumed. Moreover, Yucca Mountain itself is relatively free of faults, but the paucity of faults does not guarantee safety from future volcanic disruption (Smith et al. 1988b, pp. 1-37), because the Yucca Mountain area contains numerous faults, and the repository boundaries are defined by faults. Hence, the obvious question is: why is the methodological value judgment -- that the risk of volcanism is acceptably low -- reliable?

Risk assessors have set the probability of various accidents involving radionuclide releases at Yucca Mountain as between 10^{-6} and 10^{-9} (Jardine et al. 1987). Obviously these volcanic and accident risks are low, per year, but the inference that such values are "low enough" represents a highly questionable value judgment because, over centuries, the probability is much higher. For example, if the probability of volcanic disruption is 10^{-6} per year, then for 10,000 years, that probability would be 10^{-2} , an extraordinarily high risk. The value judgment about acceptability of such a risk is questionable in part because, although the per-year risks may appear low, the risks to future generations, who have no say in contemporary decisions about Yucca Mountain, are higher than those that we would likely accept for ourselves. Indeed, a value judgment that such future risks are acceptable arguably fails to take account of citizens' concerns about due process, equal protection, compensation, the rights of future persons, and so on (see section 3.9 in this chapter for a discussion of equity issues related to problems of radioactive

waste).

The apparent failure to take adequate account of the rights of future generations, in making the value judgment that a given level of risk is acceptable, is particularly apparent in the radiation dose limits to be used at Yucca Mountain. European scientists have been quite critical of the fact that US radiation dose limits do not extend beyond 1,000 years for the individual and 10,000 years for the population. European regulatory protection against radiation, however, extends up to 1,000,000 years -- 990,000 years longer than US protection (Emel et al. 1988b, pp. 40-41; Emel et al. 1990, pp. 4-5).

Moreover, European waste canisters have longer projected lives -- 100,000 years, and not the 300 to 1,000 years of the US canisters. This is one reason why the Swedish nuclear program has been so successful, for example, with its emphasis on long-lived engineered barriers (Emel et al. 1990, pp. 5-10). The fact that other countries appear to be making much more conservative plans for managing and containing high-level radwaste suggests that typical US levels of acceptable risk, whether from volcanism or radwaste canisters, may not be adequate. Hence, the value judgment that given levels of risk are ethically, socially, and political acceptable is highly controversial. One reason that they are controversial is that they appear to be based on purely short-term economic considerations. Indeed, they appear to rest on a highly questionable, short-term utilitarian justification. (Later, in section 3.9, we shall discuss this ethical value judgment.)

In assuming that a given number of years of canister reliability, or a given number of future cancers caused annually by Yucca Mountain, is acceptable, risk assessors presuppose that the magnitude of a risk, alone, is grounds for acceptance. Obviously, however, equity of distribution, compensation, free, informed consent, and other social considerations also play a major role in whether a given number of cancers, for example, is acceptable. Cancers caused after the first several hundred years, by the Yucca Mountain repository, are predicted to be roughly 100 to 1,000 per year, approximately the same number that would occur as a result of naturally occurring uranium ore bodies (Williams 1980, pp. 1-23). It is not clear, however, why this number of cancers is acceptable, particularly if the magnitude alone is judged as grounds for acceptance. Future persons affected by the waste will have little say in their contracting cancer, and they will have no possibility of exercising their due-process rights. Indeed, it is not clear that there is any vehicle for compensating them. In the absence of such ethical and social considerations, the value judgment -- that a given magnitude of risk or number of cancers caused by Yucca Mountain is acceptable -- appears questionable.

Moreover, in assuming that a given level of risk, or a given number of years of travel time of radioactive waste, is acceptable, risk assessors presuppose that low-probability events will not occur. Such probabilities, over the long term, are not known with real accuracy, because there is no existing frequency record, and because we have no guarantee that the future will be like the past.

If the future is not like the past, then such allegedly rare events could shorten the thousands of years alleged for radwaste migration to take place at Yucca Mountain. As several USGS geologists put it, speaking of the Maxey Flats radioactive waste repository: extreme events of low frequency may perform the work of thousand of years of creep and slope wash. For example, an eight-hour deluge of 28 inches of rain may cause several thousand years worth of "normal" erosion. Therefore, infrequent events threaten Maxey Flats' integrity more than do continuous processes (Carey et al. 1990, p. 34). The same reasoning could apply to Yucca Mountain.

Another problem with the value judgment that the given risks at Yucca Mountain are low enough -- for example, 10^{-6} or 10^{-9} -- is that these various risk estimates are subject to considerable uncertainty. As already mentioned, uncertainties of six orders of magnitude are "not unusual" in risk assessments characterized by incomplete data on long-term accident frequency (Cox and Ricci, 1989a, p. 1026). If this is true, and if similar uncertainties are applicable to the Yucca Mountain figures, then a risk of 10^{-6} of an accident involving a radionuclide release might really lie between approximately 10^{-3} and 10^{-9} . An annual risk of 10^{-3} is arguably not a low risk; indeed it is approximately three orders of magnitude higher than the risks that are normally regulated by government. Hence one good reason for questioning the value judgment that a given level of risk -- estimated for Yucca Mountain -- is acceptable is that the estimate could be uncertain and that the real risk could be quite high.

Indeed, risks associated with radioactive waste storage at past US facilities have been somewhat high. According to government estimates for the Hanford facility, for example, just the normal radiation releases from this site could result in an annual exposure of 580 person-rem (US ERDA-1538 1975, vol. 1, p. X-74; see Shrader-Frechette 1983, chapter two). Using some of the lowest government estimates, this level of exposure from only one site could cause approximately 12 cases of cancer and 116 genetic deaths over a 100-year period (US AEC 1974, p. 3-83). Given that the exposures could go on for thousands of years, that other risk estimates for cancer and death are much higher, and that the risks are likely to accelerate, the magnitude of deaths and cancers becomes quite high. Admittedly, the Hanford facility is geologically and technologically quite different from the proposed Yucca Mountain facility. Nevertheless, government projections of future Hanford leaks suggest either that there is no way to control the releases, or that they are too expensive to control. Either of these suggestions could be quite damning for Yucca Mountain. If human error helped amplify the risk at Hanford, as was already documented, then human error could likewise help amplify the risk at Yucca Mountain. For all these reasons it is not obvious that the magnitude of risk postulated at Yucca Mountain is acceptable. Nor is it clear that the risk postulated for previous radwaste facilities is acceptable.

3.3 Value Judgments That Risk Reductions Are Sufficient

Yet another faulty methodological value judgment essential to

evaluating the risk at Yucca Mountain is that by using very conservative design techniques and by reducing uncertainties as much as possible, these reductions will be sufficient to insure safety (see Tillerson et al. 1989; Nataraja and Daemen 1989).

One problem with the value judgment that risk reduction and conservative assessment strategies are conservative enough is that, in a situation where uncertainty is so great, as at Yucca Mountain, it is often not possible to know whether a given strategy is conservative enough. Hence, conclusions about site safety do not follow deductively from premises about risk reductions. In a strict sense, the scientific explanation is imperfect (see section 1.2 earlier; Hempel and Oppenheim 1948; Popper 1959). Even in a less strict sense, there do not appear to be good reasons to assume that, because assessment strategies are conservative, they insure safety. One reason they do not is that, given the heterogeneity of values for basic hydrogeological parameters at Yucca Mountain, it appears that assessors often believe that their assessments are conservative when they are not (see Lemons and Brown 1990, p. 7). For example, one official DOE document admits that "generally, categories of processes or events that have a small probability of occurrence at the site will be eliminated from consideration" (US DOE 1990a, p. 3-13). After this statement, the DOE policy document enjoins assessors to choose values such that "the realistically conservative analyses might use a conservative value that is within one standard deviation of the mean value" (US DOE 1990a, pp. 3-8 and 3-9).

However, choosing a value that is within one standard deviation on either side of a mean value would include only approximately 68 percent of all the cases in the frequency distribution. It is hardly conservative to have an analysis that takes account of 68 percent of the cases, particularly if the problems likely to arise come from the outliers, the cases associated with catastrophic failures of the repository. For example, we know that there are eight orders of magnitude of variation in the saturated hydraulic conductivities of the various tuffs at Yucca Mountain (Peters et al. 1984, p. i). If one takes a number -- one standard deviation above the mean values for the tuff -- as a conservative value for the saturated hydraulic conductivity of the tuff, this might not be adequately conservative. It could be the case that this allegedly conservative number might only represent three or four orders of magnitude of variation in the tuff. The remaining 32 percent of values not considered could include the tuffs for which saturated hydraulic conductivity was even four or five orders higher. Hence, choosing an allegedly conservative value, up to one standard deviation above the mean, might not represent the extremes that are actually occurring at Yucca Mountain. And if not, then the methodological value judgment -- that risk reductions and conservative techniques are sufficiently conservative -- could lead to errors in the final assessment of several orders of magnitude.

It is especially difficult to know that a given repository design is conservative enough, or that a given risk reduction is

large enough, because the DOE has contradictory "fundamental goals" in meeting regulatory requirements for safety at Yucca Mountain. Its allegedly conservative stance toward safety is undercut both by schedule constraints and by economics (see section 3.8 in this chapter and section 4.8 in the next chapter for further discussion of this point). The DOE explicitly seeks the goal to "minimize financial and other resource commitments" and yet to "protect public health and safety" (Cloninger et al. 1989). Likewise, its two other (of four) goals are to "comply with applicable laws and regulations" and yet to "maintain an aggressive schedule." Obviously short-term economy is at odds with health expenditures, and obviously following health regulations is at odds with maintaining a tight schedule. The fact that these four goals conflict makes it less likely that assessors can make a reasonable value judgment that designs are conservative enough or that risk reductions are great enough. Given these four goals, even contradictory policies can be justified.

In some cases, however, it is important to point out that actual risk assessments at Yucca Mountain have not been conservative. For example, in an assessment (King et al. 1989) of seismic and faulting hazards, scientists are basing their designs on the assumption that the repository can withstand quakes that occur every 10,000 years. Because moderate quakes are likely to occur during this period, and more powerful quakes approximately once every 100,000 years, if the calculations were wrong by only one order of magnitude, then the repository might not be able to

withstand a given quake. Hence, such designs appear to need to be even more conservative, more conservative than allowing for an order of magnitude of error. Because risk assessments characterized by incomplete data on long-term accident frequency (see chapter one) are typically wrong by four to six orders of magnitude, it might be more reasonable to make the value judgment that allowing for errors of higher orders of magnitude represents a more conservative value judgment.

3.4 Value Judgments That Worst-Case Hazards Are Not Credible

Another methodological value judgment that occurs frequently in Yucca Mountain risk assessments is that various worst-case hazards are not credible and need not be taken into account. For example, although some scientists use conservative models that may overestimate the risk at Yucca Mountain (see Smith et al. 1982; Dudley et al. 1988, p. 118), many assessors fail to examine worst-case models. They postulate radioactive-waste accidents, for example, none of which could result in violation of the radiation dose limits set by the NRC (Jackson et al. 1985). Likewise, they frequently claim, for instance, that fracture flow of groundwater and volcanic activity are not credible at Yucca Mountain and, therefore, they need not take these events into account, even though both could rapidly increase the transport time of radioactive leachate (see, for example, Wilson and Dudley 1986; Sinnock and Lin 1984, p. 16). Or, they claim that matrix flow predominates over fracture flow (see State of Nevada 1988a, vol. 1, pp. I-10, II-2 and II-3). It is highly questionable, however,

whether so many worst-case events can be dismissed as "not credible." Even the Nuclear Regulatory Commission notes that fracture flow at Yucca Mountain could result in groundwater travel time, from the repository to the water table, of less than 1,000 years (NRC Staff Comments in US Congress 1987a, p. 199; see also p. 712).

Such reluctance of some individual assessors to consider worst cases follows in part from the position of the DOE. It typically does not consider worst cases and assumes, for example, that the radioactive waste at Yucca Mountain would be retrievable for 50 years, but not afterwards (Goble et al. 1988, p. 31), or that the worst-case earthquake is one that might occur every 10,000 years, even though the site will be hazardous in perpetuity (see State of Nevada 1988a, pp. I-7, II-1).

One apparent DOE rationale for not considering worst cases is that, in general, the DOE claims that events whose probability is less than 10^{-5} per year are not credible (Goble et al. 1988, p. 40). However, an event having an annual probability of 10^{-5} obviously has a quite high probability of occurring, 10^{-2} , during the 1,000 years that the Yucca Mountain radwaste would be most lethal. Given such high probabilities, it appears that the DOE assumes not only that present persons have no right to be protected against worst-case accidents, but also that future generations may not have a right to be protected even against more likely catastrophes. Otherwise, DOE analyses would investigate worst-case accidents in the light of both present and future time periods.

As we showed in section 2.8 of the previous chapter, the DOE also fails to consider human-caused worst-case accidents by virtue of the fact that it subscribes to the value judgment that human error is not a significant contributor to risk. For all the reasons already discussed, this earlier value judgment is implausible; likewise, there are also reasons to believe that it is not credible to discount human-caused worst-case accidents. For one thing, for the DOE to claim that all military activities and terrorism related to Yucca Mountain are not credible is to beg the question, since there is no way of knowing what activities will be likely even 100 years from now.

In situations like Yucca Mountain, failure to consider worst cases represents a very problematic value judgment, in part because some of the "worst cases" have actually occurred at US radwaste facilities in the past. For example, at the Maxey Flats radioactive waste facility, risk assessors said that the shale was impermeable and that no migration of wastes would occur for thousands of years. They based their claim, in part, on the value judgment that fracture flow was not possible at the site, and hence that the "worst case" of leachate migrating through fractures was not credible. However, there was flow through the hairline fractures, with consequent recharge to the groundwater at Maxey Flats, via precipitation, even though the entire system was shale and sandstone (Wilson and Lyons 1991, p. 47). Hence, one of the "worst cases" happened at Maxey Flats. Analogously, as was already mentioned, there is a possibility that fracture flow and volcanism

could occur at Yucca Mountain. These probabilities of occurrence appear high enough that it appears reasonable for anyone to consider them as part of a worst-case analysis (see O'Brien 1977).

Even if the probabilities associated with parts of a worst-case analysis were not high, it might be reasonable to consider them at Yucca Mountain simply because we cannot test for a worst case, even though empirically and logically adequate scientific explanation in the strict sense requires testability (see section 1.2; Hempel and Oppenheim 1948; Popper 1959). Another major reason for considering worst cases is that the consequences could be so extreme. Often severity of consequences, not probability of occurrence, is so great that low-probability, high-consequence events merit detailed consideration (Shrader-Frechette 1991, chapter 8). And, at Yucca Mountain, the consequences could be severe. If there were little or no adsorption, thermally induced fractures, fracture flow, horizontal permeability, seismic activity, no containment after 200 years, significant leaching at the repository, and if there were populations' receiving hundreds to thousands of rems of radiation, either as a whole-body dose or as a bone dose, then catastrophic numbers of fatalities could occur (O'Brien 1977, pp. 106-169). These consequences -- together with the uncertainties associated with long-term prediction and with the near worst-cases that have occurred at places like Fernald and Maxey Flats -- are arguably a sufficient basis for considering worst cases. And if so, then the value judgment that worst cases are not credible is highly

questionable.

It is important to point out that, even when assessors claim to be doing a worst-case analysis, often their methods are not sufficiently conservative to constitute a true worst case. For example, some assessors claim to be doing a worst-case analysis at Yucca Mountain, but then they make assumptions that contradict the alleged severity of the case being considered. They assume, for instance, that in a worst-case accident, no canisters will be breached (Gram et al. 1984). In making such an assumption, they are again making the questionable value judgment that a true worst case is not credible and does not need to be considered. In the case of waste canisters, in particular, the value judgment is highly suspect because, as was already mentioned, in some experiments all canisters of the required reference material exposed to a one-year test in groundwater and tuff at the expected 200 degrees C. failed and showed stress-corrosion cracking (Pitman et al. 1986). Moreover, accidents worse than those predicted for catastrophic canister failure have already occurred (Rusche in US Congress 1987a, pp. 906-907).

Ignoring worst cases is also questionable from an ethical point of view because it fails to guard against false negatives, against erroneously assuming something could cause no harm, even though it might do so. In pure science, it often is reasonable to guard against false positives, and to risk false negatives. To do so in cases like Yucca Mountain, however, is typically judged to be ethically unsupported because it fails to take account of persons'

rights to equal protection, due process, consent, and welfare (see Shrader-Frechette 1991, chapter 9). In other words, it is arguable that in failing to guard against false negatives by considering worst cases, and in attempting primarily to avoid false positives, risk assessors at Yucca Mountain incorrectly place the burden of risk on potential risk victims. Although there is no time to do so here, it can easily be shown that the public has the right to protection against uncertain risks and therefore that risk evaluators, in a situation of uncertainty, ought to risk false positives, rather than false negatives. Any other procedure would fail to give the highest priority to protection of human welfare, and it would err ethically by using humans as means to short-term economic ends (Shrader-Frechette 1991, chapter 9). Moreover, contrary to many Yucca Mountain value judgments, members of the geology community recognize that the most protective prevention strategies for an aquifer are based on worst-case scenarios (Reichard et al. 1990, pp. 144, 160). For all these reasons, the value judgment that one need not consider worst-case risks at Yucca Mountain appears questionable.

3.5 Value Judgments That Average Risks Are Acceptable

Likewise, one of the most protective and conservative strategies for evaluating groundwater and radionuclide transport is to avoid using mere average velocities and instead to try to evaluate the risk of even the most pessimistic cases. One of the most questionable risk-evaluation judgments at Yucca Mountain is that figures for average risks provide an acceptable measure of

hazards. Like the earlier methodological value judgment about risk magnitude guaranteeing acceptability (see section 3.2), this judgment also appears implausible because no premises about average risks lead deductively to a conclusion about risk acceptability. Hence, the proposed explanation of acceptability fails to meet at least one condition of scientific adequacy in the strict sense (see section 1.2; Hempel and Oppenheim 1948; Popper 1959). This use of premises based on averages is questionable, even from an inductive or retroductive point of view, because averages hide some very high hazards among low ones, and instead lump them all together. However, even a small probability of a very great risk is cause for concern, apart from what the average probability is, because the averages themselves are often misleading. For example, as was mentioned in the previous chapter, risk assessors at Yucca Mountain have calculated the average or mean groundwater travel time from the repository to the water table, yet noted that, because of uncertainties and heterogeneities in the data, the actual travel time of groundwater could be as much as 100 percent higher than the mean or average value (Jacobson 1985, p. 90).

Some Yucca Mountain risk assessors also claim, for example, that the groundwater travel time to the water table from the repository has a mean of 43,000 years (Sinnock et al. 1986, p. i). This figure is misleadingly reassuring, however, because approximately one percent of the calculated groundwater travel times are less than 10,000 years, and the travel times for some rock units are between 3,915 years and 15,020 (Sinnock et al. 1986,

p. i). Indeed, as was already mentioned, some assessors argue that the travel times could be less than 1,000 years (Bryan 1985, vol. 1, p. I-43; Peters 1986, p. 32; see Sawyer in US Congress 1987a, pp. 709, 712).

Given groundwater travel times on the order of 1,000, 3000, and 15,000 years, it is misleading, if not incorrect, to argue that mean or average groundwater travel time of 43,000 represents a meaningful or accurate figure. These shorter groundwater travel times could be enough to cause problems of cancer and contamination. In other words, the problem with using averages is that, unless the values are clustered, the averages can mislead one about the allegedly long length of time for radwaste migration and about the allegedly high margin of safety (see Shrader-Frechette 1983, pp. 148ff.; 1985, pp. 144, 174). In cases like Yucca Mountain, it is difficult to confirm that the values are clustered, as is required for legitimate use of averages, both because there is no long frequency record for radwaste migration events, because the length of time at issue is extraordinarily long, and because there is so much uncertainty in the numbers anyway.

As has already been mentioned, the saturated hydraulic conductivities of the tuff vary by 8 orders of magnitude at Yucca Mountain (Peters et al. 1984, p. i), and there are similar ranges of heterogeneities and uncertainties for other hydraulic variables at the site. The uncertainty is a particular problem at Yucca Mountain because of the heterogeneity of the various rock units. The average hydraulic conductivity of different Yucca Mountain

rocks units, such as the Tiva Canyon Unit and the Paintbrush Unit, for example, often varies by as much as 4 or 5 orders of magnitude (Sinnock and Lin 1984, pp. 8-11). Estimating saturated flow at Yucca Mountain, and aggregating units with such widely ranging values for hydraulic conductivity, in order to obtain average groundwater travel time from the repository to the water table, could be quite misleading, in part because solubility limits and retardation factors for radioactive leachate "are site and species dependent" (Smith et al. 1982a, p. 49). Hence, when assessors aggregate disparate values and obtain an average number for groundwater travel time and consequent radwaste migration estimates, they may be providing a misleading value judgment. Hence, when an assessor claims that the travel time of water from the repository to the water table could be from 3 years to 420,000 years (Dudley et al. 1988, p. 72), using the average travel time makes no sense, because the values are so widely dispersed.

Likewise, when assessors claim that "no radioactivity from the repository will migrate even to the water table immediately beneath the repository for about 30,000 years" (Sinnock and Lin 1984, 41), the term "about" obscures the short travel times that are possible. This average migration figure is not useful, since it obscures the shortest, easiest migration times, and these are the ones of greatest concern. If one is worrying about the easiest way to breach safety, or the quickest route for radwaste migration, both of which are necessary to protect public health and safety and environmental welfare, then average travel times are meaningless.

They give a false sense of security. Hence, it is highly questionable for Yucca Mountain assessors to use average risk figures. Averages do not kill people. Maverick events do so, however, and a number of maverick events could be possible at Yucca Mountain.

Reliance on average travel times of groundwater and average percolation, precipitation, and infiltration was also a problem that helped to create the fiasco at Maxey Flats radwaste facility, in which (as we already mentioned) plutonium traveled 2 miles offsite in less than 10 years. Assessors underestimated this travel time by as much as 6 orders of magnitude (see chapter 1, this document). At Maxey Flats, for example, the mean precipitation is 45.4 inches per year, several times greater than that at Yucca Mountain. The mean figure was misleading, however, because massive rainfall, over a short period, rather than the average annual rainfall, was the main contributor to the overflowing leachate and the contamination of groundwater at Maxey Flats. Extreme events of low frequency, such as a deluge of several inches of rain in several hours, perform the work of several thousand years of erosion, infiltration, and groundwater migration (Carey et al. 1990, pp. 1, 34). Hence, the value judgment that averages can accurately represent such extremes could lead to unpredicted groundwater or radionuclide migration at Yucca Mountain.

3.6 Value Judgments That Full Liability Does Not Promote Safety

DOE and other Yucca Mountain risk assessments also may fail to be protective of the public and environmental welfare as a

consequence of their risk-evaluation judgments regarding liability at Yucca Mountain. In response to the states' recommendation for unlimited strict liability for any nuclear waste program or incident (Rusche in US Congress 1986, pp. 484, 655), the DOE position has been that "these activities should enjoy indemnity protection equivalent to other nuclear programs" (Rusche in US Congress 1986, pp. 484-485). Other US nuclear programs currently have a liability limit that is less than three percent of government-calculated costs of the Chernobyl accident (Koryakin 1990), and Chernobyl was not a worse-case incident (Shrader-Frechette 1991, 1983).

The value judgment that Yucca Mountain liability should be severely limited, as it is for the other US nuclear programs, is highly questionable for at least five reasons. First, liability is a well known incentive for behavior that is appropriate. If persons know that they are likely to be held responsible, in full, for their actions and their consequences, then they are more likely to behave in responsible ways. Not to tie responsibility to liability is analogous to not tying penalties or enforcement mechanisms to the law. Both situations, penalties and full liability, might help to generate behavior that is more socially acceptable. Hence, it is questionable both for nuclear-related industries to enjoy a liability limit and questionable for the 1988 Price-Anderson Amendments Act to exempt certain DOE contractors -- working on Yucca Mountain -- from the \$100,000 penalty for each violation of safety rules (Price-Anderson Amendments Act of 1988, P.L. 100-408,

Stat 102, pp. 1066-1085).

Second, if the Yucca Mountain operations are as safe as risk assessors and the DOE proclaim, then the government and DOE have nothing to lose from full and strict liability. Hence if Yucca Mountain is safe, then there is no compelling argument for limiting liability. Likewise, the main reason for limiting liability at Yucca Mountain is the belief that the facility would not be safe, and that large damage actions are credible. But if large damage actions are credible, then Yucca Mountain is arguably not safe. This means that assessors cannot consistently argue both that Yucca Mountain would be safe and that a liability limit is needed. Of course, proponents of limited liability might respond that the limit is needed to deter nuisance lawsuits by irresponsible persons. This response is questionable, however, because it argues against any liability whatsoever, an argument that is clearly ethically and legally suspect.

Third, it is questionable whether government should have the right to limit persons' due-process rights under the law. In arguing for limiting Yucca Mountain liability, the DOE is arguing for limiting due-process rights to less than three percent of the known costs of nuclear accidents that have already occurred (Koryakin 1990; Shrader-Frechette 1991, 1983), as was just mentioned. This means that most of the costs of a radwaste accident, by law (the Price-Anderson Act), would be borne by its victims rather than by its perpetrators. The maximum credible urban and rural nuclear/radioactive waste accidents would both greatly

exceed \$6 billion, the liability limit set in 1988 by US law. The Chernobyl costs are expected to reach \$283-358 billion, and will go higher unless more persons are evacuated (Koryakin 1990; see Resnikoff 1990). Although the 1988 Price-Anderson Act Amendments allow the liability limit to be adjusted for inflation and for the number of nuclear reactors, the figure will remain low. For example, for the 110 US nuclear reactors existing in the US in 1990, given a maximum charge of \$63 million (annually adjusted for inflation), per licensee/reactor, the total US liability limit for nuclear or radiation-related incidents in 1990 was \$7.2 billion, less than 5 percent of Chernobyl costs. Whether for nuclear accidents generally or for Yucca Mountain specifically, it is highly questionable whether the government has the right to limit liability.

In imposing the bulk of radwaste accident risks on victims and not perpetrators, and in arguing that a citizen does not have a right to full redress of grievances, even when the source of the problem is the government itself, the DOE has made a highly questionable value judgment. Not to have the right to full redress of grievances seems both unconstitutional and inequitable. Hence there is reason to make the value judgment that there ought to be full, strict liability at Yucca Mountain. As one researcher put it, "coverage under the Price-Anderson Act is clearly inadequate. Congress must take another look at the matter" (Resnikoff 1990, p. 44; see Shrader-Frechette 1983, pp. 73ff.).

A fourth reason to question the value judgment that Yucca

Mountain liability ought to be the same as for other nuclear programs is that, on the DOE's own admission, much more is known about risks associated with nuclear fission reactors than is known about radioactive waste (Hamilton et al. 1986, pp. 10-25). Indeed, the radioactive waste problem has been unsolved since the beginning of commercial nuclear fission in the US in 1956. It is not reasonable to argue that the liability provisions ought to be the same for two risks (nuclear reactors and nuclear waste), when one of the risks is much less well known than the other.

Fifth, as we have already mentioned in section 2.8 of the previous chapter, the DOE record of safety has been poor in the past. It includes violations of environmental and safety laws and regulations, as well as failure to make corrections once serious environmental problems have been noted (see, for example, US Congress 1989a). Given DOE's record, there appears to be a great need for full and strict liability in any DOE installation, such as Yucca Mountain. This need for full liability is underscored by the fact that, when the DOE nuclear materials plant in Fernald, Ohio was discovered to have serious, life-threatening problems of radioactive contamination and violations of the law -- including worker deaths and cancers among nearby members of the public -- the DOE retreated behind the doctrine of sovereign immunity in order to obtain protection from direct legal action by citizens (US Congress 1989b, p. 2). In part because of this precedent, there appears to be a great need for full liability at Yucca Mountain and for penalties for safety violations by all contractors. Hence, there

are ethical, practical, and scientific grounds for challenging the value judgment that full and strict liability is not needed at Yucca Mountain.

3.7 Value Judgments That High-Level Waste Is As Safe as Ore

Another problematic risk-evaluation judgment made in Yucca-Mountain assessments is that, after 1,000 years, if the risks from high-level waste are approximately the same as those from naturally occurring ore bodies (Rusche in US Congress 1987a, p. 376), then the risks from Yucca Mountain are acceptably low (see Williams 1980, pp. 1ff.). Like the other value judgments discussed in sections 3.2 and 3.5, this methodological value judgment appears implausible because conclusions about risk acceptability do not follow deductively from premises about naturally occurring risks. Hence, at least one of the logical conditions for an adequate scientific explanation in the strict sense appears to be violated by this methodological value judgment (see section 1.2; Hempel and Oppenheim 1948; Popper 1959). This value judgment is also questionable, even from an inductive or retroductive point of view, because it presupposes that what is normal (the risk from ore) is acceptable. Many "normal" risks, however, such as those from background radiation, causing tens of thousands of US cancers per year, are not socially acceptable. Rather, we put up with them because they are not preventable. To assume that a preventable risk (like that from Yucca Mountain) is acceptable because it is the same order of magnitude as a naturally occurring risk (like that from uranium ore) presupposes that something is acceptable, purely

because it is similar to some naturally occurring hazard. This presupposition is highly debatable, however, because we typically try to avoid even naturally occurring hazards. Moreover, what is normal is also not socially acceptable, because natural disasters typically have less serious social impacts than do technological catastrophes causing the same number of fatalities (Freudenburg and Jones 1991; Freudenburg and Gervers 1991). Also, what is normal is not necessarily morally acceptable, as G. E. Moore showed (1951, pp. viii-ix, 23-40, 60-63, 108, 146). Many dangerous and undesirable things are statistically normal, such as cruelty or unfairness, but their normalcy does not mean they are morally acceptable. Nor does their normalcy mean that governments can impose additional "normal" risks on persons, simply because they already occur (Shrader-Frechette 1983, chapter 6, esp. pp. 142-152). We do not say that a "normal" magnitude of risk is acceptable, regardless of whether it is preventable, regardless of whether persons give their free, informed consent to it, and regardless of whether it results in inequitable risk burdens. Indeed, to say that a normal magnitude of risk is acceptable, regardless of such ethical considerations, is to commit the "naturalistic fallacy" (see Moore 1951, pp. 36-40; Shrader-Frechette 1983, chapter 9), a classical fallacy of ethics.

An additional problem with the assumption/ value judgment -- that a Yucca Mountain risk of the same order of magnitude as that from uranium ore is ethically acceptable -- is that the risk from uranium ore is arguably not low. Using Environmental Protection

Agency dosimetry and environmental pathway models, some assessors (see Williams 1980, p. 23) have calculated the hazard from the ore as causing 100 to 1,000 fatal cancers per year. If these assessors are correct, and if this hazard is present for only 100,000 years, it could cause approximately 10 million to 100 million fatal cancers during that time -- hardly a low risk. Indeed, it is so high that one could arguably search for ways to reduce it. Hence it is questionable whether one ought to make the value judgment that a Yucca Mountain risk of the same magnitude as that from uranium ore is acceptable.

Another problem with using the uranium-ore risk as a criterion for acceptable risk from Yucca Mountain is that most studies of the risk from high-level waste admittedly underestimate the risk because they ignore the in-growth of Ra-226 and other radionuclides in the long-lived decay schemes stemming from the uranium and plutonium in the wastes. Ra-226 has its maximum concentration 100,000 to 200,000 years after it has been removed from the reactor. In an ore deposit, however, the amount of Ra-226 initially present would be only that quantity produced by the decay of the U-238. From 30,000 years on, concentrations of Ra-226 would be larger than those in the ore, because the high-level waste contains large amounts of Pu-238 and U-234, both of which are parent nuclides of Ra-226. As these parent nuclides decay, large quantities of Ra-226 are produced. In the ore, however, only U-238 creates Ra-226 and it is removed rapidly because of solubility. This means that concentrations of Ra-226 from the ore would be

similar to those from high-level wastes only during the first years of the repository and only about one mile from the site (O'Brien 1977, pp. 125ff.; Smith et al. 1982a, p. 183). Hence, even if the risk from ore were an ethically acceptable touchstone for Yucca Mountain, it is not obvious that the Yucca Mountain risk is even as low as that from ore. For all these reasons, the value judgment -- that the Yucca Mountain Risk is acceptable, because it is of the same order of magnitude as that from ore -- is questionable on both factual and ethical grounds.

3.8 Value Judgments about Yucca-Mountain Reliability

Yet another questionable methodological value judgment is that Yucca Mountain risk assessments, because of advances in hydrogeological modeling, are more reliable than those that have been done in the past. Indeed, the DOE maintains "that it is unfair to judge past practices by today's more stringent environmental standards." Moreover, they say the Yucca Mountain project has "many layers of external oversight, unlike the weapons facilities that were cloaked in secrecy from the start" (Carpenter 1991, p. 74).

Admittedly, the Yucca Mountain site evaluation/assessment will be scrutinized by the Nuclear Waste Technical Review Board, a panel of experts recommended by the National Academy of Sciences and appointed by the President. Moreover, the facility will be licensed by the US Nuclear Regulatory Commission. For all these reasons, both the DOE and their assessors maintain that the Yucca Mountain studies will be more reliable than those done in the past. They argue that Yucca Mountain will not fall victim to the same problems

that have plagued other radioactive waste facilities, because the site has been assessed with more care than have the earlier installations such as Hanford, Idaho Falls, Fernald, Maxey Flats, and so on.

Optimistic value judgments about the reliability of Yucca Mountain studies are questionable, however, because premises about improved assessment methods do not lead deductively to conclusions that the assessments themselves will be superior. There is no such guarantee, given the conditions for a logically adequate scientific explanation in the strict sense (see section 1.2; Hempel and Oppenheim 1948; Popper 1959). Such value judgments are problematic, even on inductive grounds, not only because they ignore the pervasiveness of human error (see section 2.8 of chapter two), not only because there have been serious problems with other DOE assessments and at other nuclear facilities such as Fernald, Hanford, Idaho Falls, Maxey Flats, and Savannah River, but also because the period of time for which Yucca Mountain assessments must be done is longer than that for any other period ever assessed in the past. Also, there is less data on radioactive waste risks generally than for risks (like those from nuclear fission reactors) commonly studied in the past (Hamilton et al. 1986, p. 10-25).

Moreover, if the usual margin of error in some risk assessments is taken as also typical of the various risk assessments done for Yucca Mountain, then it is not clear that the various Yucca Mountain risks are acceptable at all. This is because many of the Yucca Mountain risks are already at or near the limit

of acknowledged unacceptability. For example, the Yucca Mountain risk, as indicated in section 3.7 earlier in this chapter, has been said to be of the same order of magnitude as that from unmined uranium ore. If this claim is in error by as much as some other probabilistic risk assessments have been -- 6 orders of magnitude -- then Yucca Mountain might cause as many as 10^{13} to 10^{14} fatal cancers over a period of 100,000 years, or 100 million to one billion fatal cancers per year (see Williams 1980, p. 23). Given the lack of confirmation of the Yucca Mountain risk numbers, it is problematic to assume that the Yucca Mountain assessments are much more reliable than those that have been done in the past -- particularly because the consequences of over-optimism about the risk figures could have serious health and environmental effects.

Another reason (already mentioned earlier in this chapter) that Yucca Mountain assessments may not be more reliable than other comparable risk assessments -- and may not use the best available methodological techniques -- is that the work is being done far more quickly than risk assessments of other radwaste facilities throughout the world. Reviewers have spoken of the "potentially disastrous schedule" at Yucca Mountain (Sawyer 1986, p. 9). Also, the US uses far less conservative regulatory guidelines than do European countries (see section 3.2 earlier in this chapter). Moreover, the US and the UK have the most troubled radwaste programs in the world (Emel et al. 1990, p. 5). At least part of the reason for these troubles is that "US rigorous time schedules [for assessment] are inconsistent with all other countries

surveyed" (Emel et al. 1990, p. 5). The US has the earliest deadline for a high-level-radwaste repository opening, earlier than the deadline of France, UK, Sweden, Japan, Canada, and West Germany -- and the US also has the shortest in-situ research time (Emel et al. 1990, p. 206). All of these factors give one a basis for questioning the DOE's methodological value judgment that the Yucca Mountain risk assessments are/will be more reliable than other typical studies.

3.9 Value Judgments That Utilitarian Risk Theories Are Just

Risk assessors who assume that they need not consider worst-case risks, who judge the acceptability of risk on the basis of average hazard to persons, and who assume that they can do reliable risk assessments despite an extraordinarily short time frame -- as a number of Yucca Mountain assessors do -- also make another important value judgment. This judgment is that utilitarian theories of risk distribution are just or acceptable. Risk assessors who use "efficient" (rather than the most reliable) sampling methods and simulations also subscribe to the value judgment that risk may be assessed and distributed on a utilitarian basis (see, for example, Board 1989, p. 66; Stephens et al. 1986, p. xv).

Utilitarian theories direct us to provide the greatest safety/welfare or least risk for the greatest number of persons. To subscribe to utilitarian theories represents a significant value judgment because utilitarianism has a number of significant flaws (see Rawls 1971; Kasperson and Abdollahzadeh 1988;

Shrader-Frechette 1983, pp. 25ff., 136ff.; Shrader-Frechette 1985, pp. 32ff., 210ff.; Shrader-Frechette 1985b, pp. 55ff.; Shrader-Frechette 1991a, 1991b). Also, one could instead subscribe to a great many alternative ethical theories, in order to allocate the risk at Yucca Mountain. One could follow, for instance, a stewardship ethic (Passmore 1974; see Kasperson and Abdollahzadeh 1988), according to which risk was distributed so as to provide the greatest care for the earth and its inhabitants. Or, one could subscribe to a Rawlsian ethic (Rawls 1971), according to which risk was distributed to benefit the least-well-off persons. Likewise, one could follow a Paretian ethic (Sen 1970; see Kasperson and Abdollahzadeh 1988), or a libertarian ethic (Nozick 1974), and so on.

Perhaps the most important alternative to the utilitarian value judgments in the Yucca Mountain studies is to espouse some version of egalitarian views. Egalitarians follow the ethical theory that one ought to treat persons equally with respect to distribution of social risks, costs, and benefits (see Kasperson et al. 1983, 1988a; Kasperson and Abdollahzadeh 1988; Kleindorfer et al. 1988; Kneese et al. 1983; MacLean 1980; Rawls 1971; Raynor and Cantor 1987; Schultze and Kneese 1981; Shrader-Frechette 1983, pp. 25ff., 136ff.; Shrader-Frechette 1985, pp. 210ff.; Shrader-Frechette 1991, 1991b, 1991c).

On the egalitarian view, members of future generations ought not bear more risk than present persons, and those who live near to Yucca Mountain ought not bear more risk than those who live farther

away from the facility. Indeed, according to egalitarian views, radioactive risk ought to be distributed equally with respect to states, nations, generations, and social groups. Egalitarian ethical theories require not only a substantive, equal distribution of risk, but also they require that risk decisions be made according to principles of procedural equity -- so that all persons with a stake in the decisions have an equal voice, and so that democratic procedure does not violate the interests of any minority.

Investigating the plausibility of the utilitarian -- as opposed to egalitarian -- value judgments evident in the Yucca Mountain assessments is important because substantive moral or political views provide guidance for distribution of risks in a community (Reichard et al. 1990, p. 167). Moreover, economists and philosophers have shown that policy decisions are highly sensitive to assumptions about what ethical theories ought to be employed. The same actions can be shown to be defensible, for example, given a risk-cost-benefit analysis that presupposes Pareto value judgments, but indefensible, given a risk-cost-benefit analysis that presupposes Rawlsian ethical value judgments, and vice versa (Kneese et al. 1973; Shrader-Frechette 1985, pp. 261ff.) Hence, because policy conclusions -- like the suitability of Yucca Mountain for a radwaste repository -- are highly sensitive to ethical assumptions and value judgments, it is important to assess those value judgments carefully.

The major flaw in utilitarian value judgments is that they

allow minorities to be hurt. They allow various groups of persons to be treated inequitably, on grounds of expediency. Egalitarian views, on the other hand, sanction equal treatment of all persons, rather than simply using persons, perhaps violating their rights, in order to achieve some alleged social goal. Applied to Yucca Mountain, the utilitarian-versus-egalitarian issue focuses on distribution of risk. Fears about inequitable or utilitarian risk distributions are what drive the NIMBY (not in my back yard) syndrome. Few persons want to be members of the minority (like Nevadans) bearing the risk for society as a whole. Moreover, because of their emphasis on providing equal protection, equal opportunity, and equal access to due process, it is arguable, from an ethical point of view, that egalitarian theories are preferable to utilitarian theories. The main inadequacy of utilitarian theories of justice and risk distribution is that they fail to provide equal justice and equal treatment to all victims of risk, especially minorities such as persons likely to be harmed by radioactive waste. For this reason, egalitarians charge that utilitarian risk distribution theories inequitably use persons merely as means to the ends of other persons (see Shrader-Frechette 1985, pp. 84ff., 142ff.; Shrader-Frechette 1991, chapter 8).

One of the main vehicles for utilitarian theories of risk distribution, risk-cost-benefit analysis, is particularly controversial when applied to environmental and public health issues like Yucca Mountain (see Reichard et al. 1990, p. 181), because it is questionable whether benefits to a majority of

persons are ever able to offset extreme harms to a minority of persons. In other words, it is not clear that utilitarians are correct in presupposing either that everyone has a price or that it is morally acceptable to trade safety for efficiency or for monetary savings (see Reichard et al. 1990, pp. 162-163). Typically it is cheaper, for example, to employ utilitarian risk-distribution theories in risk assessment and management because one need not worry about less likely "worst-case" situations against which it is more expensive to provide protection (see Reichard et al. 1990, pp. 164-168).

An especially onerous aspect of utilitarian theories of evaluating risk is their implicit assumption that everyone does not have equal rights to protection against societal risk. Rather, the assumption implicit in utilitarian theories is that some persons, some minorities, some victims of risk are expendable, usually on grounds of efficiency or expediency, if the group as a whole will benefit (see Reichard et al. 1990, p. 164). Although proponents of utilitarian risk theories defend it as realistic and workable, opponents claim that it violates the Bill of Rights and the notion of equal treatment under law. Hence, utilitarian presuppositions in risk evaluation are highly questionable (see Shrader-Frechette 1991, chapter 8).

Apart from the ethical grounds for questioning utilitarian value judgments about risk acceptability at Yucca Mountain, there are also practical, inductive reasons for questioning such judgments. These reasons are that, in the past, DOE has used

utilitarian value judgments of risk -- has failed to make safety improvements because of cost considerations -- and these utilitarian judgments have resulted in severe radioactive contamination and threats to the public health and safety. In fact, this utilitarian evaluation of risks is exactly what occurred at the Fernald nuclear feed materials plant in Ohio. The DOE told the managers of the plant to continue operating as they were, even though environmental laws were being broken and human life was threatened. The rationale was utilitarian: it would have been allegedly too expensive to stop production, break the schedule, and correct the safety deficiencies (US Congress 1989b, esp. pp. 27-28). The fact that utilitarian value judgments -- like those made at Fernald -- have led to catastrophes in the past is arguable grounds for assessors not to subscribe to the same assumptions in evaluating the Yucca Mountain risks.

Chapter Four

Problematic Inferences in Assessing Radwaste Risks

In addition to value judgments that embody questionable inferences not fully substantiated by the data (see chapters two and three), risk assessors at Yucca Mountain have made a number of value judgments that are also logically problematic. Some of the more common of these deficiencies of logic are discussed in this chapter.

4.1 The Appeal to Ignorance

One of the most basic problems that occurs in assessing radwaste risk is the appeal to ignorance. One employs this inference in assuming, for example, that because one does not know of a way for repository failure or radionuclide migration to occur, therefore none will occur. Such conclusions are problematic because from ignorance, nothing follows. If there are fundamental uncertainties in one's premises such that one is unable to conclude A, it is deductively invalid to conclude not-A. Hence, the appeal to ignorance violates the first logical condition for an adequate scientific explanation in the strict sense (see section 1.2; Hempel and Oppenheim 1948; Popper 1959). Of course, many scientific conclusions are not deductively confirmed. They are based on good reasons and on inductive support. The problem with assessors' use of the appeal to ignorance in the Yucca Mountain case is that there are inadequate inductive grounds for many of their conclusions. For example, they have inadequate data regarding predictions of future volcanism or seismicity. Hence, in the face of incomplete

data, the assessors often make an invalid inference, an appeal to ignorance. One group of assessors, for example, claimed that there were "no significant technical obstacles to use of the world deserts as sites for a retrievable [radwaste] storage facility for 500 years" (Libby et al. 1982). Here the assessors assume that their ignorance of technical obstacles constitutes a sufficient condition for the assertion that there are no obstacles. Even the Nuclear Regulatory Commission (NRC) asserts that "spent [nuclear] fuel can be stored in a safe and environmentally acceptable manner until disposal facilities are available" (US NRC 1980, p. I-25), and that it has demonstrated "that safe and environmentally acceptable extended storage can be achieved" (US NRC 1980, p. IV-1). On the basis of such claims, risk assessors and policymakers often make the further inference that the desert sites are acceptable, or that nuclear waste storage is demonstrably safe. The problem with such inferences is not that they lack deductive confirmation, because much of science also lacks deductive confirmation. Rather, the problem is that, lacking inadequate inductive data, the assessors appeal to an invalid inference.

In other words, assessors or policymakers often draw a specific conclusion -- despite a dearth of inductive data -- purely on the basis of the absence of evidence to the contrary (Shrader-Frechette 1992). They also often draw a specific conclusion, for example, about successful long-term waste storage, despite avowed and substantial ignorance of the situation or despite the fact that there are no empirical results that confirm their conclusion. Both

instances are examples of the appeal to ignorance (see Shrader-Frechette 1983, pp. 49ff.) For example, several risk assessors admitted that "measurement of infiltration [of water] into Yucca Mountain has not been performed," (Thompson et al. 1984, p. 7). They also admitted that they had not considered fracture flow, even though it could cause rapid migration of radwaste at the site (Thompson et al. 1984, p. 47). Despite these two significant areas of ignorance, the assessors decided that radioactivity releases at the site would be "significantly less" than those imposed by government standards (Thompson et al. 1984, p. i). They also concluded that there would be less than one health effect every 1,400 years caused by Yucca Mountain (Thompson et al. 1984, pp. v-vi).

Some DOE assessors, in a fashion typical of many of the Yucca Mountain assessments, used a computer model to simulate radionuclide transport. The computer model was based on a number of conditions that were either unknown or counterfactual and unrealistic -- such as that the flow was one-dimensional, the transport was dispersionless, the geologic medium was homogenous, and the sorption was in a constant velocity field. Despite these counterfactual and unknown conditions, the assessors concluded that their model "was found to be an effective tool for simulation of the performance of the repository systems at Yucca Mountain" (Lin 1985, pp. i, 1). How could a model -- especially a model based on unproved, counterfactual conditions not known to be applicable to the specific Yucca Mountain site -- be found effective, short of

some actual empirical testing?

The same question arises for other Yucca Mountain risk assessors who write: "for the rock mass, it was assumed that nonlinear effects, including pore water migration and evaporation, could be ignored. In practice, nonlinear effects and the specific configuration of the canister, canister hole, and backfilling material would strongly influence very near field conditions" (St. John 1985, p. 2). Why assume counterfactual conditions known not to be applicable at Yucca Mountain if one is specifically doing a Yucca-Mountain study? Clearly such implicit and explicit claims about repository and canister performance, in the absence of relevant evidence, constitute classic examples of an appeal to ignorance, an invalid inference.

Value judgments that involve problems such as the appeal to ignorance are not limited to a few studies. Indeed, they are found throughout the DOE Yucca Mountain work. Some risk assessors (Borg et al. 1976), for example, claimed that information was insufficient to allow them to state that offsite migration of radwaste would never occur in Nevada, but then they concluded that there was only a small chance of contaminating public water supplies. If they are ignorant about whether offsite migration will occur, how can they know that contamination of water is unlikely? Still other assessors, after noting that changes in groundwater flow "are extremely sensitive to the fracture properties," concluded that they could simulate partially saturated, fractured, porous systems like Yucca Mountain "without taking fractures into

account" (Wang and Narasimhan 1984, p. 44; 1988). Not only does this admission appear inconsistent with their earlier claim about the importance of fracture flow, but the conclusion was based on no empirical work whatsoever, and no application to the Yucca Mountain site. Instead, it was simply derived from capillarity theory and fracture flow laws. Hence the conclusion is another classical example of an appeal to ignorance.

Some assessors have concluded that their simulation models of transport in fractured porous tuff "demonstrate that the validity of the effective continuum approximation method cannot be ascertained in general terms. The approximation will break down for rapid transients in flow systems with low matrix permeability and/or large fracture spacing, so that its applicability needs to be carefully evaluated for the specific processes and conditions under study" (Pruess et al. 1988). Moreover, many of the experiments proposed for Yucca Mountain have never been done before in an unsaturated, fractured medium (NWPO 1988, vol. 2), and very little study of hydrogeologic systems of the type have been done prior to selecting Yucca Mountain (NWPO 1989, vol. 1). If the validity of the radwaste migration methods cannot be ascertained, and if most understanding of radioactive leaching and transport is based merely on laboratory experiments and simulations (Jantzen et al. 1989), then it is impossible to state that the repository will prevent dangerous offsite migration of radionuclides.

Some of the many appeals to ignorance at Yucca Mountain explicitly involve neither simulation models of the site nor

laboratory experimentation. For example, several risk assessors listed 11 assumptions that they had made about the Yucca Mountain site, assumptions such as that the flow path from the repository to the accessible environment would be vertically downward. (This is an assumption also made at Maxey Flats and found to be erroneous after offsite radionuclide migration occurred through horizontal fractures and bedding planes at the site (Meyer 1975, p. 9; Pacific Northwest Laboratory et al. 1980, esp. pp. v, I-1, I-2, I-14, IV-6, IV-9, V-7ff.).) After making these 11 assumptions, some of which appear questionable, the assessors concluded: "Given the general assumptions and boundary conditions listed above, it is not necessary to use sophisticated groundwater flow models or complex contaminant-transport equations to estimate radionuclide transport times and amounts at a repository site....even without engineered barriers, Yucca Mountain would comply with NRC requirements for slow release of wastes" (Sinnock and Lin 1984, pp. 7, 37). This classic appeal to ignorance is based purely on the questionable assumptions made by the risk assessors. It is impossible for any scientist to guarantee regulatory compliance, as these assessors appear to have done, because of possible climate change, volcanic activity, and so on, over the next several centuries. To make such a guarantee is to appeal to ignorance. The only way assessors could have formulated their conclusions in a logically appropriate way would have been to make an "if...then" claim, such as: "if our assumptions about Yucca Mountain are reliable for the centuries required, then Yucca Mountain would comply with NRC requirements."

The same assessors also appeal to ignorance in estimating the failure rate of waste canisters (Sinnock and Lin 1984, p. 47) -- even though the final canister design/composition has not been approved, even though there has been widespread canister failure in the past at DOE radwaste facilities, and even though (in some experiments) all canisters of the required reference material have failed (within a year) because of stress-corrosion cracking (Pitman et al. 1986). It is an appeal to ignorance to estimate the failure rate of a product whose final design is not determined. It is even more of an appeal to ignorance to estimate a low failure rate for an undesigned product when current prototype products fail rapidly (within one year) and seriously. From ignorance about the final design/composition of the canister, no conclusion about failure rate can be drawn.

A number of risk assessors also commit the fallacy of appeal to ignorance in related studies of canister performance. One group of scientists, for example, used Monte Carlo simulation models for waste-package reliability (Sastre et al. 1986, p. 22) and then concluded that the general method of probabilistic reliability analysis is "an acceptable framework to identify, organize and convey the necessary information to satisfy the standard of reasonable assurance of waste package performance according to the regulatory requirements during the containment and controlled release periods" (Sastre et al. 1986, p. 65). Immediately after drawing this positive conclusion about the acceptability of their non-experimental simulation, however -- a conclusion that appears

to be an appeal to ignorance -- the assessors contradicted their own conclusion of acceptability. They wrote: "This document does not show how to address uncertainties in model applicability or degree of completeness of the analysis, which may require a survey of expert...opinions" (Sastre et al. 1986, p. 66). If the document does not address uncertainties in the model or the completeness of the analysis, how can it conclude that the model used in the document is "an acceptable framework" for Yucca Mountain?

A similar inconsistency, combined with an appeal to ignorance, occurs in another important Yucca Mountain risk assessment. The scientists admit that "in most cases, hydraulic data are insufficient for performing geostatistical analyses. Site-characterization studies should provide the hydrogeological data needed for modeling the groundwater travel time based on site statistics" (Sinnock et al. 1986, p. 58). They also admit that they may "have underestimated cumulative releases of all nuclides during 100,000 years, by an amount that is unknown, but probably insignificant" (Sinnock et al. 1986, p. 77). If the hydraulic data are insufficient, and if they have underestimated cumulative releases of nuclides by an unknown amount, then how can the same assessors conclude that the "evidence indicates that the Yucca mountain repository site would be in compliance with regulatory requirements" (Sinnock et al. 1986, pp. i-ii)?

Likewise, the DOE says that deep tests for mineral and petroleum potential at the site are not necessary. Yet, despite their ignorance in this area, the DOE has concluded that the

potential for petroleum or mineral reserves on site is low (Zhang 1989, vol. 2).

Even when assessors attempt to avoid the appeal to ignorance, they often fall into another difficulty, inconsistency. For example, the same assessors (whose conclusions were just discussed in the preceding paragraphs) admit: "Because data and understanding about water flow and contaminant transport in deep unsaturated fractured environments are just beginning to emerge, complete dismissal of the rapid-release scenarios is not possible at this time" (Sinnock and Lin 1984, p. 53). Yet, this reasonable conclusion, about rapid-release scenarios being possible, is inconsistent with their earlier claim that "even without engineered barriers, Yucca Mountain would comply with NRC requirements for slow release of waste" (Sinnock and Lin 1984, p. 53). To be consistent, the assessors would have had to claim that there was a given probability that Yucca Mountain would comply with the requirements, or that there were strong grounds for believing that it would comply, not merely that it "would comply."

Drawing a positive conclusion about the safety and effectiveness of radwaste storage at Yucca Mountain, given a variety of unknowns regarding value judgments, data, and hydrogeological theory, is not only logically problematic but empirically questionable. It is empirically questionable because assessors know that the radioactive fuel rods will be breached and eventually most of the cladding will corrode, exposing fuel to oxidation that will split the cladding and expose additional fuel.

Assessors admit that they have an "underlying uncertainty" about the rate of oxidation, and that the oxidation data that they have gathered has an uncertainty (of which they know) between 15 and 20 percent (Einziger and Buchanan 1988). Moreover, experiments on stress corrosion cracking of spent fuel cladding in a tuff repository environment indicate that the cladding C-rings broke in 25 to 64 days when tested in water; and that they would break in about 75 to 192 days in air (Smith 1988a; see Smith 1988b). Hence, assessors already know that the highly radioactive fuel is likely to be exposed, rather soon after emplacement, to the uncontained environment. Given such knowledge -- as well as fundamental uncertainties, already discussed, about unsaturated fractured geological zones, about adsorption, about seismic activity, about volcanism, and about human contribution to risk at Yucca Mountain -- it is questionable for anyone to claim that the radioisotopes at the site will be isolated from the environment for 10,000 years. Indeed, it seems questionable how anyone can guarantee the integrity of any repository anywhere for more than a century or two, given the current state of knowledge. Conclusions regarding the long-term stability of the Yucca Mountain repository for thousands of years seem not merely to result from attempting to draw a certain conclusion from ignorance, but from attempting to draw a certain conclusion from strong evidence to the contrary. This may account for the charge that the scientific integrity of the site characterization at Yucca Mountain is not acceptable (Thompson Engineering Company 1988).

The problem of appeals to ignorance, in the case of Yucca Mountain, is even more apparent when one considers that most existing US radwaste facilities have leaked in the past and continue to leak. Despite the improvements in the new high-level-radwaste technologies, and despite the past inductive evidence about radwaste migration after only short periods, it is difficult to believe that there will be no radwaste migration at Yucca Mountain for centuries. This past inductive evidence about leaks, as we have already mentioned, includes the facts that all existing means of managing radioactive wastes have resulted in major leaks of radioactivity into the biosphere. Plutonium has travelled off-site from both high- and low-level storage facilities (Kiernan et al. 1977, pp. ix-17; US ERDA-1538 1975, vol. 2, pp. 11.1-H-1 through 11.1-H-4).

At Hanford, the largest commercial storage site for high-level waste, over 500,000 gallons of high-level waste have leaked accidentally from storage containers (Hart 1978, p. 6). Officials from the US Environmental Protection Agency have indicated that, because of migration patterns of radioactivity released directly to the soil and water at Hanford, normal annual radiation releases from this facility "could result in a yearly impact of 580 man-rem total body exposure" (US ERDA-1538 1975, vol. 1, p. X-74; see Shrader-Frechette 1983, chapters two and three). In fact, more than 50 percent of the radioactivity released directly to the soil at certain Hanford sites reaches the Columbia River (via groundwater) in four to ten days (US ERDA-1538 1975, vol. 1, p. II.1-57). Based

on the great number of radioactive leaks from high-level storage tanks, the government has stated: "extrapolation of past data would indicate that future leaks may occur at a rate of 2 to 3 per year" (US ERDA-1538 1975, vol. 1, p. III.2-2).

In addition to the Hanford leaks, radioactive migration also has occurred at two other major waste disposal areas in the US (Savannah River and Idaho National Laboratory), including widespread plutonium contamination in the ground water (US ERDA-1537 1977, pp. II-20 and IV-2; see also US ERDA-1536 1977, p. E-41). If the government did not prevent these leaks in the past, over a decade or two, and if they even project them into the future, suggesting government is not doing enough to prevent them, then it is controversial whether government can and will prevent leaks in the thousands of years to come at Yucca Mountain. This past inductive evidence at Hanford, Savannah River, and Idaho National Laboratory all provides even further reasons for questioning risk assessors' appeal to ignorance in evaluating future potential risks at Yucca Mountain. Indeed, the US Environmental Protection Agency has warned that it is in practice impossible to predict, beyond the next 100 years, what the institutional conditions and costs associated with such storage or management will be, or whether storage or management will even be possible (US EPA 1978, p. 26).

4.2 Begging the Question

In many of the cases of the appeal to ignorance, just cited, the reasoning also presents classical examples of another logical

problem, an invalid deductive inference known as "begging the question." If one assumes what one is trying to prove, then one can be said to beg the question. For example, if one assumes that the health effects of Yucca Mountain will be minimal or that the facility will comply with government radiation standards, then one begs the question. Likewise, if one assumes that a counterfactual model -- that cannot in principle be tested conclusively because of the centuries requiring confirmation -- provides an "effective" simulation of Yucca Mountain (Lin 1985, pp. i, 1), then one begs the question. Indeed, to assume the conclusion, as these assessors did, in the absence of inductive evidence necessary for drawing a conclusion, one way or the other, is a classical example of begging the question, an invalid inference. Begging the question thus violates the first logical condition for an adequate scientific explanation in the strict sense (see section 1.2; Hempel and Oppenheim 1948; Popper 1959). Although science need not be deductively confirmed, reliable science avoids deductive fallacies such as begging the question. Rather than begging the question, assessors who use this inference ought instead to conclude that there is some probability that their conclusion is true, instead of to conclude, invalidly, that it is true. In other words, they ought to have used good probabilistic, inductive, or retroductive reasoning.

Examples of begging the question occur throughout the Yucca Mountain literature. As one assessor put it: "DOE has the confidence that the capability will exist to...conduct the

assessments required for near-term site evaluation and repository-design activities" (Alexander et al. 1990, p. 1283). How could DOE be confident of some capability whose existence could only be established in the future? Indeed, one of the major reviewers of the DOE risk-assessment work at Yucca Mountain concluded: "Much of the data is assumed and not field measured" (GeoTrans 1986, p. 1). For example, the repository design is still indeterminate (State of Nevada 1989b, p. 3; Sawyer 1990, p. 37), and there are many uncertainties regarding the fracturing and radionuclide transport. Yet, assessors repeatedly maintain that their analyses show that the Nevada site would be acceptable (see, for example, Sinnock et al. 1986, pp. i-ii).

Assessors also make claims such as the following: "The subsurface radar profiling system has been demonstrated in the field to be an effective tool in the arsenal of remote sensing devices that can be applied to the location and identification of subsurface disturbances" (Beers and Morey 1981, p. 43). Likewise they claim that "the method [used at Yucca Mountain] can be applied...providing credibility and documentation for decisions regarding the acceptability of any particular site when substantial uncertainties are present," or that "there is no technical obstacle to applying methodology of this type on a larger scale...This application will lead to realistic (rather than simply demonstrative) results" (McGuire 1990, pp. iii, 12-2). How could one possibly claim, correctly, that an unknown application will lead to realistic results? Obviously such a claim begs the

question.

Likewise, how could an assessor claim, for example, that continuum models of the site are "probably sufficient for analysis of the thermomechanical response of excavations in welded tuff" (Board 1989, pp. iii, 66)? Clearly such conclusions assume what they need to prove. Although the Nuclear Regulatory Commission regulations require "use of verifiable and tested scientific models" (Lemons and Brown 1990, p. 6), such examples indicate that assessors nevertheless draw conclusions that beg the question.

Not only the individual assessors but the DOE itself may be guilty of begging the question. The state of Nevada has charged that the site characterization plan of the DOE makes the implicit assumption that the Yucca Mountain site is acceptable (State of Nevada 1988a, vol. 1, pp. 4, I-1), and that the DOE has adopted a site-advocacy approach (State of Nevada 1989c, vol. 2, p. 2), especially because it addresses the question of whether DOE has met licensing requirements, rather than whether the site is suitable (State of Nevada 1988a, vol. 1, pp. I-1 through I-4). The state warns that the DOE's approach "is more one designed to confirm its own preconceived notion of a simplified site model than it is to determine through site investigations the most likely conceptual model for the site that can be supported by objective and comprehensive data collection and analysis" (State of Nevada 1989c, p. 3).

It is surprising that invalid inferences, like begging the question, have occurred in what purports to be excellent scientific

work. One explanation for the problems such as these was offered by the state of Nevada. Nevada charged that the same risk assessors who performed the various scientific and engineering studies and environmental assessments for site suitability would be those used by the DOE to do further studies, both before and after the site is accepted. Hence, argued the state, the assessors have vested interests, if they wish further employment at the site, in presenting an optimistic picture of Yucca Mountain (Bryan 1985, vol.1, pp. I-48 through I-49). Of course, there is no way to confirm or falsify Nevada's claim, but it might provide some insight, if true, into the tendency of assessors to beg the question. Similar claims, about the DOE's pushing the schedule and being more interested in production and siting than in risk assessment -- if true -- could also explain assessors' these difficulties.

Admittedly, given the fact that Yucca Mountain is a "unique, first-ever effort," and that there was virtually no baseline work on the site prior to the Yucca Mountain investigations (Winsor and Malone 1990, pp. 196, 205-206; see Malone 1990b), it is not surprising that assessors often do not have the evidence that they seek. When they do not, however, the solution is to admit such deficiencies, rely on inductive or probabilistic evidence, but not to beg the question. Another way to avoid begging the question is to develop several alternative conceptual models, as the Nuclear Regulatory Commission said ought to be done at Yucca Mountain (State of Nevada 1988b, p. 39). That way, assessors would be less

likely to assume that a model was adequate, just because it was consistent with the available data. Instead, they would be forced to determine which, of a variety of models, were better substantiated by the empirical data. Several examples of the sort of honesty required by the assessors who face major uncertainties in the data and theory relevant to the site are the following admissions:

Objective estimates of probabilities for future resource exploration beyond more than a few years are not possible now; this probably will remain true indefinitely because resource estimates contain a large component...that cannot be predicted realistically (Hunter and Mann 1989, p. 3).

No method is adequate to quantitatively assess, with a high degree of certainty, the probability of tectonic activity at the Yucca Mountain site (Hunter and Mann 1989, p. 7).

There are no good probabilities of volcanism at Yucca Mountain because of the uncertainties owing to limited numbers of events; a statistically good sample population does not exist (Hunter and Mann 1989, p. 10).

It is impossible to predict volcanic eruptions because there is too much uncertainty (Matuska 1988, pp. 11-12).

If assessors followed the procedures of developing alternative models and attempting to test them, or of admitting uncertainties that made their predictions and probabilities unknown, then they could avoid begging the question. They could also avoid the criticism that the tone of the DOE Yucca-Mountain work conveys the conclusion that few problems exist. If the jury is "still out" regarding Yucca Mountain, then it is impossible to conclude, without begging the question, that few problems exist.

4.3 The Expertise Inference

Another important way in which some Yucca Mountain risk

assessors err is in inferring that their calculations and assessments are more reliable than they are. They often assume that it is possible for experts alone to distinguish "actual risk" -- as a property of a technology, policy, or action -- from so-called "perceived risk" postulated by laypersons. Once they make the distinction between actual and perceived risk, some assessors assume that the (misguided) perceived risks of laypeople cause most controversy over technology and environmental impacts (see Whipple in Paustenbach 1989, pp. 1112-1113; Cohen in Paustenbach 1989, p. 575). As a consequence, they work on how to mitigate risk perceptions (which they assume to be erroneous), rather than on how to mitigate the risk itself. They assume that public relations, "risk communication," is their only problem (see Whipple 1989, p. 1113; Liebow 1987; Liebow and Fawcett 1987; Liebow and Herborn 1987; Nealey and Liebow 1988). They assume that the experts understand risk, and that those who disagree are the victims of faulty perceptions. DOE assessors, for example, make precisely this assumption when they reject lay views of risk acceptability, without evidence, and appeal to their own "professional judgment" (see, for example, US DOE 1986a, vol. 2, p. 6-294; US DOE 1986b, vol. 3, p. c. 5-56).

Contrary to the expertise fallacy, however, one cannot completely separate risks and risk perceptions (see Freudenburg 1988; Freudenburg and Jones 1991; Gould et al. 1988; Heimer 1988; Johnson and Covello 1987; Petterson 1988; Slovic 1987; Slovic et al. 1979; and Tversky and Kahneman 1974). All known risks are

perceived, and for at least nine reasons. Before explaining why we cannot completely separate risks and perceived risks, however, it is important to emphasize that we can sometimes distinguish risks from risk perceptions. That they cannot be completely separated, however, does not force us into a complete relativism regarding risk. Even though a risk is perceived, it need not be biased or unreal. The risk of death, for example, although real, is not certain, because it is in part a probability. The risk of death is merely perceived, theoretical, or estimated until death becomes a certainty. Indeed, the occurrence of death, in a particular case, reveals how accurate our perceptions or estimates of the risk of death were. But if this reasoning is correct, then (more generally) although all risks of some X occurring are real, the exact degree and nature of these risks are not, in principle, confirmable until X actually occurs. Prior to this occurrence, risk perceptions can be judged as more or less accurate only on the basis of nonempirical and theoretical criteria like explanatory power, simplicity, internal coherence, and so on. Nevertheless, risk perceptions are often real and objective, at least in the sense that empirical evidence, e.g., accident frequency, is relevant to them and is capable of providing grounds for amending them. This means that all risks (the probability p that some X will occur) are both perceived and real. They are objective, because empirical data are often relevant to them; but they are partially subjective -- a function of one's beliefs -- because their formulation always involves methodological value judgments. Their exact nature and

magnitude become more fully knowable, however, insofar as more instances of X occur. Therefore, because a risk can be both perceived and real, avoiding the expertise inference does not commit us to complete relativism.

Avoiding the expertise inference instead commits us to the belief that we cannot completely separate risks and risk perceptions, even though we can often distinguish them. Why is a complete separation of risks and risk perceptions not possible? First, one cannot establish that a perception about a risk (and not the risk itself) caused a particular impact. It is not enough to establish correlations between particular impacts (e.g., aversion to a particular danger) and specific risk perceptions, because this would not show that the perceptions caused the alleged effects. For example, there might be a correlation between catastrophic risks and the impact of high risk aversion. Yet this correlation might be accidental. Instead, the real cause of high risk aversion might be the lack of control over the hazard, not its catastrophic nature. If so, then it may be difficult to separate completely the impacts of risks and the impacts of risk perceptions.

Second, risk probabilities often do not reflect risk frequencies. This is in part because there are numerous difficulties of hazard estimation that do not admit of analytical, probabilistic resolution by experts. Often the risk problem is not well enough understood to allow accurate predictions, as the use of techniques like fault-tree analysis shows. Hence assessors are forced to rely on subjective or perceived risk probabilities,

instead of on actual empirical accident frequencies established over a long period of trial. Even if assessors based their notions of probability on actual, empirical, accident frequency, this move would not always deliver their estimates of risk from the charge of being "perceived." Since there are reliable frequencies only for events that have had a long recorded history, use of historical accident/hazard data for new technologies can result in an underestimating of the danger; this is because certain events may not have occurred between the inception of a technology and the end of the period for which the risk information is compiled. Moreover, low accident frequency does not prove low accident probability. Only when the period of observing accident frequency approaches infinity would the two, frequency and probability, converge.

A third reason why one cannot completely separate actual from perceived risk, in any wholly accurate way, is that actual risk estimates are sometimes very rough and imprecise. For some phenomena (see chapter one), assessments typically vary from two to six orders of magnitude. Indeed, some level of imprecision is unavoidable, whether the estimates are based on probabilistic calculations or on actual experience. On the one hand, if they are based on probabilities, then assessors are forced to employ a number of value-laden theoretical assumptions and mathematical models. On the other hand, if the risk estimates are based on actual experience, or accident frequency, they are likewise "perceived" because probability does not equal frequency, as has already been argued. Moreover, even actual frequencies do not

provide a precise measure of a particular risk, because this number is typically formulated as an average, and such averages, by definition, do not take particular, perhaps site-specific, deviations into account.

Fourth, some of the most important aspects of hazards, whether real or perceived, are not amenable to quantification. (What experts call) "actual" risk estimates are based on the presupposition that risk is measured by probability and consequences, and that both can be quantified. Yet most laypeople would probably claim that what makes a thing most hazardous are factors that are not susceptible to quantification, factors such as a risk being imposed without consent, or being unknown, or posing a threat to civil liberties or to rights of future generations (MacLean 1986; Shrader-Frechette 1985, pp. 176ff.; Shrader-Frechette 1991, chapter 2; Andrews 1988, pp. 85-97; Cox and Ricci in Paustenbach 1989a, pp. 1017-1046).

Completely separating risks and risk perceptions is likewise impossible because both are theoretical concepts and hence not completely amenable to precise empirical prediction or confirmation. In general, "risk" is defined in terms of expected utility theory and hence is a theoretical concept carrying with it all the baggage of this specific decision theory (see Shrader-Frechette 1991, chapter 8). In particular applications, "risk" is always defined on the basis of a whole host of theoretical assumptions, many of which are often controversial. For example, a number of incompatible "cancer models" (dose-response

models), each with attendant assumptions, has been used to estimate the incidence of tumors in populations exposed to formaldehyde. In 1987, the US Environmental Protection Agency (EPA) researchers called formaldehyde a "probable human carcinogen." They said that those exposed to formaldehyde-treated pressed wood could face a cancer risk, over 10 years, of 2 in 10,000. Experts at the Harvard School of Public Health, however, criticized the EPA risk assessment as premature and said the true formaldehyde risk was uncertain. Still other experts, including scientists at the American Cancer Society and the Consumer Product Safety Commission, argued that the EPA models were incorrect, but in the opposite direction. They said EPA findings underestimated the cancer risk (Ricci and Henderson 1988, pp. 288-293; Paustenbach 1989, pp. 38-39; Gammage and Travis in Paustenbach 1989, pp. 601-611). The formaldehyde case, as well as those of EDB, dioxin, and methylene chloride, all illustrate that, even as late as the nineteen eighties, particular accounts of risk are highly controversial and theory-laden. But if risk is known in terms of the categories of a particular scientific or modeling theory, then there is no actual hazard that is completely separable from some particular theoretical account of it. Hence, there is no uncontroversial way to completely separate "actual" from "perceived" risk.

Sixth, because risk perceptions often affect risk probabilities, and vice versa, it is frequently impossible to completely separate hazards from perceptions of them. This is well known to social scientists as part of the "self-fulfilling

prophecy." For example, if I perceive my chances of getting cancer to be high, then my perceptions can exacerbate stress and therefore increase the probability that I actually do become a cancer victim. Hence it is often impossible to separate actual and perceived risk.

There are also a number of reasons for arguing that the complete separation of actual and perceived risk cannot be based on the alleged objectivity of expert estimates, as opposed to the alleged subjectivity of lay risk estimates. Admittedly, laypersons typically overestimate the severity of many technological hazards. However, even if it could be established that the public exaggerates the accident probabilities associated with some technology, e.g., liquified natural gas (LNG), this fact alone would be a necessary, but not a sufficient, condition for establishing the thesis that laypersons erroneously overestimate risks. This is because, even though laypersons' perceived probabilities may be erroneous, they may not completely explain their risk aversion. The public might view risks as high, not only because of their accident probabilities, but also because their consequences are potentially catastrophic, or involuntarily imposed, or for some other reason.

Eighth, apart from whether probabilities alone explain risk judgments, there is reason to believe that, at least in some areas, expert estimates of probabilities are not necessarily superior to those of laypeople. In their classic studies of the heuristic judgmental strategies that often lead to error in probability estimates, Kahneman and Tversky concluded that experts were just as

prone as laypeople to judgmental error regarding probabilities whenever they had merely statistical data. Experts are particularly susceptible, for example, to the fallacy known as representativeness, the gratuitous assumption that a particular sample is similar in relevant respects to its parent population and that it represents the salient features of the process by which it was generated. Kahneman and Tversky showed not only that experts were just as prone to this probabilistic bias as laypeople, but also that, even after the error was explained to the experts, the bias could not be "unlearned" (Tversky and Kahneman 1982, pp. 23-31; Kahneman, Slovic, and Tversky 1982; Kahneman and Tversky 1982, pp. 46-47).

Another common judgmental error of mathematically trained professionals is overconfidence; this occurs because experts' trust in their probability estimates is typically a function of how much information they have gathered, rather than a function of its accuracy or its predictive success. Since everyone, even those highly trained in probability and statistics, must make simplifying assumptions in estimating probabilities, and since experts are just as prone as laypeople to these judgmental errors, there is little reason to believe that experts are always able to calculate actual or real risk, while laypeople are merely able only to construct perceived or subjective risk (see Oskamp 1982, pp. 287-293).

A ninth difficulty is that those who attempt to separate "actual risk" and "perceived risk" are wrong to assume that the latter is merely an erroneous understanding of the former (Whipple

1989 and Cohen 1989). They are wrong because there is no universal definition of risk underlying the two concepts. For one thing, assessors disagree as to whether (and when) to employ concepts such as "individual risk," "relative risk," "population risk," and "absolute risk" (Cox in Woodhead et al. 1988, pp. 233-243; see Ames, Magaw, and Gold 1989, pp. 1083ff.; Layard and Silvers in Paustenbach 1989, p. 159; Harley in Paustenbach 1989, p. 620; and Cohen 1989, p. 574). Moreover, as was already suggested, the term 'risk' in "actual risk" and "perceived risk" has neither the same referent nor the same meaning. What Hafele, Okrent, Jones-Lee, Morgan, and others (see Shrader-Frechette, chapter 3) call "actual risk" is the probability of a particular hazard occurring, times the magnitude of its consequences. What they call "perceived risk," alleging that it is an incorrect view of actual risk, however, is not merely (an incorrect) perception of probability times consequences. Rather, most laypeople would claim that (what typical risk assessors call) "perceived risk" includes more than mere probability. Hence when laypeople say that something is a "high risk," they do not necessarily mean only that it has a high probability of causing death. (See the next chapter for more discussion of this point.) And if so, then "actual risk" is not mere probability times fatality, and "perceived risks" are not merely perceptions of probability times fatality.

In sum, no complete separation is possible between perceived risks and actual risks. If there were hazards that were not perceived, then we would not know them. Because we know them, in

some sense, proves that risks are perceived, even real risks must be known via categories and perceptions. This is related to the earlier point that all known risks are, in part, theoretical constructs, not completely empirical, not wholly capable of confirmation. And if not, then the expertise inference apparently violates at least the third logical condition for a scientifically adequate explanation in the strict sense, that its premises have empirical, testable content (see section 1.2; Hempel and Oppenheim 1948; Popper 1959).

Some Yucca Mountain assessors have fallen victim to the expertise inference, assuming that a complete separation is possible between actual risk calculated by experts and perceived risk estimated by laypersons. (For discussions of risk perception see, for example, Freudenburg 1988; Freudenburg and Jones 1991; Gould et al. 1988; Heimer 1988; Johnson and Covello 1987; Petterson 1988; Slovic 1987; Slovic et al. 1979; and Tversky and Kahneman 1974.) They have ignored the fact that all known risks are perceived and hence value-laden, and they have assumed that risks calculated by experts are free of subjective perceptions. For example, one industry assessor (Yasinsky 1983) argued that public concern over radwaste was caused primarily by the absence of a structured, scheduled waste-management program, rather than by real concern over long-term safety. In other words, the assessor assumed that he understood the risk objectively, that the "real" risk was minimal, and that the problem with laypersons was merely their misperception of the risk. However, there is no known "real" risk

that is not structured by experts' value judgments about it. Thus there is no easy assurance that the allegedly "real" radiation risk is minimal. Hence, those who use the expertise inference typically beg the question of risk acceptability.

Dismissals of lay risk perceptions regarding radwaste are all the more questionable because some researchers (Davis 1988) have reported that 74 percent of Nevadans believe that the state should do everything in its power to stop the Yucca Mountain repository. The percentage of Nevadans who would vote against a repository is at least 80 percent (Slovic et al. 1991, p. 1604). Such statistics suggest that something more is at issue than merely faulty perceptions of an allegedly "real" risk that is minimal.

Instead, in cases like that at Yucca Mountain, there is a quantitative, "expert" definition of risk, as opposed to a qualitative, allegedly subjective notion of lay risk perception. Those who fall victim to the expertise inference typically assume that risk can be defined purely probabilistically, for example, as an average annual probability of fatality (see Shrader-Frechette 1991, chapter four). They likewise assume that anyone (e.g., a layperson concerned about consent, equity, etc.) who does not subscribe to this purely probabilistic definition has an erroneous risk perception, rather than an accurate, alternative risk perception. It will not do to stipulatively define one type of risk (that of laypeople) merely as a misperception of another type of risk (that of experts), however. All known risks are perceived, and all risk judgments involve methodological value judgments.

There are no perception-free risks that are known, and hence there are neither wholly objective risk assessors nor wholly accurate risk perceptions.

What is important about lay risk perceptions is that most laypeople would probably claim that what makes a thing most hazardous are factors that are not susceptible to quantification, factors such as a risk's being imposed without consent, or being unknown, or posing a threat to civil liberties or to the welfare of members of future generations. Such factors are part of the reason why consideration of potential human error and the social amplification of risk is so important at Yucca Mountain (Slovic et al. 1989), even though most probabilistic risk assessment ignores the social amplification of risk (Burns et al. 1990).

Moreover, if laypersons have perceptions of mismanagement or managerial incompetence at Yucca Mountain, then this perception is likely to influence any response to hazardous events to the same degree as does the likely scale of some feared event (Burns et al. 1990, p. 660). Perceived risks are often good predictors of socioeconomic impacts and of people's reactions to them (see Petterson 1988; Peters and Hennen 1988). Hence, no complete separation may be possible between actual and perceived risk.

Admittedly, at Yucca Mountain, there is a large gap between the public and lay perceptions of the risks associated with the repository (Slovic et al. 1990, p. i). However, even if it could be established that the public exaggerates the threatening probabilities associated with some facility, like Yucca Mountain,

this alleged exaggeration might not be the main reason for opposition to Yucca Mountain. The opposition could be based, for example, on potential threats to future generations or on future socioeconomic impacts. Hence, the lay risk perceptions might not be so much wrong, compared to those of experts, as they are based on different values about risk.

Apart from the fact that it is not possible to completely separate risk from risk perceptions, if policymakers assume that there is a perceived risk/real risk distinction, and that expert assessors can describe "real" risk, then at least two undesirable consequences could occur. One consequence is that there would be less reason for policymakers to take account of lay views, because they were allegedly erroneous. ("Error has no rights.") Employing the expertise inference could lead to disenfranchising the public, since their views of risk often conflict with those of experts. This appears to be one of the causes of concern at Yucca Mountain. As our earlier discussion of human error (see section 2.8 of chapter two) suggested, Nevadans are worried about being disenfranchised and about decisions being made that are not in their interests. Hence, it behooves all risk assessors to avoid the expertise inference and to attempt to understand lay risk perceptions. They are important, at least because of the lack of trust that often lies behind them (Slovic et al. 1990).

4.4 The Linearity Inference

Another common inference to which risk assessors sometimes subscribe is the linearity inference. This is the belief that for

any rational and informed person there is a linear relationship between a risk (defined as an annual probability of fatality) and the value of avoiding the risk (Cohen 1989, p. 575; Whipple 1989, pp. 1112-1113; Shrader-Frechette 1982). Following this inference, many hazard assessors "explain" a societal aversion to certain low-probability technological risks by assuming that the public does not know the accident probabilities in question. They maintain that, given knowledge of the actual likelihood of death, rational persons always are more averse to high-probability risks than to low-probability ones.

The linearity inference can be problematic for risk analysts in part, because the restriction of risk to "probability of fatality" is highly questionable. There are obviously many other cost burdens, e.g., "decreasing the GNP by a given amount," whose probability also determines the value of avoiding a given risk. In other words, just as we noted in sections 3.2, 3.5, and 3.7, so also here there is no deductive connection between premises (specifying risk as some probability of fatality) and a conclusion (about acceptable risk). And if not, this inference fails to meet the first logical condition for an adequate scientific explanation in the strict sense (see section 1.2; Hempel and Oppenheim 1948; Popper 1959). Likewise, there appear to be no compelling inductive reasons for relying on the linearity inference because the value of avoiding a given risk is often a function of the benefits to be gained from it, or whether it is distributed inequitably (Cox and Ricci in Paustenbach 1989a, pp. 1017-1046; Rowe 1977, p. 926). In

fact, if Fischhoff and other assessors who employ psychometric surveys are correct, then risk acceptability is more closely correlated with equity than any other factors (Fischhoff, Slovic, and Lichtenstein 1980, p. 207; Kates and Weinberg, et al. 1986). Catastrophic potential and the fact that low-probability/high consequence situations are often the product of societally imposed (as opposed to privately chosen) risks may also explain risk aversion. There is evidence that the psychological trauma (feelings of impotence, depression, rage) associated with the imposition of a public risk is greater than that associated with the choice of a private risk of the same probability. One author even suggests that widespread despair and an increasing suicide rate may be attributable to the hazards and fatalities caused by "industrial cannibalism" (Samuels in Woodhead et al. 1988, pp. 113-120; Pahner 1975, p. 575). If so, then there may be good reason why society's risk aversion is not proportional to probability of fatality.

Moreover, although according to utility theory, a high-probability/low-consequence event (10,000 accidents, each killing 1 person) and a low-probability/high-consequence situation (1 accident's killing 10,000 persons) may have the same expected value, reasonable persons are typically more averse to the low-probability/high-consequence situation. One explanation may be that the high-consequence events, like nuclear accidents or catastrophic global warming, are often more difficult to quantify (Gleick and Holdren 1981, p. 1046; Van Horn and Wilson 1976, p. 19). Regardless of the reason, however, it is clear that many

rational people do not believe that the value of risk aversion is directly proportional to the probability of fatality associated with it. And if not, then to infer this proportionality is to subscribe to the linearity inference.

Exemplifying the linearity inference, one Yucca Mountain quantitative risk assessment (QRA) argued that it was too expensive to fabricate a 10,000-year waste package merely to meet Environmental Protection Agency (EPA) and Nuclear Regulatory Commission (NRC) standards for carbon-14 dioxide because the numbers of persons likely to be benefitted were quite small (Park and Pflum 1990). The assumptions underlying this inference are that only large risks to the general population, not smaller risks to a restricted population, are worth expensive controls. Another value judgment here is that equity in risk distribution is not important, only the overall magnitude of risk. Likewise the inference presupposes that the value of risk avoidance is proportional to the probability of fatality.

Whenever they fall victim to the linearity inference, assessors discount the importance of the cumulative nature of radiation risks, the inequities imposed by "average" standards, and the necessity of consent and compensation for all those on whom risks are involuntarily imposed. In ignoring all these social and ethical determinants of risk acceptability, assessors likewise make a number of questionable utilitarian value judgments (see section 3.9 in the previous chapter), such as that the rights of the minority -- to protection from risk -- can be ignored. They also

reduce risk to purely "physical" impacts and ignore the fact that low-probability, high-consequence risks could be unacceptable. For all these reasons, the linearity inference ought to be avoided in Yucca Mountain QRA.

4.5 The De Minimis Inference

Another problem that frequently occurs at the risk evaluation stage of risk assessment is the inference that, because a particular exposure to risk is below a certain threshold or within a certain standard, therefore the exposure is harmless or acceptable. Like other value judgments and inferences criticized earlier in sections 3.2, 3.5, 3.7, and 4.4, this inference does not meet the first logical condition for scientific adequacy in the strict sense because there is no deductive connection between the premises (about a level of risk) and the conclusion (about risk acceptability). Hence, the inference is flawed (see section 1.2; Hempel and Oppenheim 1948; Popper 1959). Even on inductive or retroductive grounds, the inference is also problematic, especially in the case of radiation, because exposures are cumulative. Hence, numerous allegedly small exposures to radiation could yield a cumulative dose that causes injury or death. It is inconsistent and dangerous to condone sub-threshold hazards but to condemn the deaths caused by the aggregate of these sub-threshold harms. It is irrational for risk assessors to say both that sub-threshold exposures to a cumulative hazard are harmless, and yet that the additivity, or contribution, of these doses causes great harm. If they claim that sub-threshold risks are unacceptable, then they

face the undesirable consequence that government must somehow regulate or compensate for such risks, an extraordinarily difficult and expensive task, since attaining zero risk is technically and practically impossible. If they claim that sub-threshold risks are acceptable, then they must admit that, while it is immoral to murder fellow citizens, it is moral to allow them to be killed by hazards such as radiation, little by little. The only consistent path is to admit that even small exposures to a cumulative hazard are harmful (see Shrader-Frechette 1991, pp. 70ff.).

A related difficulty occurs because society must declare some threshold, below which a hazard is judged to be negligible. Often this de minimis level for a given risk is set at what would cause less than a 10^{-6} increase in one's average annual probability of fatality (Comar, 1979, p. 319; Cox and Ricci 1989a, pp. 1028-1041). The reasoning behind setting such a level is that a zero-risk society is impossible, and some standard needs to be set, especially in order to determine pollution-control expenditures. Choosing the 10^{-6} standard also appears reasonable, both because society must attempt to reduce larger risks first, and because 10^{-6} is the natural-hazards death rate (Starr 1979, pp. 14ff.; Cox and Ricci 1989b, pp. 134-135). The problematic inference arises because no de minimis standard is able to provide equal protection from harm to all citizens. On one hand, if one rejects the de minimis standard, then pollution-control requirements would be difficult to determine. On the other hand, if one accepts the de minimis standard, then citizen protection would be based on some average

annual probability of fatality, not on equal protection for all.

Because the 10^{-6} threshold seems acceptable, on the average, does not mean that it is acceptable to each individual. Most civil rights, for example, are not accorded on the basis of the average needs of persons, but on the basis of individual characteristics. Hence, why is a 10^{-6} average threshold accepted for everyone, without compensation, when adopting it poses risks higher than 10^{-6} for the elderly, for children, for persons with previous exposures to carcinogens, for those with allergies, for persons who must lead sedentary lives, and for the poor? Hence, for risk assessors to make the de minimis inference and claim that average exposure data or average levels of risk are harmless or acceptable can be problematic. To use such average levels requires somehow that persons consent to possible additional risk that they may bear and/or that they be compensated for possible risk that exceeds the average level (see Shrader-Frechette 1991, pp. 71ff.).

One of the clearest examples of the de minimis inference occurs in a DOE document stating: "the rule of thumb is that scenario classes in which combinations of processes and events have less than 1 chance in 10,000 of occurring during the period of interest are generally excluded from further consideration" (US DOE 1990a, p. 3-14). The judgment is problematic for all the reasons already considered, as well as questionable for a number of other reasons. One reason is that the DOE has claimed (Rusche in US Congress 1986, pp. 484-485) that it regulates Yucca Mountain consistent with other nuclear facilities. Yet the regulations

governing other nuclear facilities specifically require consideration of all risks greater than 10^{-6} per year (see Shrader-Frechette 1991, chapter 5). This means that the DOE is being inconsistent in allowing Yucca Mountain risks to be two orders of magnitude higher than other nuclear risks before they are subject to analysis and potential regulation. The more serious problem, however, is that the DOE assumes that some level of risk, below 10^{-4} , is acceptable merely because it is of a certain magnitude (see Shrader-Frechette 1991, chapters 5 and 7). As we have already explained, magnitude alone does not make a risk acceptable; one must take account of factors such as accuracy of the estimates, equity, consent, compensation, due process, and so on.

Similar de minimis assumptions and value judgments have also been made by some Yucca Mountain assessors when they concluded that risk from transport of radioactive materials to and from Yucca Mountain was "small" merely because they predicted it to be below the level of natural background risks already occurring in the US (Neuhauser et al. 1986). The researchers predicted Yucca Mountain truck, rail, and radiological fatalities to be as high, respectively, as 38, 8, and 12 deaths during the first 26 years of the operation of the repository. Their judgment of smallness, in turn, carries with it a presupposition of acceptability of the Yucca-Mountain risk. However, no risk is small enough if it is avoidable or not necessary or unfair or inequitably distributed. Hence, it should not be assumed that some de minimis risk level is

acceptable purely because of its magnitude.

4.6 The Consent Inference

Another risk-evaluation problem occurs whenever assessors forget that, all things being equal, rational persons are more averse to risks to which they have not consented than to those voluntarily received. As a consequence of human rights to free, informed consent, imposition of certain risks is ethically legitimate only after consent is obtained from the affected parties. Questions of consent pose problems for risk evaluation because all those genuinely able to give legitimate consent to a particular risk are precisely those who likely will never do so, whereas those alleged to have given consent to a particular risk are often those who are unable to do so. A good example of this arises in workplace situations. Here there is an alleged compensating wage differential, noted both by economists and risk assessors. According to the theory behind the differential, the riskier the occupation, the higher the wage required to compensate the worker for bearing the risk, all things being equal (Brown 1980, p. 113-134; Dillingham 1979; McLean et al. 1978, pp. 97-107; Olson 1979; Smith 1973; Thaler and Rosen 1976, pp. 265-298; and Viscusi 1979; Graham and Shakow 1981, pp. 14-20, 44-45, and Graham et al. 1983, pp. 14-27).

Moreover, imposition of these higher workplace hazards is legitimate apparently only after the worker consents, with knowledge of the risks involved, to perform the work for the agreed-upon wage. Yet, who is most likely to give legitimate

informed consent to a workplace hazard? It is a person who is well educated and possesses a reasonable understanding of the risk, especially its long-term and probabilistic effects. It is a person who is not forced, under dire financial constraints, to take a job that he knows is likely to harm him. Yet, sociological data reveal that, as education and income rise, persons are less willing to take risky jobs or to tolerate risky facilities in their communities, and that those who do so are primarily those who are poorly educated or financially strapped (Eckholm 1977, pp. 31-33; Berman 1978; see also Paustenbach 1989, pp. 34-35, and Samuels 1988, pp. 113-120).

If these sociological data about situations of consent are accurate, and if one does not wish to sacrifice either workers or citizens who have not given free, informed consent to the risks that they face, then risk assessors ought to evaluate involuntarily imposed hazards more negatively. Or, risks ought to be assessed as less acceptable, all things being equal, to the degree that potential victims are less likely to have given genuine free, informed consent (see Shrader-Frechette 1991, pp. 72ff.). Frequently, however, assessors do not evaluate involuntary risks more negatively.

In the Yucca Mountain work, virtually none of the DOE assessments are dedicated to assessing whether the repository has jeopardized citizens' rights to free, informed consent and thus imposed an undesirable ethical and social burden on the public. One of the ways in which the Yucca Mountain assessments have reflected

problems involving consent is in failing to provide adequate information to citizens about the nature of the possible risks that they might face because of the repository. The reluctance of the DOE to consider worst cases and to assess possible events having a probability lower than 10^{-4} per year indicates that the site studies will have limited information about the repository risk. Other causes of limited information at Yucca Mountain are the insistence of DOE on meeting the schedule for completion of assessments (US Congress 1987a, p. 212) -- rather than on assessing the risks in a comprehensive way -- and the secrecy and bias that have pervaded DOE repository activities (US Congress 1987a, p. 213). Indeed, until the DOE was sued, it refused to fund Nevada requests for independent experts to study the site (US Congress 1987a, pp. 216, 726). As a result, Nevadans have charged the DOE with not consulting adequately regarding the evaluation of the site (US Congress 1987a, pp. 699-746).

Affected citizens from Nevada, Texas, Washington, and Mississippi also have charged that the DOE has withheld data regarding the nuclear-waste-siting activities or radioactive facilities in their respective states (US Congress 1987a, pp. 216-245, 466-509). As a result, the GAO concluded that the "DOE has not allowed them (states and Indian tribes) to participate in the program to the extent intended by the [Nuclear Waste Policy] Act [of 1982] (US Congress 1987a, p. 923). Dozens of lawsuits have been brought against the DOE regarding its handling of the waste program (US Congress 1987a, p. 747). Because the DOE has made it difficult

for the public to obtain adequate information about Yucca Mountain, the public cannot exercise its rights to free, informed consent to the risk. And if the assessment process has jeopardized the public's exercise of free, informed consent to the Yucca Mountain risk, then that assessment process is likely flawed.

4.7 Inferences of Specious Accuracy

Risk assessors at Yucca Mountain also appear to have confused the precision of their quantitative results with their applicability in the specific situation (what will be termed "specious accuracy"). For example, economists use "price" to stand for "value." They then infer that, because the substituted concepts have predictive and explanatory power, therefore they have captured the original phenomena. In inferring that they have captured the original phenomena, as Morgenstern (1963, p. 62) explains, they fall victim to "specious accuracy," to confusing precision with applicability. They confuse precisely accurate, but irrelevant and inapplicable, results with real explanation. In so doing, they simplify the situation, but in a way that misrepresents it or that renders objective risk assessment impossible. They become like the drunk who looks for his watch under the street light, not because he lost it there, but because it is the only place he can see. Likewise, assessors often calculate results that are available, rather than those that are relevant. For example, some assessors evaluated the test-selection process for Yucca Mountain and outlined information needs, but then asserted that determination of acceptable levels of confidence was outside the scope of their

investigations (see, for instance, Roberds and Bauhof 1983). Yet, without determination of an acceptable confidence level, results are not obviously applicable or reliable. Other assessors likewise calculated rates of radionuclide discharge at Yucca Mountain by using methods that assumed that transport was of a single radionuclide; that the rock contained uniform parallel fractures; or that the flow was one-dimensional (see, for example, Erickson et al. 1986). By making all these (and other) assumptions, assessors were able to get precise quantitative results. Without the assumptions, no calculations would be possible. Yet the precise results were not applicable to the situation since the assumptions were counterfactual, at least in the Yucca Mountain case. Hence, the results exhibited a specious accuracy.

Such specious accuracy has caused problems at radwaste repositories in the past. Consider, for example, the counterfactual assumption in many of the Yucca Mountain groundwater models, that the flow is one-dimensional or vertical (see, for example, Sinnock and Lin 1988; Huyakorn et al. 1987; Gutjahr et al. 1987). Because this assumption was made at the Maxey Flats radioactive waste site, assessors missed the lateral components of flow that appear to have been one of the main vehicles for release of the radioactive leachate. This particular methodological value judgment, about one-dimensional flow at Yucca Mountain, should be scrutinized all the more carefully because some researchers (Rulon et al. 1986) have indicated that there is great potential for lateral flow through faults and fractures at Yucca Mountain. If so, we could

repeat Maxey Flats mistakes in Nevada unless Yucca Mountain assessors continue to model multi-dimensional vertical and lateral flow, and not merely one dimensional, vertical flow (see Project History in US DOE 1990b, p. viii). The above illustration is not intended to infer that Yucca Mountain and Maxey Flats are analogous hydrogeologically. Rather, the same problem in logic in assessing performance appears to be operative in both instances.

Of course, some researchers have recognized and avoided inferences of specious accuracy. They have specifically noted that their conclusions are based on "best scientific judgment" but that they may not be applicable to specific sites, given the disanalogies between the general models and the heterogeneous field situations (Mara 1980). Nevertheless, a number of risk assessors appear to have forgotten the limits on reliability imposed by their value judgments. Clearly, however, there are no compelling scientific grounds for the move from premises (about precise site characteristics) to a conclusion (about the acceptability of those characteristics). And if not, then there is reason to question inferences of specious accuracy.

4.8 Inferences Regarding the Multiple Maximand

Another problematic inference that occurs frequently in the Yucca Mountain QRA is the claim that it is possible to maximize both safety and efficiency in storing radioactive waste. The DOE mandates Yucca Mountain repository performance, for example, that is both safe and efficient (US DOE 1990a, pp. 2-5). This mandate presupposes a problematic goal, because it is impossible to

observe. Greater safety is more expensive, and greater efficiency of time and money results in less safe radwaste management. The value judgment that one can maximize two variables is clearly problematic, because only a priority ranking is mathematically possible, with one or the other being maximized at a time. Of course, some multiple-objective analyses are possible, particularly by using differential equations. Actually maximizing multiple variables, however, is not possible.

Apart from the mathematical impossibility of maximizing two variables, like safety and efficiency, there is also a practical reason for questioning the claim that one can maximize safety and efficiency at Yucca Mountain. This practical reason is that the US DOE is in charge of both production and safety at its installations; US Representative Tom Luken calls this the "big similarity" between Chernobyl and DOE facilities, and US Representative Ron Wyden has talked about the fox (the DOE) guarding the henhouse, the DOE facilities (US Congress 1987b, pp. 5, 6).

As another representative put it: "The DOE system of virtual self-regulation is incompatible with the built in pressures for production" (US Congress 1987b, pp. 7-9; see Malone 1989a, p. 92; State of Nevada 1988b, pp. 20-23; Alexander et al. 1990). As a result of such self-regulation, at DOE radiation-related facilities like the feed-materials plant at Fernald, Ohio, efficiency and production have always had the highest priority. According to Rep. Philip Sharp and representatives of the Fernald labor union, the

tradeoffs between safety and production have been very pronounced and the source of many difficulties at the Ohio facility. Production and "meeting the schedule" have always come first (US Congress 1986, p. 107; US Congress 1987b, p. 144). Indeed, as we already mentioned, the competition between safety and production, according to Representative Tom Luken, caused government either to ignore reports of health and safety violations or to retaliate against the whistleblowers (US Congress 1987b, p. 108; US Congress 1989b, pp. 1-3, 54ff.).

K. O. Fultz of the Government Accounting Office (GAO) confirmed that, because of the push to meet production schedules (efficiency), the DOE has repeatedly allowed safety to be compromised in the name of alleged efficiency. Fernald, Lawrence Livermore, Savannah River, Rocky Flats, Hanford, Oak Ridge, Rocky Flats, and Idaho Falls all have extensive soil and water contamination caused by pressure to meet the schedule and to work cost effectively. Moreover, Washington, Nevada, Mississippi, Minnesota, and other states have complained about DOE's pushing its schedule above all else (US Congress 1986, pp. 133ff., 219ff., 235ff., 269ff., 506ff., 625, 667ff.; US Congress 1987a, p. 2; US Congress 1989a, p. 28). As US Representative Tom Luken put it, "in many cases the DOE decided the costs [of removing safety violations] were prohibitive and therefore the health [of workers and the public] would be sacrificed" (US Congress 1989b, p. 25). In 1985 the DOE (in the Kane Report) and said that the Department's environmental, health, and safety program was a "toothless

watchdog...a disgrace" (US Congress 1987b, p. 2).

Such 1985 criticisms of the DOE apparently did little to accomplish reform because, in 1989, every nuclear materials reactor in the US was shut down because of safety problems (US Congress 1989a, pp. 36-45). As US Representative Tom Luken put it, this suggests that the DOE record of inductive evidence on safety indicates that short-term efficiency often is allowed to take precedence to safety. Hence there is a strong empirical base for doubting that the DOE at Yucca Mountain would be likely to maximize safety considerations if they got in the way of considerations of efficiency. Indeed, reviewers have already charged that, at Yucca Mountain, "the schedule constraint appears to be driving the heavy reliance on analytical models in determining site suitability, rather than determining suitability through the use of empirical findings" (State of Nevada 1989c, vol. 1, p. 3).

Risk assessors themselves have claimed that tight schedules for producing final versions of environmental assessments for Yucca Mountain have prevented their using developed equations for estimating releases of radionuclides into groundwater (Sinnock et al. 1986, p. 75; see State of Nevada 1988b, pp. 20-23). Other assessors (see, for example, Board 1989, p. 66) have claimed that they chose particular models of the Yucca Mountain site because they were easier and more efficient to use. Hence, it is not surprising that the state of Nevada has argued before Congress that the DOE is "driven by schedule" rather than by safety considerations, and that the environmental assessment of Yucca

Mountain is based on "incomplete, inaccurate, and sometimes manipulated data" (US Congress 1987a, pp. 212-213).

Representatives of other citizens affected by DOE facilities in other states -- Ohio, Washington, Texas, for example -- have made similar charges (US Congress 1987a, pp. 245-271). If schedule efficiency prevents adequate risk studies, then there is reason to believe that other considerations of alleged efficiency might compromise safety at Yucca Mountain in the future, just as they have at other DOE facilities and as they appear to have done already at Yucca Mountain. And if so, then there are additional social, political, and practical grounds for believing that it is impossible to maximize both safety and efficiency at radwaste facilities, including Yucca Mountain.

4.9 Affirming the Consequent

Yet another problem that manifests itself frequently in the Yucca Mountain risk assessment is "affirming the consequent." This occurs whenever one postulates that a hypothesis is true or accurate, merely because some predicted test result -- predicted to follow from the hypothesis -- actually occurs. Such a conclusion, however, obviously does not follow deductively from premises that have successfully predicted certain occurrences. In fact, however, test results can only falsify theories, never verify them. A particular test result's occurring never establishes the truth of the hypothesis from which it follows, because "h entails r" is not the same as "r entails h." All that can be validly inferred from a test is that the results are consistent with the hypothesis or that

the results have falsified the hypothesis, h, because of the failure of r. In other words, from "h entails r," one can infer "not r entails not h." To assume that one can infer "r entails h," from "h entails r" is to affirm the consequent and thus to make an invalid inference.

Admittedly, there is substantial value in testing one's hypotheses, in order to determine whether the data falsifies them or tends to confirm them. Moreover, the greater the number of tests, and the more representative they are, the greater assurance is there that the data are consistent with the hypotheses. Indeed, one of the repeatedly acknowledged failures of the Yucca Mountain assessments is that the models are often not tested (see, for example, State of Nevada 1989c, vol. 1, p. 3; vol. 2, p. 2). It is important to test the models, to attempt to falsify them, and to determine the degree to which they are consistent with the data. If the models do turn out to be consistent with the data, however, it is not appropriate to assume that they have been "verified" or "validated" because, short of affirming the consequent, it is impossible to verify or validate any model. It is possible merely to achieve higher degrees of probability, through testing, that the hypothesis or model is confirmed to this or that degree.

At Yucca Mountain, risk assessors repeatedly propose to test some h, some hypothesis, such as that some number of calculated groundwater travel times are less than 10,000 years. When the calculations, data, and models are shown to be consistent with the hypothesis, then the assessors assume that the hypothesis has

predictive power or is "verified." For example, one group of assessors, studying groundwater travel time, concluded that it was slow enough to meet regulatory requirements (Sinnock et al. 1986). Many other risk assessors speak of "verifying" their models (see, for example, Barnard and Dockery 1991, p. 1-3; Hunter and Mann 1989, p. 5) and "validating" them (see, for example, Brikowski et al. 1988, p. 51; Hunter and Mann 1989, p. 4; Stephens et al. 1986, p. xvi; Brikowski et al. 1988, p. 51; Stephens et al. 1986, p. xvi; Barnard and Dockery 1991, p. 1-3). For instance, one group of assessors concluded that the tools they used demonstrated "verification of engineering software used to solve thermomechanical problems" at Yucca Mountain (Costin and Bauer 1990, p. i; see Hayden 1985, pp. 1-1, 1-2).

Admittedly, software and systems engineers speak of computer models being "validated" and "verified." Yet, such "validation" language obscures the fact that the alleged validation really only guarantees that certain test results are consistent with a model or hypothesis; it does not validate or verify the model or hypothesis because avoiding the invalid inference of affirming the consequent prevents legitimate validation or verification. In using this "validation" language, both official DOE documents and individual risk assessments for Yucca Mountain are systematically misleading as to whether the repository studies are reliable. For example, the DOE (US DOE 1990a, p. 3-1) affirmed:

Validation...is a demonstration that a model as embodied in a computer code is an adequate representation of the process or system for which it is intended. The most common method of validation involves a comparison of the measured response from

in-situ testing, lab testing, or natural analogs with the results of computational models that embody the model assumptions that are being tested.

The same official DOE document, used to provide standards for Yucca Mountain risk assessments, also talks about the need to verify computational models of the waste site. It says:

Verification, according to the guidelines in NUREG-0856...is the provision of assurance that a code correctly performs the operations it specifies. A common method of verification is the comparison of a code's results with solutions obtained analytically....Benchmarking is a useful method that consists of using two or more codes to solve related problems and then comparing the results (US DOE 1990a, p. 37).

Although the term "verification" -- as used by DOE assessors -- suggests that the computer models or codes accurately represent the phenomena they seek to predict, it is merely a misleading euphemism for "benchmarking," comparing the results of two different codes (computer models) for simulating an identical problem. On this scheme, one "verifies" a model of Yucca Mountain against another model. What is required in the real world, instead, is validating a model against reality. This validation or confirmation can be accomplished only by repeated testing of the code or model against the real world, against field conditions.

Even with repeated field testing, however, compliance can never be confirmed, short of full testing of all cases throughout all time periods. Classic studies of the problem of induction show that complete testing is impossible. Therefore, the shorter the time of testing and the fewer the cases considered, the less reliable and the less confirmed are allegedly "validated" computer models or codes. The tests can only falsify or confirm a

hypothesis, not validate or verify it. To assume otherwise is to risk affirming the consequent. Hence, every conclusion of compliance with government regulations, or every conclusion of repository safety, on the basis of "verified" or "validated" test or simulation results, is an example of the problem of affirming the consequent. One cannot prove safety. One can only demonstrate that one has attempted to falsify one's results and either has failed in doing so or has done so. Therefore, both the DOE risk policy and risk assessors at Yucca Mountain invite problems when speaking of "validation" and "verification" at Yucca Mountain because:

(1) Real validation and verification is impossible, because of the problem of induction and because of the invalid inference of affirming the consequent. Only falsification of an hypothesis, or determining that the data are consistent with it, is possible. In the latter case, when one obtains repeated results indicating that the data are consistent with the model or hypothesis, one is merely able to increase the probability that the model or hypothesis has been confirmed.

(2) DOE's and assessors' use of the terms "verification" and "validation" misleads the public about the reliability of studies allegedly guaranteeing repository safety.

(3) Use of the term "verification" by DOE assessors is, in particular, misleading because they typically only compare different computer codes or models, with no reference to the real world, and because any model can be tuned or calibrated to fit any pattern of data, even when the model is not well confirmed.

To avoid the problem of affirming the consequent, risk assessors need to refrain from the claim that their results "indicate" or "show" or "prove" compliance with government regulations or with some standard of safety. They also would do well to avoid misleading claims that they have "verified" or "validated" the

mathematical models at Yucca Mountain and elsewhere (see, for example, Hopkins 1990, p. 1). Such terms suggest a level of reliability and predictive power that is both impossible in principle anywhere, as well as impossible in practice at Yucca Mountain because of the long time periods and the precise predictions required by the government. Instead, assessors should speak in terms of probabilities that a given model or hypothesis has been confirmed. They should avoid misleading claims about verification.

4.10 The Appeal to Authority

If it is impossible to "verify" or "validate" Yucca Mountain repository safety or its future compliance with government regulations, then what is the basis for repeated claims of safety and compliance? Obviously, more testing and modeling -- especially "risky" testing designed to falsify erroneous hypotheses -- could help to provide a basis for sound conclusions regarding Yucca Mountain. It could help to increase the probability that the reliability of certain models or hypotheses is confirmed. Often, however, much of the risk assessors' basis for their conclusions is mere opinion. But the use of expert opinion sometimes involves assessors in an appeal to authority.

An appeal to an authority is no foolproof, logical basis for a conclusion because authorities can be wrong, and because only data and logic force a conclusion to be true. An authority's guarantee, alone, does not make a conclusion true. Rather, if a conclusion is true (because of the data and logic supporting it),

then an authority will be correct in supporting it. The reverse is not true, however. Hence, in the absence of good data, when risk assessors merely appeal to authority to support their conclusions, they exhibit an invalid deductive inference. Moreover, premises (about an authority's affirming something) do not logically and deductively lead to conclusions (about the something). Because there is no deductive connection, the appeal to authority violates the first logical condition for an adequate scientific explanation in the strict sense (see section 1.2; Hempel and Oppenheim 1948; Popper 1959).

In many areas of science, we are often forced to rely on the judgments of authorities. Typically such reliance on expert opinion is plausible to the degree that we are able to test the scientists' claims and therefore to confirm the correctness of the opinion of some authorities. The appeals to authority in the Yucca Mountain case are problematic because such appeals cannot in practice be tested over 10,000 years. In other words, the Yucca Mountain appeals to authority are troublesome not primarily because they are deductively invalid inferences, but because they are used to take the place of testing and discovering inductive evidence. In science, appeals to authority are not used typically as substitutes for testing and inductive confirmation. Yet, at Yucca Mountain, appeals to authority are used in this problematic way.

Appeals to authority also are particularly damaging in cases like Yucca Mountain because they intimidate citizens and laypersons who have neither the power nor the position to influence

risk-assessment outcomes, even though they are likely to be affected by the assessment. As several Yucca Mountain researchers put it: even when the data do not support the optimistic conclusions, the tone of the DOE risk assessment work conveys the attitude that few problems exist at Yucca Mountain (Emel et al. 1988b, p. 41). Such a tone and attitude is part of an appeal to authority that has no logical relationship to empirical confirmation of the conclusions expressed by the experts.

Specific examples of appeals to authority on the part of Yucca-Mountain risk assessors include the claims that radioactivity releases at the site would be "significantly less" than those imposed by government standards (Thompson et al. 1984, p. i), and that there would be less than one health effect every 1,400 years caused by Yucca Mountain (Thompson et al. 1984, pp. v-vi). The assessors gave both assurances after noting that they had not measured water infiltration into Yucca Mountain (Thompson et al. 1984, p. 7), and that they had not considered fracture flow (Thompson et al. 1984, p. 47). Hence, the appeal to authority here is used as a substitute for testing and for gathering inductive data. Other assessors, in a fashion typical of some Yucca Mountain assessments, used a computer model to simulate radionuclide transport at Yucca Mountain. The computer model was based on a number of counterfactual and unknown conditions, yet the assessors concluded that their model "was found to be an effective tool for simulation of the performance of the repository systems at Yucca Mountain" (Lin 1985, pp. i, 1). Assertions such as these at Yucca

Mountain indicate not only that assessors are guilty of an appeal to ignorance (see section 4.1 in this chapter), but also that, in the absence of data, the assessors often appeal simply to their own authority. Again, the main problem is not the deductive invalidity of such an appeal, but the fact that it is used (atypically of other sciences) as a substitute for actual testing and inductive confirmation.

The assessors' appeal to authority appears to be generated in part by DOE adherence to the same appeal. The DOE claims, for example,

in the past 35 years, the Department [of Energy] and its predecessor agencies have accumulated thousands of man years of experience in managing radioactive wastes at various sites around the country. During this time, active health and safety programs have been maintained to reduce industrial and radiological accidents to levels as low as reasonably achievable. Accidents and releases of radioactive materials have occurred, but there have been no injuries to members of the public or serious environmental damage as a result of these operations (US NRC 1980, p. I-3).

Such a claim contradicts the explicit statements of the DOE's own Kane Report (see US Congress 1987b), as well as the conclusions of many Congresspersons who have investigated DOE facilities (US Congress 1987a, 1987b, 1989a, 1989b). Hence, the DOE assertion appears to be merely an appeal to authority.

The DOE likewise claimed, after a particularly damaging set of criticisms of its health and safety record, that "these reviews [of radioactive materials/waste facilities], while identifying possible improvements, have shown that the Department's operations have not and do not present a significant hazard" (US NRC 1980, p. I-4). Given the earlier discussions of bias, cover-up, retaliation

against whistle-blowers, and GAO (General Accounting Office) criticism of DOE environmental and safety standards (see section 2.8 of chapter two and sections 4.6 and 4.8 in this chapter), such claims seem to be little more than appeals to DOE authority.

Appeals to authority in the Yucca Mountain case are especially suspect because of the disastrous consequences, in the past, that have resulted from appeals to authority. As already mentioned at the beginning (chapter one) of this analysis, when hydrogeologists had inadequate data about possible radwaste migration at the proposed Maxey Flats site, they merely did some well and pumping tests, then relied on expert opinion to claim that the waste would not migrate for centuries. As we already mentioned, their expert predictions erred by 6 orders of magnitude. Given short-term tests of the Maxey Flats site and inadequate knowledge of the fractured, unsaturated zones, the earlier assessors' optimistic appeals to authority regarding site suitability have obviously been proved wrong.

Moreover, despite 10 years of public outcry against conditions at the (now closed) Maxey Flats facility, current levels of radioactive pollution (tritium), outside the burial trenches, are 5 orders of magnitude above the Environmental Protection Agency (EPA) limits for groundwater pollution (Wilson and Lyons 1991, p. 36). Radionuclide migration at the site is getting worse, not better. Authorities not only denied that any problem would exist in the future, but when they were proved wrong, the same authorities did little to resolve the problems of radioactive contamination.

This means that government experts have not merely erred in the past when they were predicting future events about which they should have shown more care, but they also have failed to correct dangerous conditions at radioactive facilities, even after managers and whistleblowers attempted to get their attention. At the Fernald (Ohio) uranium feed materials plant, for example, the engineers and scientists on site made "no attempt to monitor these kinds of releases [illegal uranium emissions to the air and water], take corrective measures or give estimates of what these releases might have been" (US Congress 1989b, p. 67). Indeed, safety conditions were so serious at the DOE plant that the plant manager informed DOE that he would shut down the plant unless DOE told him in writing to continue operating. The DOE site manager said to keep operating (US Congress 1989b, p. 132).

Indeed, one of the reasons why some risk assessments (those dealing with low-frequency events or untested technologies) can be off the mark by 2 to 6 orders of magnitude is that, in the absence of complete data, assessors often extrapolate or use their opinions and value judgments as a basis for prediction. When scientists and engineers completed the most famous, and allegedly best, risk assessment ever performed, WASH 1400 (US NRC 1975), it was used as a basis of US policy and standards regarding commercial nuclear reactor safety. Much of the assessment was based on mere appeals to authority, however, in the absence of data (see Shrader-Frechette 1983, 1991). Later, when Dutch researchers compared the opinions of WASH 1400 authorities to the actual data, they discovered a severe

overconfidence bias in WASH 1400. The assessors in the Netherlands used actual empirical frequencies obtained from a study done by Oak Ridge National Laboratory to calibrate some of the more testable subjective probabilities used in WASH 1400. Obtained as part of an evaluation of operating experience at nuclear installations, the frequencies were of various types of mishaps involving nuclear reactor subsystems.

The Dutch study of Oak Ridge data used operating experience to determine the failure probabilities for seven reactor subsystems (loss-of-coolant accidents, auxiliary feedwater-system failures, high-pressure injection failures, long-term core-cooling failures, and automatic depressurization-system failures for both pressurized and boiling water reactors). Amazingly, all the values from operating experience fell outside the 90 percent confidence bands in the WASH 1400 study. However, there is only a subjective probability of 10 percent that the true value should fall outside these bands. This means that, if the authors' subjective probabilities were well calibrated, we should expect that approximately 10 percent of the true values should lie outside their respective bands. The fact that all the quantities fall outside them means that WASH 1400, the most famous and allegedly best risk assessment, is very poorly calibrated. It also exhibits an overconfidence bias on the part of the authorities or experts.

Appeals to authority and resultant difficulties do not occur merely in risk assessments like those done for commercial nuclear fission (for example, WASH 1400) or for proposed radwaste

repositories (for example, Maxey Flats and Yucca Mountain). Rather, problems are predictable any time even a well trained scientist or engineer goes beyond the data, and attempts to substitute mere opinion for a probabilistic or scientific analysis of the facts. As we argued in chapter four, during the discussion of the expertise inference, Kahneman, Tversky, and others have discovered that experts typically fall victim to overconfidence and representativeness. Indeed, they behave in many of the same ways as do laypersons whenever they are conjecturing beyond the level of the data that they have. Hence, on the grounds of the work of Kahneman, Tversky, and others, there are strong reasons to question any expert's appeal to authority, any expert "opinion" whenever the data is limited, as in cases like Yucca Mountain.

Yet another reason, in addition to those already discussed, to avoid the appeal to authority in Yucca Mountain QRA is that most of the authorities appealed to are those who have a vested interest in siting a waste repository at Yucca Mountain. They work for DOE or obtain their funding from DOE, both conditions that could influence the outcome of their expert opinions. Indeed the National Academy of Sciences said that it was concerned that DOE's using only its own experts would "mask the degree of real uncertainty" in studies (US Congress 1987a, p. 446).

Moreover, as this analysis has indicated -- and as many government hearings (for example, US Congress 1987a, 1987b, 1988, 1989a, 1989b) and risk experts (for example, Kunreuther et al. 1990, p. 483) have confirmed -- numerous incidents have compromised

the integrity of the siting process (including risk assessment) and the reputation of the US DOE. A 1986 study by the US GAO found that 90 percent of DOE's 127 nuclear facilities had contaminated groundwater that exceeded regulatory standards by a factor of up to 1,000 (State of Nevada 1989b, pp. 2; Winsor and Malone 1990, pp. 197, 205; Sawyer 1988, pp. 8-9, 13). The fact that various states (in which repositories have been proposed) have criticized the DOE for failing to provide adequate funding for independent studies and monitoring at the possible radwaste sites suggests that DOE has relied on an appeal to its own authorities (US Congress 1986, pp. 133, 219, 321, 328; Golding and White 1990, pp. 28ff.; Lemons, Malone, and Piasecki 1988, p. 25; Emel et al. 1988b, p. 42), rather than on actual empirical substantiation of its claims.

The failure of the DOE to provide adequate funding for external review, as recommended by the US National Academy of Sciences (US Congress 1987a, p. 446), until it was forced to do so by the courts (US Congress 1987a, p. 726), also suggests that at least some of its claims would not stand up to independent review. Indeed, if the conclusions of DOE experts would stand up to empirical and logical scrutiny, and were not based on questionable appeals to authority, one wonders whether the DOE would have had dozens of lawsuits filed against it (see US Congress 1987a, p. 747; see Sawyer 1986, pp. 92ff.; Malone 1990a).

Apart from all the logical reasons for faulting Yucca Mountain assessments because of their appeal to authority, an additional problem with experts' use of such an appeal is that it encourages

use of the expertise inference (section 4.3 earlier in this chapter). As a consequence, it encourages assessors to ignore public views of risk and the social amplification of risk. As the accidents at Three Mile Island (Burns et al. 1990, p. 1ff.), Goiania, Brazil (Pettersen 1988), and Gorleben, Germany (Peters and Hennen 1988) reveal, public perception and risk evaluation are just as important, if not more important, in determining socioeconomic impacts as the physical magnitude of the accidents themselves. Hence, whatever diminishes our understanding of these impacts -- as the appeal to authority is likely to do -- diminishes the quality of risk assessment. Moreover, expert appeals to authority sometimes are as much examples of risk perceptions as are the views of laypersons.

In summary, there are at least four reasons why assessors at Yucca Mountain are seriously at risk when they appeal to authority, rather than to logic and to actual empirical or probabilistic studies, to justify their conclusions.

- (1) The appeal to authority is a an invalid inference.

- (2) Appeals to authority in the past have repeatedly been wrong, especially in the case of risk assessments of radwaste facilities like Maxey Flats and Fernald and in the QRA of commercial nuclear reactors, such as WASH 1400.

- (3) Appeals to authority, in the Yucca Mountain case, sometimes are not even based on the considered opinion of relevant experts in the field; rather they may be biased by political considerations and by a desire to promote a particular technology or repository site.

- (4) Appeals to authority, in the Yucca Mountain case, are likely to prejudice assessors and decisionmakers against lay perceptions of risk. This prejudice, in turn, is likely to harm the democratic foundations of risk assessment, risk evaluation, and risk management.

Chapter Five

Conclusions and Recommendations

If the preceding analysis of some of the methodological and ethical value judgments and inferences that are found in a number of the quantitative risk assessments (QRA) at Yucca Mountain is at least partially correct, then it suggests that several deficiencies plague the study of the Nevada site. Admittedly the site has a number of good features: the apparently thick unsaturated zone; low precipitation at present; apparently long groundwater paths; and limited groundwater development. Despite these assets, however, QRA's at the site are problematic. Not only are the assessments suspect because of questionable methodology (chapters two and three), but in a number of instances, they fall victim to inconsistencies and deficiencies in scientific reasoning (chapter four).

5.1 Subjective Opinions and Value Judgments at Yucca Mountain

As chapter two argued, because of the presence of some questionable methodological value judgments (many of which were avoidable) used by Yucca Mountain assessors in estimating risks, it is doubtful whether an accurate estimate of many risks at the site is even possible. Many of these questionable methodological value judgments arise because of the tendency of risk assessors to use conceptual models that are untested. They are untested, in part, because the site hydrogeology is so complex, because so much of the data is unavailable, because long-term testing is impossible, and perhaps because of scheduling pressure from DOE (see section 4.8 in

the previous chapter). As a result, the Yucca Mountain assessments and site characterization plan, in the words of one State of Nevada representative, lay out "a plan of information management for the hydrogeological and geochemical issues, instead of a plan for scientifically valid site characterization" (State of Nevada 1989c, vol. 2, p. 2).

Methodological value judgments about the validity of long-term conclusions made on the basis of short-term studies are in general highly questionable, as are judgments about the migration of groundwater or leachate in heterogenous, fractured, unsaturated media. Yucca Mountain QRA's are likewise plagued by numerous value judgments about model reliability, simplification of the phenomena, representativeness of the sampling, extrapolations and interpolations. Indeed, chapter four argued that problems involving all these value judgments have occurred at other radiation-related DOE facilities, such as Fernald, Hanford, Maxey Flats, and Savannah River.

One of the most disturbing value judgments in many of the Yucca Mountain assessments is that human error is not a significant contributor to the repository risk. Not only are there important grounds for questioning this assumption in general, but human error (of both individuals and institutions) appears to be the basis of many of the serious problems of contamination that have occurred at DOE sites in the past. All of these problematic value judgments in estimating risk cause one to question, as we did near the end of chapter two, whether a more basic value judgment is correct. This

value judgment is that the sensitivity and the precision of the analyses at Yucca Mountain are adequate to insure regulatory compliance and repository safety. Our conclusion is that, given the deficiencies and value judgments already noted, the analyses are probably not sensitive or precise enough to provide this assurance. As one reviewer of the Yucca Mountain site characterization plan claimed, it is full of "misapplied concepts fueled by foregone conclusions....one of the most disturbing aspects is the lack of attention given to the geohydrologic setting and its performance at the Yucca Mountain site" (Thompson Engineering Company 1988, pp. 5, 13).

Chapter three investigated the various value judgments assessors are making in evaluating the Yucca Mountain risks. These include the judgments that one can accurately evaluate a single site, that a given magnitude of risk is acceptable, that risk reductions undertaken at Yucca Mountain are sufficient, that certain worst-case accidents are not credible, that using averages for figures like groundwater velocity is acceptable, that full liability would not help guarantee safety at Yucca Mountain, that the Yucca Mountain repository risk is acceptable because it is approximately the same as that of unmined ore, that the Yucca Mountain assessments are more reliable than those of other facilities, and that utilitarian risk-evaluation theories are ethically acceptable.

One of the most problematic of these judgments about evaluating the Yucca Mountain risk is that utilitarian ethical

theories are acceptable. As we argued in section 3.9 of chapter three, this questionable judgment allows risk assessors to ignore many of the distributive and procedural inequities among states, nations, generations, and social groups. Indeed, the problematic value judgment about utilitarianism is part of a deeper difficulty in the Yucca Mountain assessment program: there is no plan for a systematic analysis of all of the ethical issues that are related to handling nuclear waste, especially ethical issues such as free, informed consent.

In assessing these representative value judgments in chapters two and three, we showed not only that there are strong grounds for questioning each of them, but also that risk assessors -- especially at other radiation-related facilities like Maxey Flats -- who used such judgments in the past appear to have drawn problematic risk conclusions. They have done so, at least in part, because of their adherence to the very methodological value judgments that we have identified as questionable.

5.2 Problematic Inferences at Yucca Mountain

QRA's at Yucca Mountain are inadequate not only because of questionable value judgments but also because of problematic scientific reasoning that undercuts the validity of the conclusions themselves. Moreover, nearly all of the problems that throw the question of Yucca Mountain repository safety into question -- including the appeal to ignorance, the expertise inference, the linearity inference, the de minimis inference, inferences regarding the multiple maximand, affirming the consequent, and the appeal to

authority -- have caused serious consequences whenever they were used in risk assessments of radiation-related facilities (such as Hanford, Fernald, and Maxey Flats) in the past. The presence of invalid inferences, more than any unavoidable methodological value judgments, casts doubt on at least some of the Yucca Mountain QRA enterprise.

Chapter two of the analysis has demonstrated that there are fundamental uncertainties and methodological value judgments in the theoretical and mathematical models describing Yucca Mountain hydrogeology, volcanism, and seismic activity, as well as fundamental uncertainties in the input data for the actual risk estimates. Chapters three and four have shown that, because of all the uncertainties, value judgments, and inconsistencies, in the evaluation of the Yucca Mountain risk, there are fundamental uncertainties in the Yucca Mountain policy analysis of the risks and in the decisions for controlling and managing them.

Because different responses to these uncertainties in risk estimation and evaluation can promote or frustrate social goals such as repository safety (Reichard et al. 1990, p. 181), it is important to recognize the potentially catastrophic consequences that could result from the uncertainties, value judgments, and invalid inferences that we have uncovered. In general, there appears to have been an inappropriate tendency in some Yucca Mountain assessments to resort to methodological value judgments and questionable logical inferences, rather than to admit questionable uncertainties. Likewise, there has been a tendency to

succumb to optimistic, often unsupportable, value judgments rather than to reveal the dangerous extent of what we do not know. Too often, Yucca Mountain assessors make admissions such as: we may "have underestimated cumulative releases of all nuclides during 100,000 years, by an amount that is unknown" (Sinnock et al. 1986, p. 77). Despite such damning admissions, nevertheless the same assessors draw contradictory conclusions such as the following: the "evidence indicates that the Yucca Mountain repository site would be in compliance with regulatory requirements" (Sinnock et al. 1986, pp. i-ii). Such inappropriate tendencies to underestimate problems at Yucca Mountain are methodologically suspect and could have far-reaching consequences.

5.3 Science at the Service of Regulation Is Problematic

The upshot of this analysis is not that science is itself defective. Nor do we believe that quantitative risk assessment (QRA) is fundamentally flawed. As we explained earlier, QRA has produced some excellent and objective results in areas such as automobile transportation risk, areas where the data and models used are more complete and testable. Rather, we believe that some uses of science, and some applications of QRA are defective, especially in situations (such as Yucca Mountain) characterized by probabilistic uncertainty, incomplete data, untested models, and the need for accurate long-term predictions. In such situations, a traditional procedure of scientists and risk assessors may lead to problems. Scientists, engineers, and risk assessors typically use the best available model whenever they are attempting to explain or

predict some phenomenon. They reason that some model or theory, however defective or approximate, is typically better than none.

In cases like Yucca Mountain, where science is at the service of public policy, and where assessors ought not ignore citizens' rights to equal treatment, consent, and compensation, however, the practice of "choosing the best model" may be faulty (see Shrader-Frechette 1990). Indeed, if the uncertainties are severe, and if unknowns could lead to substantial public risk, then even the best model of a site may not be a sufficient basis for essentially ethical and social public choices about site selection. Even the best models in cases like Yucca Mountain may not be adequate for public decisionmaking. And if they are not, then requiring such a decision may be asking government agencies (like the Department of Energy) to do the impossible.

Regardless of whether the DOE is being asked to "do the impossible" at Yucca Mountain, however, the scientific uncertainties at Yucca Mountain argue for some vehicle for deciding how to deal with these uncertainties and value judgments. To the degree that the scientific parameters governing a societal risk are uncertain or laden with questionable value judgments, to that extent ought the risk debate to be subject to greater scrutiny.

5.4 Recommendations Regarding Yucca Mountain

If the conclusions of this evaluation of some Yucca Mountain quantitative risk assessments (QRA's) are in general accurate, then there are a number of methodological and policy changes in the assessment process that might promote more scientific, equitable,

and consistent analyses of the repository risks. Many of these methodological and policy changes might be accomplished if risk assessors and decisionmakers investigated the possibility of following a number of recommendations:

1. In estimating risk, assessors at Yucca Mountain ought to admit the methodological uncertainties -- regarding model simplifications, sampling reliability, extrapolations, interpolations, and so on -- that could jeopardize their conclusions. They ought to avoid making methodological value judgments that the uncertainties are insignificant or acceptable. The persons affected by the Yucca Mountain risks also have the right to evaluate the significance of the uncertainties associated with them, and they cannot do so unless assessors explicitly admit the shortcomings of their work.
2. In estimating risk, specialists should be trained, so far as possible, to overcome probabilistic bias.
3. In estimating risk, assessors at Yucca Mountain ought to undertake systematic and extensive studies of the potential for human error related to the Yucca Mountain repository. They ought to insure that the funding level and comprehensiveness for social-science work is as great or greater than that already expended for the physical-science studies (hydrology, geology, and so on) at Yucca Mountain.
4. In estimating risk, assessors at Yucca Mountain ought to examine the feasibility of avoiding inappropriate use of probabilistic language, since the scientific uncertainties implicit in such probabilistic judgments are so great (see State of Nevada 1989c, vol. 4, esp. pp. 3-4; Cranwell et al. 1990, p. 77; Smith et al. 1989; Hunter and Mann 1989, pp. 1-18; Brown and Lemons 1991, pp. 315-319). A desirable alternative would be to examine comprehensive strategies for preventing possible accident scenarios from taking place (see Emel et al. 1988b, pp. 14, 43). In other words, risk assessors ought to evaluate the justification for, and the likely consequences of, a move from a probabilistic risk strategy to a hazard-prevention strategy.
5. In estimating risk, assessors at Yucca Mountain ought to examine the causes of, and the remedies for, the social amplification of risk apparently caused in part by citizens' lack of trust in the DOE.
6. In estimating risk, assessors at Yucca Mountain ought to devise null models capable of testing their risk-estimation

results (see Emel et al. 1988b, pp. 46ff.). Instead of providing questionable, untested, uncertain simulations, assessors ought to be required to determine whether their results can survive risky testing. If they can survive, assessors ought to evaluate how much confidence they warrant. They ought to seek to invalidate, as well as validate, their models.

7. In evaluating risk, assessors at Yucca Mountain ought to express groundwater velocities, radionuclide migration rates, and other critical parameters in terms of a range of values. They ought to include consideration of low-probability and worst cases, rather than only average value.

8. In evaluating risk, assessors at Yucca Mountain ought to analyze all the ethical, social, and political threats related to (and likely to be caused by) Yucca Mountain. They ought to take special care to determine potential violations of rights to due process, rights to equal treatment (to distributive equity across states, nations, generations, and social groups), rights to free, informed consent, rights to full liability protection, and rights to full compensation from all risks related to Yucca Mountain.

9. In evaluating risk, assessors at Yucca Mountain ought to employ all possible procedural safeguards against bias in the assessment process. They ought, for example, to require the development of alternative models for the site, to require independent review of all risk assessments, and to fund data collection and studies done by alternative interest groups (see US Congress 1986, p. 395; Emel et al. 1988b, p. 42). It is also important to involve different interests groups in the assessment process, from the beginning, and to provide interested parties with more than a merely consultative role. Such procedural safeguards of consent, equity, and the right-to-know are especially important at Yucca Mountain because of the degree of uncertainty in the scientific results and because of the absence of alternative proposed repository sites.

10. In estimating risk, assessors at Yucca Mountain ought to investigate the possibility of implementing radioactive-waste-facility assessment procedures that have provided successful repository-assessment programs in other countries, such as Sweden. For example, assessors should undertake systematic and extensive studies of the nonphysical components of risk, and they should take care not to push an assessment timetable that is so short that it compromises scientific integrity.

5.5 Science, Risk Assessment, and Public Accountability

A comprehensive recommendation for promoting more accurate

risk assessment and risk management at Yucca Mountain would be to devise ways, in addition to independent review, to hold scientists, risk assessors, and government (especially DOE employees) ethically accountable for their scientific and policy judgments. As we argued in chapters one, two, and three, science always involves some degree of judgment or voluntary control. Because it involves epistemic or methodological value judgments, assessments of these values are necessary to explain and to evaluate both scientific practice and risk assessment. Hence, assessors have an ethical duty to adhere to unbiased methodological value judgments in their work. High quality scientific work likewise requires an assessment of the reliability of these value judgments.

There are also practical, as well as theoretical, reasons for holding scientists and assessors ethically responsible for their professional judgments. As we argued earlier in chapter two, human error may be a significant contributor to the risk at Yucca Mountain. Also, as we argued in chapter four, because of repeated use by risk assessors and policymakers of the appeal to authority, it makes sense to attempt to hold scientists and assessors accountable for their professional claims.

Admittedly, many persons may disagree that scientific judgments and agents ought to be subject to moral praise or blame. They may object that science is concerned with epistemic judgments, and hence that ethical appraisal is not appropriate for it. Scientists do, however, have a number of ethical duties, and the existence of these ethical duties indicates that science probably

ought to be subject to ethical assessment. Scientists have the duty not to be biased in presenting, withholding, or interpreting data, for example. Therefore, scientists have an ethical obligation not to be closed-minded. Hence, scientists have a duty not to be biased against innovative theories or politically unpopular results (Shrader-Frechette 1989b). Also, given the pressures on scientists and risk assessors as a result of there being only one potential high-level-radwaste site, at Yucca Mountain, it makes sense to attempt to insure that risk assessors are not biased for or against the site because of political, ethical, economic, or personal reasons. The absence of competitor sites, against which Yucca Mountain can be evaluated, makes ethical and methodological analysis of scientific judgments all the more important. Citizens have the right to no less.

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