AIIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910

301/587-8202

Centimeter

Inches

MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 1

2

Conf-940553--74

UCRL-JC-116350
PREPRINT

Limitations on Scientific Prediction and How They Could Affect Repository Licensing

Richard A. Van Konynenburg

This paper was prepared for submittal to the
American Nuclear Society
International High Level Radioactive Waste Management Conference
Las Vegas, NV
May 22 - 26, 1994

January 1994

Lawrence Livermore National Laboratory

LIMITATIONS ON SCIENTIFIC PREDICTION AND HOW THEY COULD AFFECT REPOSITORY LICENSING

Richard A. Van Konynenburg
Lawrence Livermore National Laboratory
P.O. Box 808, L-352
Livermore, California 94550
(510) 422-0456

ABSTRACT

The best possibility for gaining an understanding of the likely future behavior of a high level nuclear waste disposal system is to use the scientific method. However, the scientific approach has inherent limitations when it comes to making long-term predictions with confidence. This paper examines some of these limiting factors as well as the criteria for admissibility of scientific evidence in the legal arena, and concludes that the prospects are doubtful for successful licensing of a potential repository under the regulations that are now being reconsidered. Suggestions are made for remedying this situation.

I. INTRODUCTION

The standard[1] and regulations[2] governing a potential high level nuclear waste repository at Yucca Mountain are currently being reconsidered. Those previously developed by the EPA and the NRC called for rather detailed predictions of the behavior of natural and engineered systems (as well as potential human intruders) out to 10,000 years in the future, with "reasonable expectation" or "reasonable assurance."

The prescribed approaches for making these predictions were "use of data from accelerated tests and predictive models that are supported by such measures as field and laboratory tests, monitoring data, and natural analog studies,"[2] as well as "performance assessment."[1] Performance assessment was defined as "an analysis that: (1) identifies the processes and events that might affect the disposal system; (2) examines the effects of these processes and events on the performance of the disposal system; and (3) estimates the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant processes and events."

Inherent in these approaches is an appeal to the scientific method. Since the high level waste standard and regulations now are being reexamined, and since the previous versions called for science-based predictions to be used in licensing, now is the time to take a careful look at two categories of issues: the factors that limit our ability to make such predictions, and the difficulties inherent in using scientific predictions in the licensing arena.

While the scientific method is unquestionably a powerful tool and, in fact, our best hope for attempting to look into the future, we must be careful not to deceive ourselves or others into believing that science is capable of reaching beyond its inherent limitations. If we are to successfully accomplish repository licensing, we must have regulations that are based on a realistic view of what is scientifically possible. We must also gain acceptance of science-based predictions in the courtroom.

The author offers this paper in hopes that a careful review of these issues will help to improve mutual understanding among scientists, regulators, program managers, and the public, and will help lead to a more efficient rulemaking and licensing process.

Before proceeding, it is important to start with an agreed-upon understanding of the meaning of what has come to be called the "scientific method." For purposes of this paper, it will be defined as the process of bringing about a state in which there is no known disagreement between hypothesis and actual observation, however one gets to this point. This means that the "acid test" of an idea for explaining some phenomenon of nature is a comparison of the predictions of that idea with what one can actually observe, either in the natural environment or in a controlled experiment. The use of this method rests on the assumed validity of the "Principle of Causality" and the "Principle of the Uniformity of Nature," and the accessibility of the phenomenon of interest to observation.

The Principle of Causality can be stated as follows: for every event there is a causal explanation such that it must be thought of as arising out of previous events. The Principle of the Uniformity of Nature holds that the laws of nature are universal, the same throughout time and space. Finally, it is clear that to apply the scientific method one must be able to observe the thing one is attempting to explain by hypothesis.

II. LIMITATIONS ON MAKING SCIENTIFIC PREDICTIONS IN NUCLEAR WASTE MANAGEMENT

There are various factors that limit the ability to make science-based predictions in the field of nuclear waste management. Some of them are quite general and are associated with the philosophical basis of science itself. Others are of a more practical nature, or are specific to the particular problems encountered in nuclear waste management. Some present absolute limits on what can ultimately be achieved, while others only place impediments in the way of progress. However, such impediments can still have serious effects in any scientific program of finite duration.

A. Epistemological Problems

Any attempt to deal comprehensively with the limitations on science should make mention of epistemology. This is the branch of philosophy that investigates the nature, scope, and quality of human knowledge. One of the early investigators in this field was Rene Descartes,[3] who considered the following question: What basis do we have for believing that the thoughts in our minds bear any relation to reality in the universe outside our minds? In other words, how can we be sure that we are not deluded, deceived, or dreaming?

Another important epistemological question was raised by David Hume:[4] What basis do we have for believing that we can make any inferences at all about the future from the present and the past?

These questions strike at the heart of what it means to know something and whether we can be confident about predicting anything. They apply to nuclear waste management as well as to all other fields of human knowledge. While philosophers continue to struggle with them, most working scientists are not particularly troubled by these questions. From an operational point of view, we assume that our thoughts are in touch with reality, and we assume, based on experience, that the future will resemble the past in certain important ways, which we call the laws of nature. We have found that if we operate according to these assumptions, we can make what appears to us to be progress in understanding nature. These assumptions thus serve as the basis for the whole scientific enterprise and for the engineering and technology that are based upon it. However, from an epistemological point of view, we must admit that we cannot prove the philosophical assumptions upon which science is based.

B. The One-Sidedness of Hypothesis Testing and the Tentative Nature of Scientific Understanding

All of us who have studied, watched, or participated in the progress of science over a significant period of time have been made keenly aware that our understanding at any point in time must be considered subject to change as more research is carried out. The reason for this, as explained by Karl Popper,[5] is that we can never prove that a hypothesis is true. We can only make attempts to show that it is false. So long as we fail to show that it is false, it stands and is accepted as true for the time being.

According to Popper, the theories in which we can have the most confidence are those that have made clearly testable predictions and have not been found to be incorrect in those predictions, particularly when the predicted observations were totally unexpected and seemed improbable beforehand. He said that such theories possess a high degree of "falsifiability." If they have then withstood the attempts to falsify them, they can be regarded as very strong. But we must never make the mistake of believing that any scientific theory is absolutely proven for all time.

This situation should have the effect of making us cautious when we are called upon to predict future events on the basis of scientific theory. We can never be sure that we have the ultimate understanding of the relevant phenomena, in nuclear waste management or in any other field in which the scientific method is applied.

C. Inaccessibility of the Distant Future to Observation or Experiment

The future is, of course, always inaccessible to us in the present, and according to Hume's arguments[4] we have no rational basis for inferring anything about it. However, as a practical matter, when we are dealing with times not too far into the future, we have become comfortable with the idea of performing and repeating observations or experiments of a similar duration in order to test our hypotheses, and then using the resulting theories to extrapolate into the future by assuming the validity of the Principle of the Uniformity of Nature and the Principle of Causality. This is also the basis for what engineers call "good engineering practice."

But scientists and engineers alike run into difficulty when the times involved are orders of magnitude longer than those accessible to observation, experiment, or engineering experience. Predictions out to such long times in the future become increasingly uncertain as the time becomes longer. Predictions that rest on thermodynamic or other conservation principles are probably the safest in this regard, but application of these principles still rests on assumptions about future circumstances that can't be confidently extrapolated. When one can no longer compare hypothesis to observation, one is no longer practicing the scientific method. This problem is particularly acute in nuclear waste management, because of the long time scale over which predictions are desired.

D. Gödel's Incompleteness Theorem

Science proceeds along the two complementary paths of theory and observation or experimentation, which are linked to the philosophical schools of rationalism and empiricism, respectively. The theoretical approach often makes use of mathematical argument. Many people have developed such a healthy respect for the validity of mathematics that they have come to believe that if something can be derived mathematically, it must be true. However, the work of Kurt Gödel[6] should cause such people to reconsider. He showed that any proof that a formal mathematical system is free from contradictions necessarily requires methods beyond those provided by the system itself. The upshot of this is that a mathematical theory of a physical phenomenon can never in principle claim to be a complete, final, or ultimate description. This places a limit on what we can hope to achieve with the theoretical approach by itself. As a practical matter, scientists find mathematics to be a powerful tool for developing physical understanding, but it cannot stand alone as a means of determining physical reality, either in nuclear waste management or any other field of science.

E. The Statistical Basis of Physical Laws Applying to Many-Body Systems

The motion of a physical system involving more than two bodies interacting simultaneously via gravitation, electromagnetic, or strong nuclear forces cannot be solved analytically. For some systems having a few bodies, numerical methods of approximation have been applied, and these can produce satisfactory results so long as the capacity of available computers is not exceeded. However, for larger systems, for example macroscopic systems having numbers of atoms on the scale of Avogadro's number, typically a few tens of grams of matter, such methods are not practical. In these cases, one must resort to the methods of statistical mechanics or thermodynamics. These methods deal with average properties of a system of particles, and they have been very useful in physics, chemistry, and engineering. However, inherent in these methods is the possibility of fluctuations from the average, which are not predictable in a deterministic sense.[7]

The consequence of this is that in principle any thermodynamic prediction is subject to uncertainty because of the possibility of fluctuations. This is true even apart from any quantum mechanical considerations. However, in practice this is probably not of serious concern for systems of macroscopic size that exhibit nonchaotic behavior, since the probability of a significant fluctuation becomes very small for such systems, and the results of calculations are not overly sensitive to initial conditions (However, see the comment at the end of the next section).

F. Heisenberg's Uncertainty Principle

A fundamental source of uncertainty in what can be achieved experimentally is expressed by Heisenberg's Uncertainty Principle.[8] One statement of this principle is that one can never determine exactly both the position and the momentum of a particle at the same time. This has important consequences for systems of atomic size, but the relative uncertainty becomes very small when one is dealing with large, macroscopic objects. This principle probably does not place significant limits on the predictions desired in nuclear waste management, although it should not be ruled out completely. Krauskopf[9] raised the question as to "whether the indeterminacy of particle behavior is additive over time, thus making geologic conclusions about the distant past to some extent unsure." If this is the case, it would apply as well to predictions in the distant future. Krauskopf wrote that as far as he knew, "this possibility has never been explored."

G. Chaos Theory[10]

In recent years it has been realized that there are many systems in which the final outcome depends very sensitively on the initial conditions. These are termed "chaotic" systems, and are described by nonlinear equations. For all practical purposes, the behavior of chaotic systems cannot be predicted, because it is impossible to specify the initial conditions with exact precision. One very familiar example of a chaotic system is the weather. Because of its chaotic nature, prediction of the weather is always subject to considerable uncertainty even over relatively short times, and accurate prediction will probably never be possible beyond times of less than a week.

Whether chaos will be present in systems of significance to nuclear waste management remains to be seen. Some hydrodynamic systems are chaotic. In such systems prediction is in principle hopeless, except as it relates to the general qualitative nature of the system.

H. The Limited Size of a Modeled System and the Problem of Determining Boundary Conditions

Any model for a nuclear waste management system necessarily must be confined to representing only a part of the universe. Consequently, it will be necessary to establish artificial boundaries for the modeled system, and conditions at the boundaries must be specified. Prediction of these boundary conditions far into the future necessarily involves uncertainty. Examples of problems in this area are climate change, volcanism, and even meteorite impact. Some relief can be obtained by moving the boundaries farther out by increasing the size of the modeled system, but as the size increases, problems are encountered with increased complexity, growing demands for input data, and the limits of computational power. There thus remains some unavoidable uncertainty in predictions due to the finite size of the modeled system.

I. Limits on Precision of Measurement

Apart from the fundamental limits set by Heisenberg's Principle, there are always practical limits on the precision with which measurements can be made. As noted above, chaotic systems are extremely sensitive to initial conditions. If measured data are to be used as input to a computer model, the limits on precision of measurements will be fatal to predictions for chaotic systems. However, measurement precision will also set less severe but nevertheless real limits on predictability of non-chaotic systems.

J. Limits on Characterizing a Geological System

In order to model the long-term behavior of a geological system, one needs to know its initial conditions in sufficiently fine detail. The detail needed is determined by the desired application and by the variability in properties and conditions on the scale of interest. In addition to the limits on measurement precision already discussed, there is also the problem that characterizing the system in sufficient detail could significantly change it. An example would be riddling Yucca Mountain with boreholes to more precisely catalogue the fractures.

K. Complexity of the Processes and Their Interactions

Scientists are accustomed to the analytical approach of dividing complex systems into smaller parts, developing an understanding of these parts individually, and then putting them back together. Difficulties arise, however, when a system is very complex. In such cases, the time, effort, and resources required to develop such an understanding grow, and the behavior of the system can be very sensitive to interactions, which become difficult to sort out. The interactions between hydrology and geochemistry are a case in point. There are two important consequences of this. The first is that if an understanding of the processes and their interactions cannot be worked out, prediction is impossible. The second is that even if such an understanding is achieved, development of a manageable model may require considerable idealization and simplification, and then one is faced with the problem of determining how well the idealized model actually represents the behavior of the complex system. It may not be possible to find this out in the absence of observations over the time span of interest.

L. Establishing that a "Natural Analog" is Truly Analogous

Regulation 10CFR Part 60[2] recommends the use of "natural analog studies." The notion of a natural analog implies a natural system or process that is sufficiently similar in composition, properties, or history to the system or process of interest that one can apply conclusions from the behavior of the former to that of the latter. A significant problem with this approach is that no two natural systems are exactly alike, and the burden of establishing that they are sufficiently similar that a valid analogy exists becomes significant. If this cannot be established, use of the supposed natural analog will not be very helpful in making confident predictions. Perhaps a better approach would be to consider the natural analog as simply another natural system and to use it to test the models to be applied to the modeled system, without trying to make the case that they are analogous. This is in fact the approach used by Glassley at our Laboratory.

M. Establishing the Applicability of Accelerated Tests

Regulation 10CFR Part 60[2] also recommends use of data from accelerated tests in predicting long-term behavior. This approach has been described in an ASTM Standard Practice.[11] However, as is alluded to in the Standard Practice, the results of accelerated tests are only directly applicable if one can be sure that the chemical mechanisms and physical processes active in the accelerated tests are the same as those active in the nonaccelerated system. It is not clear how this can be established for behavior of the system in the distant future.

N. Sociological Aspects of the Conduct of Science

In this category, two factors will be mentioned that place limitations on the ability to develop confident predictions. The first is the specialization and compartmentalization that have resulted from the growth of the body of scientific knowledge and from the practice of scientific reductionism. This specialization impedes the treatment of phenomena that cut across several disciplines, and slows down progress when scientists try to predict the behavior of a multifaceted system, such as a potential repository. A single researcher does not have a grasp of all aspects of the problem. Progress thus requires communication and cooperation among scientists and engineers having different specialties. This is made difficult by the different approaches used in the various disciplines, different concepts and terminology, and general lack of understanding between the different subcultures of science.

The other factor is the existence of paradigms, as discussed by Thomas Kuhn.[12] Kuhn has defined a paradigm as a "disciplinary matrix" shared by the members of a particular scientific community. This disciplinary matrix includes "symbolic generalizations," shared commitments to certain beliefs, values, and "exemplars."

Paradigms are helpful in enabling scientists within a particular specialty to have a common way of looking at things so that they can communicate with each other and coordinate their attack on the unknown, but paradigms can also be an impediment, supplying inertia to discredited ideas that should be abandoned. To the extent that the latter occurs, paradigms get in the way of building scientific understanding as a basis for prediction.

O. Practical Limits

In the "real" world of nuclear waste research and development, there are practical limits on time, money, and resources available, and there are political, legal, and bureaucratic influences that affect the steadiness and constancy of the program. Combined with the complexity of the problem and the need for data from experiments lasting as long as is practicable, these factors also erect very real impediments to the scientific development of long-term predictions.

III. LIMITATIONS ON THE USE OF SCIENCE-BASED PREDICTIONS IN POTENTIAL REPOSITORY LICENSING

Once a scientific basis for prediction has been established to the degree it can be, given the above limitations, the next challenge is to gain acceptance for it in repository licensing proceedings (This assumes that the site has been found suitable, and that the DOE has proceeded to apply for a license).

A. Admissibility of Scientific Evidence

According to 10CFR 2.743(c),[13] the criteria for admissibility of evidence in NRC licensing proceedings are that it be "relevant, material, and reliable" in the opinion of the presiding officer. NRC licensing proceedings are carried out under the provisions of administrative law, and are not bound by the requirements on the federal courts, but these do provide guidance. Also, if the results of the licensing proceedings are legally contested, the case will go to federal court, where these requirements do apply. It is therefore relevant to examine the Supreme Court ruling in the case of Daubert vs. Merrell Dow (the "Bendectin" case). The decision in this case was announced on June 28, 1993.[14] The case dealt with the standard for admitting expert scientific testimony in a federal trial.

In Daubert vs. Merrell Dow, the court held that the Federal Rules of Evidence[15] are the standard, and that they supersede the older Frye rule.[16] The Frye rule required that in order for expert testimony to be admissible, "the thing from which the deduction is made must be sufficiently established to have gained general acceptance in the particular field in which it belongs." Rule 702 of the Federal Rules of Evidence, on the other hand, states the following:

> If scientific, technical, or other specialized knowledge will assist the trier of fact to understand the evidence or to determine a fact in issue, a witness qualified as an expert by knowledge, skill, experience, training, or education may testify thereto in the form of an opinion or otherwise.

Under Rule 104 of the Federal Rules of Evidence it is the responsibility of the federal judge who is presiding to decide on the admissibility of expert testimony using this criterion. According to the decision in Daubert vs. Merrell Dow, "the requirement that an expert's testimony pertain to 'scientific knowledge' establishes a standard of evidentiary reliability," and furthermore, "In a case involving scientific evidence, evidentiary reliability will be based upon scientific validity."[14]

What all of this means is that federal judges are now called upon to decide themselves whether expert testimony is scientifically valid and therefore admissible, rather than using the standard of general acceptance in the scientific community. The judges are supposed to use the following criteria in making such decisions:[14]

1. Whether [a theory or technique] can be (and has been) tested.

2. Whether the theory or technique has been subjected to peer review and publication.

3. In the case of a particular scientific technique, ...the known or potential rate of error.

4. The degree of acceptance within a relevant scientific community.

B. Deciding Between Conflicting Expert Testimony

Once expert testimony has been admitted, there is always the potential for conflicting testimony. In this case, it is up to the court (or the licensing board) to decide between the experts. In the case of federal courts, Daubert vs. Merrell Dow calls for the use of "vigorous cross-examination, presentation of contrary evidence, and careful instruction on the burden of proof." The criteria used in NRC licensing proceedings, on the other hand, are the following:[17]

1. The degree of expertise possessed by the expert as evaluated by academic degrees, training, and experience.
2. The logical consistency of the testimony.
3. The consistency of the testimony with what are taken to be "known facts."
4. The ability of the expert to respond to cross examination.
5. The degree of factual support or logical theory presented.
6. Whether there is an appearance of speculation.
7. The degree of acceptance of theories within the scientific community.

IV. HOW WOULD SCIENCE-BASED LONG-RANGE PREDICTIONS STAND UP IN THE LEGAL ARENA?

A consideration of these various legal criteria in combination with the limitations on making science-based long-range predictions discussed earlier, reveals a number of problems, as judged by the present author:

1. It may be very difficult to convey a sufficient degree of understanding of the various technical issues to those called upon to decide on admissibility of evidence and to judge between conflicting expert testimony. Indeed, Chief Justice Rehnquist alluded to this problem in his minority opinion.[14]
2. Long-range predictions are not subject to direct testing.
3. It is not possible to evaluate accurately the rate of error or degree of uncertainty for long-range predictions.
4. It may be difficult to obtain wide acceptance in the scientific community for research results that are unique or novel.
5. Equally qualified experts, as judged by the criteria given, may differ on long-range predictions.
6. Long-range predictions are speculative by their very nature.

V. CONCLUSIONS AND RECOMMENDATIONS

Successful licensing of a potential repository is not likely in a regulatory climate in which science is called upon to make long-range predictions with "reasonable expectation" or "reasonable assurance," since such predictions are not likely to satisfy the criteria for admissibility in licensing hearings or federal court.

What should be done? Two efforts are needed. First, we certainly need to use the scientific method as best we can to project into the future, given our limitations, particularly to assist in choosing between alternative courses of action. Second, we need to develop regulations and a schedule that will allow for building our understanding in a careful step-by-step way, using a phased approach, rather than an all-or-nothing licensing process carried out without sufficient opportunity to gather data over an extended period from a pilot facility, and demanding predictions which cannot be confidently made.

Some would object that this approach would unacceptably delay the day when it could be concluded that a solution to the high level waste disposal problem had been demonstrated. I would suggest that the best solution to this problem is to reexamine what must constitute such a demonstration.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy, Office of Civilian Radioactive Waste Management, Yucca Mountain Site Characterization Project Office, Las Vegas, NV and performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48. The opinions expressed in this paper are the author's, and do not necessarily correspond to those of the sponsor or of the organizations of which he is a part.

REFERENCES

1. Environmental Protection Agency, "Environmental Radiation Protection Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Waste," Title 40, Code of

Federal Regulations, Part 191, U.S. Government Printing Office, Wash., D.C. (1992).

2. Nuclear Regulatory Commission, "Disposal of High-Level Radioactive Wastes in Geologic Repositories-Technical Criteria," Title 10, Code of Federal Regulations, Part 60, U.S. Government Printing Office, Wash., D.C. (1993).

3. R. Descartes, *Meditations on First Philosophy*, translated by Donald Cress, Hackett Publishing Co., Indianapolis, Indiana (1979).

4. D. Hume, *An Enquiry Concerning Human Understanding*, edited by Charles W. Hendel, Macmillan, New York, New York (1957).

5. K. R. Popper, *The Logic of Scientific Discovery*, Hutchinson, London (1959).

6. K. Gödel, *Collected Works*, Vol. 1, edited by S. Feferman et al., Oxford University Press, New York, New York (1986).

7. R. C. Tolman, *The Principles of Statistical Mechanics*, p. 629, Oxford University Press, London (1938).

8. W. Heisenberg, *The Principles of the Quantum Theory*, University of Chicago, Chicago, Illinois (1930).

9. K. B. Krauskopf, "A Tale of Ten Plutons," Geol. Soc. of America Bulletin 79, 1 (1968).

10. I. Stewart, *Does God Play Dice? The Mathematics of Chaos*, Basil Blackwell Inc., Cambridge, Massachusetts (1989).

11. American Society for Testing and Materials, "Standard Practice for Prediction of the Long-Term Behavior of Waste Package Materials Including Waste Forms Used in the Geologic Disposal of High-Level Nuclear Waste," C1174-91, ASTM, Pittsburgh, PA (1991).

12. T. S. Kuhn, *The Structure of Scientific Revolutions*, Second Ed., U. of Chicago Press, Chicago (1970).

13. Nuclear Regulatory Commission, "Rules of Practice for Domestic Licensing Proceedings and Issuance of Orders," Title 10, Code of Federal Regulations, Part 2, U.S. Government Printing Office, Wash., D.C. (April 30, 1992).

14. Daubert v. Merrell Dow, U.S. Supreme Court case no. 92-102 (June 28, 1993).

15. U.S. Congress, "Rules of Evidence," Public Law 93-595, 88 STAT. 1926 (1976).

16. Frye v. United States, 54 App. D.C. 46, 47, 293 F. 1013, 1014 (1923).

17. M. G. Malsch, Deputy General Counsel, U.S. Nuclear Regulatory Commission, Luncheon talk presented at Fourth Annual International Conference on High Level Radioactive Waste Management, Las Vegas, NV (1993).

DATE FILMED

8/29/94

END