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Collision Course

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R. A. Van Konynenburg

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SCIENCE AND LICENSING: LET'S GET OFF THE COLLISION COURSE

R. A. Van Konynenburg
Lawrence Livermore National Laboratory, P.O. Box 808, L-352
Livermore, CA 94550

ABSTRACT

Our best possibility for gaining an understanding of the likely future behavior of a high level nuclear waste disposal system is use of the scientific method. However, science has inherent limitations when it comes to making long-term predictions with confidence. This paper examines 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 were binding until recently. Suggestions are made for remedying this situation.

INTRODUCTION

The U.S. government standards and regulations that were to govern the licensing of a potential high level nuclear waste repository at Yucca Mountain are currently being reconsidered in response to Title VIII of the Energy Policy Act of 1992. As originally promulgated, they called for detailed prediction of the behavior of natural and engineered systems out to 10,000 years in the future. The means that were prescribed for making such predictions were "the 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 [1]," as well as "performance assessment [2]." Inherent in these prescriptions is an appeal to the scientific method, although the writers of the regulations did not spell this out explicitly, perhaps because they were aware that the predictions called for were beyond what science is usually called upon to produce. Indeed, both 40CFR Part 191 and 10CFR Part 63 acknowledged that "Proof of the future performance ... is not to be had in the ordinary sense of the word." The first regulation then called for "reasonable expectation," and the second for "reasonable assurance," terms which were not further defined.

During this period of reconsideration, it would be helpful for all of us, scientists, regulators, program administrators, and the public at large to take a hard look at the limitations of the scientific approach in this context. By so doing, we can take best advantage of what science can do, while not deceiving ourselves or others into believing that science can accomplish things of which it is not capable, and thus bringing about the inevitable day when someone points out that "the emperor has no clothes."

Can science make a significant contribution to the prudent management of nuclear wastes? By all means! I believe it to be our best hope in attempting to understand the likely future behavior of a disposal system. This seventeenth symposium is testimony to the fact that I am not alone in this belief.

Can science confidently support detailed predictions of the behavior of a nuclear waste disposal system thousands of years or more into the future? The first part of this paper considers this question. The second part addresses the issues involved in bringing the products of scientific investigation into the legal arena of repository licensing proceedings. An opinion is then offered about the prospects for success if we maintain our present course, and suggestions are made for changes.

LIMITATIONS ON MAKING SCIENTIFIC PREDICTIONS IN NUCLEAR WASTE MANAGEMENT

There are various factors that limit our 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.

Epistemological Problems

The first issues I want to consider are in the area of epistemology, the branch of philosophy that investigates the nature, scope, and quality of human knowledge. First is the question considered by Rene Descartes [3], which essentially was "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?" Descartes was able to satisfy himself on this point on the basis that God exists and is no deceiver. However, others have shown that proofs for the existence of God based on human logic always have loopholes. One can choose to believe in God on the basis of faith, but one cannot get to this point solely by deductive reasoning. So where does this leave us with respect to the question raised by Descartes? We are left with the problem that we cannot prove that our thoughts correspond at all to external reality. From an operational point of view, all of us assume that we are in touch with reality, and we go on living our lives on this basis. But it is significant to note that we are operating on an unproven assumption when we do so.

Now let's consider the question raised by David Hume [4], which essentially was "What basis do we have for believing that we can make any inferences at all about the future from the present and the past?" Hume concluded that we have no rational basis for believing that we can do this. We have simply assumed, based on experience, that the future will resemble the past, but we cannot logically prove that it will. This is important in justifying the conduct of science, because we carry out much of our work using inductive logic, assuming the validity of the so-called Principle of the Uniformity of Nature and the Principle of Causality. Using this approach, we have found that we can make considerable progress in understanding nature. We have therefore accepted the

validity of these principles, and most scientists aren't particularly troubled by Hume's question. Nevertheless, we must still face the fact that we are operating again on unproven assumptions when we do this.

Use of science to predict the behavior of a nuclear waste disposal system is subject to the same epistemological problems that affect science in general.

The One-Sidedness of Hypothesis Testing and the Provisional Nature of Scientific Understanding

The use of inductive reasoning in science leads to the situation emphasized by Karl Popper [5]: our understanding must always be considered to some degree tentative and provisional, because we can never prove that a hypothesis is true. We can only make attempts to show that it is false, and so long as we fail to show that it is false, it stands and is accepted as true for the time being. The theories that we can have most confidence in are those that have made clearly testable predictions and have been found to be correct in those predictions, particularly when the predictions were totally unexpected. Popper 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. All of us who have watched 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. This should have the effect of making us cautious when we are called upon to predict future events. We can never be sure that we have the ultimate understanding of the relevant phenomena, in nuclear waste management or in any other field.

Sociological Aspects of the Conduct of Science

In this category, I want to mention two factors which place limitations on our ability to develop confident predictions. The first is the specialization and compartmentalization that result from the practice of scientific reductionism and from the growth of the body of scientific knowledge. This specialization impedes the treatment of phenomena that cut across several disciplines, and slows down our progress when we try to predict the behavior of a multifaceted system, such as a potential repository. A single researcher does not have a grasp of all facets of the problem, and committees are subject to their own characteristic weaknesses and failings.

The other factor to which I want to call attention is the existence of paradigms, as discussed by Thomas Kuhn [6]. Paradigms are helpful in enabling us to have a common way of looking at things so that we can communicate with each other and coordinate our attack on the unknown, but they can also be an impediment, supplying inertia to old 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.

Godel's Incompleteness Theorem and the Heisenberg Indeterminacy (or Uncertainty) Principle

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 usually makes use of mathematical

argument. Many of us have developed such a healthy respect for the validity of mathematics that we have come to believe that if something can be derived mathematically, it must be true. However, the work of Kurt Godel [7] should cause us 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.

In a somewhat analogous manner, Heisenberg's principle [8] sets a limit on what can be achieved experimentally: we can never determine exactly both the position and the momentum of a particle at the same time.

Together, Godel's and Heisenberg's work fundamentally limit the two approaches we use in developing scientific understanding and hence, prediction. As a practical matter, however, we still find mathematics to be a reliable method for developing physical understanding, and when we are dealing with systems of macroscopic size, the relative uncertainty resulting from Heisenberg's principle becomes small. Nevertheless, we must note that these principles do place limits on our ability to make deterministic predictions.

The Statistical Basis of Physical Laws Applying to Systems of Many Particles

The motion of a physical system involving more than two particles cannot be solved analytically, but numerical methods can be used for systems of many particles, so long as the capacity of available computers is not exceeded. For larger systems of macroscopic size, however, we must resort to the methods of statistical mechanics or thermodynamics. These methods deal with average properties of a system of particles, and are very powerful. However, inherent in these methods is the possibility of fluctuations [9] from the average, so that any statement made using such approaches is necessarily subject to an uncertainty. In practice, for large enough systems, the fractional uncertainty becomes extremely small, and we are not particularly concerned. Nevertheless, statistical uncertainty is another factor that places a limit on our ability to predict.

Chaos Theory

In recent years it has been realized that there are some systems in which the final outcome depends very sensitively on the initial conditions. These are termed "chaotic" systems [10]. For all practical purposes, the behavior of chaotic systems cannot be predicted, because it is impossible to measure the initial conditions of a system with perfect accuracy. One common example of this is the weather. Some geohydrodynamic systems also fall into this category. In such cases, prediction is, in principle, hopeless. This makes it imperative that we rule out chaos before attempting predictions.

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 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 observations or experiments of a similar duration in order to test our theories, and then using these 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 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 we can no longer compare hypothesis to observation, we are no longer practicing the scientific method.

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 have boundaries, 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 meteoritic impact. Some relief can be obtained 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 uncertainty in our predictions due to the finite size of the modeled system.

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, 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. Without an understanding of the processes and their interactions, accurate prediction becomes impossible.

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. I have already noted that this is fatal to predictions in chaotic systems, but it also sets limits on the predictability of non-chaotic systems.

Limits on Characterizing a Natural System

In order to model the long-term behavior of a natural system, one needs to know its initial conditions in sufficiently fine detail. 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.

Establishing that a "Natural Analog" is Truly Analogous

Regulation 10CFR Part 60 recommends the use of "natural analog studies." A significant problem with this approach is that no two natural systems are exactly alike, and the burden of establishing that there is a true analogy between them becomes significant. Perhaps a better approach is 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.

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 long-term experiments, these factors also place very real limits on the scientific development of long-term predictions.

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.)

According to 10CFR2.743(c) [11], 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. 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*, which was decided on June 28 of this year [12]. This 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 [13] are the standard, and that they supersede the older *Frye* rule [14]. 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."

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 [12]:

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.

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 [15]:

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.

In considering these various legal criteria in combination with the limitations on making science-based long-range predictions discussed earlier, I can see a number of problems:

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 [12].
2. Long-range predictions are not subject to direct testing.
3. It is not possible to evaluate the rate of error or degree of uncertainty for long-range predictions.
4. It will be difficult to obtain wide acceptance in the scientific community for research results that are unique or novel.
5. Equally qualified experts may differ on long-range predictions.
6. Long-range predictions are speculative by their very nature.

CONCLUSIONS

I conclude from this that 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." What should be done? I would suggest that two efforts are needed. First, we need to use the scientific method as best we can to project into the future, given our limitations, and to assist in choosing between alternative courses of action. Second, we need to develop regulations 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 from a pilot facility and demanding predictions which cannot be confidently made.

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