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MEMORANDUM FOR: Hubert J. Miller, Chief
Repository Projects Branch
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THROUGH: James E. Kennedy, Section Leader
Repository Projects Branch
Division of Waste Management

FROM: Dennis A. Clark, Summer Intern
Repository Projects Branch
Division of Waste Management

SUBJECT: QUANTIFICATION OF GEOLOGIC SCENARIO PROBABILITIES FOR USE IN A PRA: CAN IT BE DONE AND DOES IT MEAN ANYTHING

In researching how the probabilities were determined by Lawrence Livermore National Laboratories for seismology and Sandia National Laboratory for scenarios, I began to notice inconsistencies in the assumptions being used within the methodologies for analyzing the data and for predicting far-future results. The problem centers on the assumption that the rates of processes, i.e., semismicity, erosion, sedimentation, corrosion, and hydro-geochemistry, to name but a few, will remain at their present rates into the future. This assumption is called stationarity.

Stationarity assumes "the present is the key to the future," which is analogous to uniformitarity's "the present is the key to the past". Uniformitarity does not always prove to be valid because processes have occurred in the past that have no equivalent today, i.e., the accumulation of large dolomite formations or the development of komatiitic crust and associated greenstone belts. My feeling is that stationarity has a similar problem.

Although a stationarity may be valid in the short-term, non-stationarity is more likely the case in the long-term, especially in the case of geologic processes.

The stationarity assumption is built into the simulation models that are used to predict far-future data and probabilities. The resulting output may appear reasonable, but in actuality there exists a higher degree of uncertainty than that associated with the initial input data and data-processing procedures.

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As for whether probabilities may be determined for the different geologically repository-significant scenarios, the answer is "yes". Relative probabilities have been used in PRA's for nuclear power plants for years and will likely prove useful in repository PRA's, provided the EPA does not require a quantitatively rigorous PRA for performance assessment. Now, whether the probabilities and the PRA's they are used in have any value, the answer lies somewhere between "no" and "maybe" at this point. Given the questionability concerning the current use of stationarity-based data to predict future performance, the answer leans heavily towards "no". The reason being that the uncertainty of the output could sufficiently subjugate any realism in the output data to render it useless. Should the non-stationarity assumption be substituted for stationarity in predicting far-future probabilities, then the reliability of the probability data, including the relative probabilities, would be greatly improved.

I thank you for a challenging (and educational) project. I hope that the enclosed report, "Quantification of Geologic Scenario Probabilities for Use in a PRA: Can it be done and does it mean anything?" is to your satisfaction.

"ORIGINAL SIGNED BY"

Dennis A. Clark, Summer Intern
Repository Projects Branch
Division of Waste Management

Enclosure:

Quantification of Geologic Scenario Probabilities for Use in a PRA: Can it be done and does it mean anything?

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OUTLINE FOR ENCLOSURE 1

BY DENNIS A. CLARK, JR. AUGUST 1984

TOPIC: GEOLOGIC PROCESS PROBABILITY QUANTIFICATION FOR USE IN A PRA; CAN IT BE DONE AND DOES IT MEAN ANYTHING?

PURPOSE: 1) LOOK AT HOW EPA STANDARD APPROACHES THE DETERMINATION AND USE OF PROBABILITIES AS GUIDANCE FOR NRC DIVISION OF WASTE MANAGEMENT ON AN OVERALL BASIS, NON-SITE SPECIFIC.
2) LOOK AT LIMITATIONS IN UTILIZING PROBABILISTIC APPROACH TO GEOLOGIC HAZARDS AND RISK ANALYSIS FROM A GEOLOGIC VIEWPOINT.

INTRODUCTION
- TOPIC
- PURPOSE
- BRIEF DESCRIPTION AND OUTLINE OF PAPER

BODY
- I. NATURE OF THE EPA STANDARD (GTP AND FEHRINGER, EQUATION + DESCRIPTION)
- II. NRC INTERPRETATION OF THE EPA STANDARD (GTP AND FEHRINGER, 10CFR60)
- III. PROBLEMS/QUESTIONS CONCERNING QUANTIFYING PROBABILITIES
  - A. VALIDITY OF CCDF
  - B. WHERE DO THE NUMBERS COME FROM?
    - 1) HOW LLNL DID SEISMOLOGY
    - 2) DISTINCTION BETWEEN DETERMINISTIC AND PROBABILISTIC (AEROSPACE)
  - C. USE OF RELATIVE PROBABILITIES FOR UNKNOWN VALUES
    - 1) SKEW DATA IN SAME DIRECTION
    - 2) PROBLEMS WITH USING IN A PRA (SANDIA)
- IV. PRA FROM GEOLOGIC SYSTEMS VIEW
  - 1) DISTINCTION BETWEEN GEOLOGIC AND REPOSITORY SIGNIFICANCE WITH EXAMPLES
  - 2) CONSIDERATIONS OF DATA BASE
- V. CONCLUSION
- VI. REFERENCES

INTRODUCTION

One of the many problems facing the Nuclear Regulatory Commission (NRC) in reviewing a licensing application for a high-level nuclear waste repository is the validity of the probabilistic risk analysis (PRA) and the accuracy of the probabilities associated with the various geologically repository-significant scenarios. Many of the probabilities used will be relative values from sources, such as expert opinion or conservative estimations, as opposed to absolute probabilities, such as tossing a coin or rolling a die.

While the use of relative probabilities in PRA's for surface nuclear facilities, such as power plant reactors, has not been shown to be a problem, caution must be exercised when using relative probabilities to assess the performance of a repository over its intended 10,000 year life expectancy. The assumptions that are the foundation for the probabilities should be given careful consideration about their validity, given the amount of time that they must remain unchanged. Also, the uncertainties associated with a probabilistic approach must be carefully screened so that the probability distribution function (PDF) of the PRA has meaning and is not negated by the uncertainties masking the values.

This report addresses the probability quantification of geologic, repository-significant processes for use in a PRA and where some of the uncertainties arise that could possibly be made more certain. This is accomplished by analyzing the limitations in using a probabilistic approach to geologic hazards and risk analysis from a geologic viewpoint and by considering the problems associated with the data base collection methodology.

NATURE OF THE EPA STANDARD

Nuclear Regulatory Commission (NRC) regulation 10 CFR 60 section 112 establishes the Environmental Protection Agency's (EPA) standard (40 CFR 191) as the overall release limit for a repository in a geologic medium system. The draft EPA standard is a probability-based standard for which a formal probabilistic treatment of releases similar to the probabilstic risk analyses (PRA) used for nuclear power plants and other applications would be required as one of the bases for evaluating repository acceptibility (Fehringer, 1984).

The proposed EPA standard addresses the release of radionuclides to the accessible environment. To address release of radionuclides on a probabilistic basis, it is necessary to evaluate events, processes, and conditions that may affect the repository's performance. The evaluation includes: 1) the identification of a complete set of release scenarios; 2) the determination of the consequences of the release scenarios; 3) the determination of the probability of occurance of each release scenario; and 4) the combination of the risks of releases into a complementary cumulative distribution function (CCDF) that assesses the probability that the EPA standard limits will be exceeded (GTP-Licensing Assessment, 1984). This approach can be formally described as:

$$P(r \geq R) = \sum_{i=1}^{n} P(r \geq R/S_i) P(S_i) \qquad \text{[eq. 1]}$$

where $R = \sum_{j=1}^{k} R_j/RL_j$

$j = j^{th}$ radionuclide

R = release rate to the accessible environment

RL = EPA release limit;

r = a release to the accessible environment

$S_i = i^{th}$ release scenario

$P(n)$ = probability of outcome n

$P(n/m)$ = conditional probability that event n will occur, given that event m has occurred

The establishment of "reasonably foreseeable" release probability values of <0.1 and "very unlikely" release probability values of <0.1 but >0.001 for a 10,000 year period, by the EPA standard, are based on very conservative values that, in their calculation,gave no credit for engineered barriers nor retardation. These values are intended to be the upper bounds of acceptibility in a performance assessment of a proposed repository. The EPA standard recognizes that numerical estimates of the probabilities or frequencies of future events may not be meaningful (EPA-520/3-80-006, p.96). What is required is "reasonable expectation, on the basis of the record before the implementing agency, that compliance with 40 CFR 191.13(a) will be achieved" (Working Draft No.4 - Final 40 CFR 191, p.79, May 1984 version). This would include expert opinion, which is qualitative evidence, in the determination of the performance assessment for licensing.

NRC ASSESSMENT OF THE EPA STANDARD

The NRC staff considers the proposed EPA standard to require a formal probabilistic treatment of releases similar to the PRA used for the analysis of nuclear power plants and other applications as part of the decision-making process. Since the EPA standard has not been finalized, the staff notes that the extent that a PRA will be required in the licensing process has not been finally determined. In any event, the license application must quantify to the extent practicable the full range of uncertainties that exist in the assessments of performance. The EPA intends that the estimate of risks and uncertainties be used to construct a CCDF, which will be compared to the EPA containment requirements of 40 CFR 191 to determine whether the repository will comply with the release limits established in the standard (GTP-Licensing Assessment, 1984).

VALIDITY OF CCDF

Questions concerning the validity of the CCDF have been raised by Ornstein et al.(1984). These issues include: 1) the absence of a concensus in the geological community concerning the appropriateness or possibility of constructing a meaningful CCDF. This is a result of the technically and philosophically divergent views of the geologists, who use subjective intuition to determine system parameters and uncertainties, and the performance assessment modelers, who quantify the geologist's intuition; 2) the alternative theories concerning certain geologic processes that must be reconciled to able to reach a concensus about the probabilities and consequences of different scenarios that result from the fundamental differences of opinion in data interpretation and/or theory in perspectives of how to fill in sparse or missing data; and 3) selection and differentiation of various scenarios may not be obvious due to the subtle differences in events that effectively create a continuum of scenarios. In this case, the calculated hazard is very sensitive to the PDF assumed, which affects the probability range of the scenario.

HOW LLNL DID SEISMOLOGY

The fundamental problem of both deterministic and probabilistic approaches is calculating hazards for extreme cases where little or no data exists and for which the physical processes involved are little understood, as is the case in seismic hazard analysis. Even in the western United States, where seismically active structures can be identified, subjective inputs and empiricle adjustments to the models are required to realistically predict seismically induced ground motions.

In order to deal with this problem, Bernreuter and Minichino (1983) developed the uniform hazard methodology (UHM) whose features include: 1) explicitly subjective input from experts; 2) final hazard assessment using all earthquakes, large and small, in a region; 3) the resulting seismicity spectrum combines exceedance probabilities due to earthquakes from all sources at any distance; and 4) formal treatment of the uncertainties.

The UHM approach considers both systematic uncertainties, which are associated with errors in the form and parameters of the model used in the analysis, such as elements of the attenuation law, upper bound magnitudes, and site amplification factors, and random uncertainties, which are associated with independent variations in the parameters, such as magnitudes of different seismic events given their common distribution. A detailed discussion of the treatment of systematic and random errors is given in Bernreuter and Minichino (1983, vol.2, Appendix A).

Two time periods, 150 and 1,000 years, were considered because of the controversy involved with extrapolating results from short time intervals to long time intervals due to the possible non-stationarity of seismicity. This non-stationarity is evidenced in the historical seismicity records of China and Japan where the rate of seismicity shows changes in 300-500 year cycles during the 3,000 years that records have been kept (M. Blackford, 1984, pers.comm.). The 150 year period was chosen because it approximates the amount of time that seismicity has been historically recorded in the eastern United States. The 1,000 year period was chosen to exclude uncertainties associated with extremely long-term geological variations (but does it really?).

The experts in the study were asked to consider the largest seismic event they expected to occur within the current tectonic framework in each source zone, irrespective of time period. They based their answers on the recorded data, whether past history can be used to predict the future, and whether additional information could be drawn from the tectonics, theoretical studies, and similarities with other regions in the world (Bernreuter and Minichino, 1983). An underlying assumption of this study is stationarity of the seismicity, i.e., the rate of seismicity remains constant, which is not necessarily a valid assumption.

Bernreuter and Minichino (1983) found that: a) it is not a simple task to determine the importance of parameter variations when the parameters interact, such as in the case where a large upper magnitude cut-off can be partially cancelled by a "steep" Richter b- value, which results in the occurance of relatively few predicted, large, seismic events; and b) that general conclusions are site dependent as well as being dependent upon the return period of interest, which is also expressed by Ornstein et al. (1984). They also found that using expert judgement and insight to supplement deficient data sets is a viable approach (a similar approach was used by Bernreuter et al. in 1984 to assess the seismic hazard of the eastern United States). However, direct verification of their results is not obtainable, and, therefore, their results must be considered as relative seismic hazards at the sites studied.

USE OF RELATIVE PROBABILITIES

The above discussion brings up the point that in cases where data is lacking, relative values for the probabilities may be used for quantification, as in the case of scenario occurrance (Hunter, 1983).

The use of conservative relative values is beneficial in areas where data is lacking because they assist in locating which scenarios are likely to occur and which ones may be discounted. Another advantage to conservative relative values is that they tend to skew a PDF conservatively, which also skews the corresponding CCDF in the same direction. However, using uncertain or relative probabilities in computations to calculate absolute risks is a misuse of the relative probabilities (Hunter, 1983).

This leads to some problems because relative probabilities are being used in performance assessment models, which are deterministic in design, and have been considered for use in [eq. 1] to quantify the $P(S_i)$ values (Davis and Runchal, 1983; Davis et al., 1983) for a PRA. In order to resolve this problem prior to licensing, the finalized EPA standard should not require rigorous or absolute determination of all the risks in a licensing PRA.

DETERMINISTIC vs. PROBABILISTIC

A distinction needs to be made between the deterministic and the probabilistic approaches to quantifying the different scenario occurrances and consequences. The deterministic approach involves the use of mathematical expressions that result in definite values for an output variable, such as a component's time of failure, for a specific set of model input parameter values in a computer simulation.

The probabilistic approach involves the quantification of uncertain input parameters based upon the distribution of values around the most probable value. The uncertainty in the input parameters arises from the uncertainties associated with experimentally determined parameters and from estimates of environmental factors that may vary over a wide range, and as such can only be determined in broad terms (Aerospace, 1984), as in the case of qualitative information or expert opinion.

Quantifying the uncertainty in a PDF may be addressed using uncertainty and sensitivity analyses. Uncertainty analysis is the study of the uncertainty in the output of a model as a result of uncertainties in the input parameters, i.e., the probabilistic distribution of output values around the most likely output value as a function of the probability distribution of the input values (Aerospace, 1984). Sensitivity analysis determines the significance of a parameter on the model output without regard to the actual uncertainty of that parameter. This permits assessment of the experimental parameters that require extra care when being measured to optimize reduction of the uncertainty associated with critical parameters (Aerospace, 1984).

GEOLOGIC-SIGNIFICANCE vs. REPOSITORY-SIGNIFICANCE

Over the intended 10,000 year life expectancy of a high-level nuclear waste repository in a geologic medium, many processes, i.e., erosion, sedimentation, seismicity, climate, geochemistry, tectonics, glaciation,and hydrology, may become significant in their resultant effects on the geomorphology, geology, and topography of an area. These processes are therefore worthy of consideration, but emphasis should be placed on those processes that have a potential effect on the repository's designed function: to isolate radioactive wastes from the accessable environment.

The repository-significant processes encompass anything that significantly affects the repository, especially those processes that may result in a release above the maximum permitted by the EPA standard. Examples of geologic processes that may be potential repository-significant processes include: changes in the groundwater geochemistry of the host rock; ground acceleration of a magnitude greater than that designed for; and the development of a fault in the near-field of the repository.

DATA BASE

In looking at probabilistic risk analyses (PRA) from a geoloigic systems viewpoint, the overriding problem to quantifying the probabilities seems to be a insufficient data base.

Attempts at quantifying the probabilities of occurrance for repository-significant processes for use in a PRA run into problems resulting from these insufficient data bases. These insufficient data bases are a function of: 1) a highly uncertain understanding of the physical properties, parameters, and physical states of the phenomenon under study; 2) the time frame involved, i.e., geologic time versus the amount of time the data has been collected over; and 3) the methodology of the data collection.

A consideration that needs to be kept in mind when analyzing a repository in a geologic medium is that each component of the repository becomes a part of the larger geologic system. This geologic system contains many branches and feed-back processes that may be conceptually envisioned as being similar in appearance to a fault or event tree diagram, but having branches providing input to other branches. Many of these branches are interdependent and as such, they impose a variability to the responsiveness of the overall system. While changes in one branch may result in changes in another, the branches are also affected by events occurring in the far-field environment that may have no immediate effect on the structural integrity of the repository, but over time may significantly influence a branch that does influence the repository, conceptually similar to common-cause failures in traditional PRA's.

Suppose the hydro-geochemistry of an aquifer changes both regionally and locally. Over time this would be expected as water infiltrating the recharge zone under a particular set of environmental conditions reaches the repository site, or as groundwater from other aquifers intrudes the repository's aquifer, or through other processes. This change would occur slowly. Given the 10,000 year life expectancy of the repository, system non-stationarity should be assumed.

A hypothetical repository's engineered components, i.e., waste package, backfill, and barriers, would have been designed to provide maximum protection given the conditions indicated by the 20 years data collected during the design phase under an assumption of system stationarity. Stationarity would be assumed because a) hydro-geochemical changes during site characterization may be so slight as to be masked by the measurement uncertainty and/or b) the uncertainties involved with dealing with the non-stationarity assumption would be unmanageable.

When a phenomenon is initially studied, it typically is uncoupled by separating it into its component parts for ease of simplification. Certain assumptions are made concerning the relationships of the components if their relationships are not already known. The assumptions are probabilistic in nature and involve uncertainties. Since some of the relationships are unknown, some of these relationship assumptions involve relative probabilities.

The assumptions are passed on to a computer model of the phenomenon as input values. The computer model uses a deterministic approach, i.e., for a given input the program gives a certain output. The output received may not support nor negate the original hypothesis and assumptions, which results in several alternative hypotheses for the same phenomenon, which results in problems associated with the CCDF as previously descibed.

In the aquifer example, uncertainty in the relationships between the geochemical parameters may exist. When the new physical parameter values become dominant, if they do become dominant,the original PDF, and a CCDF that depends on that input, may no longer be valid. New ones will need to be calculated, but more uncertainty exists under the new conditions than under the initial conditions, i.e., the corrosion rate, Eh and pH values, waste package and repository integrity, and other physical parameter are now unknowns. They can be assigned values and a conditional, relative PDF may be determined, but as far as being useful enough to produce a meaningful PRA, the new data may be of limited use.

The time frame reference chosen also significantly contributes to the uncertainty. The longer the time frame, the more the uncertainty may overshadow the input and output values significance. Stationarity may be a valid assumption for repository significant processes for possibly only a few hundred years. Beyond this, non-stationarity should be assumed. In the case of human intrusion, non-stationarity should be assumed from the start, since the rate of advance or retreat of Man is completely uncertain beyond the near-future and even the near-future data is shaky at best.

Most experiments, including accelerated-time experiments, assume stationarity of processes. The practice of using accelerated-time data as input for predicting results 1,000 years or more into the future, such as in waste package (K. Chang, 1984, pers. comm.), may run into relativistic time problems, i.e., trying to use data from one frame of reference to predict data in another frame of reference without changing the assumptions to match the frame of reference to be predicted. As a result, the predicted output would have a high degree of uncertainty associated with it that is not accounted for by the input parameter uncertainty, nor the data-processing uncertainty.

Another time-related problem involves the length of time the available data bases have been collected over in order to quantify the probabilities. These data bases may not be statistically representative of the phenomenon being studied to produce an accurate PDF. At the Hanford Site (BWIP), they have 24 years of networked, instrumentally recorded seismograph data, but the largest earthquake recorded in the Columbia Plateau (5.75 magnitude) occurred 24 years before the network was established. Twenty-four years of data base versus a life expectancy of 10,000 years is not a good statistical sample.

As discussed above, the seismicity PDF's assume stationarity in the rate of seismicity, which is probably invalid since the Chinese and Japanese records show cyclicity of 300-500 years over a 3,000 years sampling period. The work of Bernreuter and Minichino (1983), Bernreuter et al. (1984), and Ibrahim (1984, pers.comm.) state that the seismicity of the United States and seismic hazard analyses for surface nuclear facilities , respectively, can only be regarded as relative hazard probabilities, not absolute hazards. This being the case, the use of these probabilities in a rigorously quantitative PRA may be a misuse of these relative probabilities.

CONCLUSION

In researching the feasibility of quantifying the probabilities of occurrance of the geologic scenarios that may affect a high-level nuclear waste repository, it appears that most of the scenarios may be quantified, either absolutely or relatively. Those probabilities that can be quantified absolutely by using mathematical expressions to describe the processes involved do not pose a problem in their ability to be used in a risk analysis. However, those probabilities that are determined in a relative sense, due to uncertainties in the data, do pose a problem. When the relative probabilities are used, care should be taken with regard to the assumptions that underlie the relative values and also in how the probabilities are used.

In researching this report, it became evident that relative probabilities, in the form of expert opinions, have been used in nuclear power plant PRA's for years with no apparent problems. It appears that relative probabilities will be used in repository related PRA's in areas where data is lacking or highly uncertain. This seems to be an adequate solution provided that the relative probabilities chosen are conservative values. The methodologies used to arrive at the relative probabilities for nuclear power plants seems to be adequate enough to be used for determining relative probabilities for scenarios associated with the repository, until the assumptions involved are analyzed.

One of the assumptions associated with a surface nuclear facility risk assessment is that the rate of a process will remain the same for the life of the facility, i.e., stationarity, which is valid for a power plant, given its approximately 40 year life expectancy. However, in the case of a repository whose life expectancy is 10,000 years, stationarity of many of the processes is not a valid assumption. A review of geologic history indicates that 10,000 years is ample time for many changes to occur. Yet data collected under the assumption of stationarity is used in simulations to predict far-future results.

This brings up the question of whether the predicted data and probabilities mean anything. Predictions and probabilities using stationarity have far more uncertainty associated with them than can be accounted for by the uncertainty in the input data and the data-processing procedures. Enough uncertainty exists to more than mask any validity the output might have had, which in essence renders the output probabilities and predictions useless, even where conservative values were used. Far-future predictions that use non-stationarity as an assumption would tend to have a higher reliability since they more closely resemble the real situation, even though they will tend to have a high degree of uncertainty associated with the values.

The probabilities can be quantified, even relatively, but in order for the probabilities to have any meaning, care should be taken to be certain that the assumptions, especially those that are unstated, should reflect the system being dealt with over the time period being considered.

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