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ON THE APPLICATION OF EXPERT SYSTEMS IN ENVIRONMENTAL PERFORMANCE ASSESSMENT

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ABSTRACT

Several methodologies have been developed to assess the nature and form of human impact on the environment. Each technique attempts to address the uncertainties surrounding the functional relationships that govern environmental systems and the form, diffusion, and persistence of human impact. As technological advances increase society's ability to cause environmental change, the need to understand the long-term implications of human actions beyond the planning horizons of present social and political systems becomes more urgent. The emerging methodology of environmental performance assessment holds promise in this regard. However, environmental performance assessment is hampered by the lack of a comprehensive environmental framework and a failure adequately to integrate aftermath effects into overall descriptions of risk. In this article, the concept of environmental performance assessment is reviewed, and an approach is introduced that uses an expert system to integrate the facts and relations defining a coupled human-environmental system so as to produce an "intelligent" event tree capable of expressing long-term environmental risk.

INTRODUCTION

Questions regarding the irreversibility of human impact and the long-term viability of environmental systems threatened by human activities have been difficult to resolve. Characterizing human impact requires a set of variables as diverse and complex as those governing the environmental systems under consideration. Complicating matters further is the high level of uncertainty in our

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understanding of environmental processes, and of the form, diffusion, and persistence of human impacts. The speed with which modern technology is developing assures that decisions made by society will increasingly risk affecting environmental systems well beyond the planning horizons of present-day socio-political systems [1]. This fact is evidenced in the controversies surrounding recent concerns over global warming and climate change, nuclear waste disposal, hazardous waste disposal, tropical deforestation, habitat destruction, and forced species extinctions.

Such issues have tremendous implications for future societies that may have to adapt to an environmental system that may have shifted to a new equilibrium (or to unstable states). To meet this challenge, new methodologies must be designed to evaluate the impact of human activities that may have environmental consequences for periods of 100 to 10,000 years or more.

Environmental impact assessment has been the principal means of understanding human impacts on the environment within a structured decision-making framework. In the past twenty years many approaches to impact assessment have been introduced and well over 200,000 environmental assessments have been conducted in the United States alone [2, 3]. However, impact assessments have traditionally emphasizes short term environmental impacts. In a recent review of the broader-scale consequences of human impacts on environmental systems, Coates and Coates suggest that the existing concepts and methods that guide impact assessment are inadequate when effects over time periods exceeding 50 to 100 years are considered [4].

Although prediction has always been a feature of environmental impact assessment, the primary role of environmental impact assessment has been to guide decision makers in making an informed trade-off among conflicting aspects of a proposed activity [5, 6]. Consequently, environmental impact assessments have been deficient in providing decision-makers with defensible and useful forecasts when human actions and the environment are viewed in concert over the long-term [7]. In light of the recent concerns regarding the anthropogenic "forcing" of environmental systems, and the increased potential for irreversible changes in vital earth-system processes, a model is sought that can forecast the long-term aspects of human activity and its effect at some future state of the environmental system. The emerging technique of environmental performance assessment holds promise in reaching this goal. However, as noted by Malone, a tractable methodology for conducting environmental performance assessments has not been formally described in the literature [1]. The purpose of this article is to delineate the concept of performance assessment and extend this methodology through the application of expert systems technology. The use of an expert system helps integrate the long-term impact of human activity with the components of the environmental system. Once linked, the system forms what might be thought of as an "intelligent" event tree capable of characterizing uncertain events that are presently modeled using expert judgment.

FORMALIZING ASSESSMENT METHODOLOGIES

The concept of performance assessment has been most fully developed for issues surrounding high-level nuclear waste repository siting in complex geologic environments [8-12]. In this context, a performance assessment provides a quantified description of a system's current behavior, its expected future behavior, and the acceptability of that behavior when compared to a set of standards that specify the degree of safety required in the system over time [13]. Conducting the assessment entails a detailed analysis and documentation of the processes, events, and uncertainties that could act to destabilize a nuclear waste repository site, identifying the potential consequences of one or more destabilizing events and their likelihood. With this information, the ability of a site to conform to a set of safety standards can, in principle, be evaluated before the site is committed to an irreversible use that could have cross-generational consequences.

In the repository siting problem, the spent nuclear fuel must remain isolated for a minimum of 10,000 years, and the site itself must remain geologically stable as environmental processes and potential human interference act on that location over time. The implications of the siting problem and the complications associated with the assessment of environmental performance has been the subject of recent investigations [1, 14]. Considering the magnitude and risks associated with the siting problem, the question is not only whether a particular site, given its environmental characteristics, will perform as desired, but whether the approach taken to evaluate its future state is adequate. The performance assessment must therefore consider:

1. The risk associated with the environmental components that describe the site;
2. Their interaction as presently understood through the application of predictive models across the selected time horizon;
3. The nature and scope of uncertainties; and
4. The impact and ramifications of a failure in performance.

Beyond the high level waste disposal problem, similar situations can be described where prolonged exposure to human activities is threatening to drive environmental systems to new states. In these cases the scope of an environmental performance assessment can be broadened to include not only a specific human action or piece of engineering, but also the usefulness of policy tools intended to control or manage human actions. Performance assessment, in this context, can focus on the mitigation measures available to reduce adverse consequences, and can evaluate whether those measures will keep impacts below environmental thresholds over the long-term. Uncertainties associated with human activity can be identified, and environmental trends attributable to such activity can be projected.

The steps in conducting performance assessments have been summarized by Brandstetter and Buxton [8]. In general outline, the assessment consists of a series of iterated procedures, beginning with the collection of facts and data characterizing the planned human action, and culminating in estimates of levels of confidence in the system's performance by means of sensitivity and uncertainty analysis. Perhaps the most critical stages in performance assessment involve developing conceptual and analytic models of man-environment interactions, processes and events that could t rigger a failure in the system, and possible human actions in response to a triggering event. Progressing through these stages leads to the selection and analysis of scenarios that provide decision makers with a set of estimates of the probability and consequences of a failure.

SCENARIO DEVELOPMENT AND ANALYSIS

A scenario is a description of a possible future [15]. In the context of performance assessment, a scenario may be thought of as a possible sequence of processes and events that can be characterized by equations connecting specified physical parameters [16].

Developing a scenario requires listing all phenomena potentially relevant to the specific problem, including processes and events that might trigger a disruption [17, 18]. The level of detail required varies from problem to problem. In any event, compiling this list combines expert judgment with technical and physical data so as to identify a chain of causal processes that could contribute to a failure in the system or compromise the standards established for safe performance. Because decision makers cannot assay the possible effects of a man-made project on all conceivable environmental components, a limited number of environmental elements is selected to ensure that the decision making process is not overloaded with information [7].

The first step in scenario development is to identify a set of potentially disruptive events. Their identification relies on a brief general description of the system and a comprehensive list of events or processes that might effect a change in the environmental system. Once scenarios have been developed, a set of "credible" scenarios must be selected for analysis. In most instances selection is based on estimates of their likelihood according to the judgment and imagination of informed individuals [19]. Currently, three techniques have been employed to aid in the complex task of scenario selection. Ross identifies these as the methods of expert judgment, event tree analysis, and simulation [18]. Each method begins with a list of potentially relevant physical processes, and proceeds to eliminate events and processes that are considered irrelevant, incredible, or unlikely. Since such judgments lie very often in the eye of the beholder, it is not surprising that in the relatively short history of performance assessment, scenario development and selection procedures have undergone extensive review and critique [20]. Scenario development and selection remain two of the more problematic aspects of a performance assessment and strongly influence the treatment of uncertainty throughout the procedure [21].

In most instances, the likelihood of a particular scenario is construed as a scenario probability [17, 18, 22]. However, as noted by Hodgkinson and Sumerling, to estimate a probability requires that the process be stochastic and that relevant statistics be available to model its behavior [20]. Because a scenario is based on processes that are often difficult to quantify due to a lack of data or lack of theoretical knowledge, estimates of causality frequently depend on the application of subjective probabilities or expert judgment [23]. The fact that no single methodology for conducting a performance assessment has emerged reflects, in part, the large degree of subjectivity that guides scenario analysis [13].

Of the techniques introduced so far, the method of event tree analysis offers the greatest potential for scenario development, particularly for applications beyond the repository siting problem. Event tree analysis is an especially promising starting point for the development of expert system applications to performance assessment [21]. The event tree describes a network of cause and effect that illustrates the pathways a potential triggering event or process may take that will culminate in a system failure [24]. In the nuclear waste disposal problem, the event tree explains the sequence of phenomena leading to the release of radionuclides from the repository site. For environmental applications in general, the event tree can detail specific factors central to the assessment of long-term risk. The tree's nodes and branching pattern identify specific knowledge about the natural and human factors descriptive of the problem (see Figure 1). This pattern is similar in concept to that of decision trees used to structure the knowledge-base of an expert system. Again, the design of the event tree must capture the causal sequences that end with the "triggering event" that changes the environmental system. When this point in the tree is reached, the scenario proper is completed. However, to complete the assessment of environmental impact the effects of the triggering event must also be considered. This should assist decision making by introducing aftermath effects directly into the decision making process (see Figure 2).

Two general procedures for scenario development and selection have been proposed (see Table 1). Cranwell, *et al.*, outline a six stage process for scenario development [25]. Roberds, *et al.*, devise a five-step process [26]. Ideally, scenarios developed with either approach should [27]:

1. Be mutually exclusive;
2. Comprehensively describe all possible future states in the environmental system;
3. Estimate the consequences of each scenario; and
4. Assign a probability of occurrence to the event.

In practice, the task of reducing the number of scenarios to manageable levels has proved quite difficult. Recent applications of event tree analysis have relied on

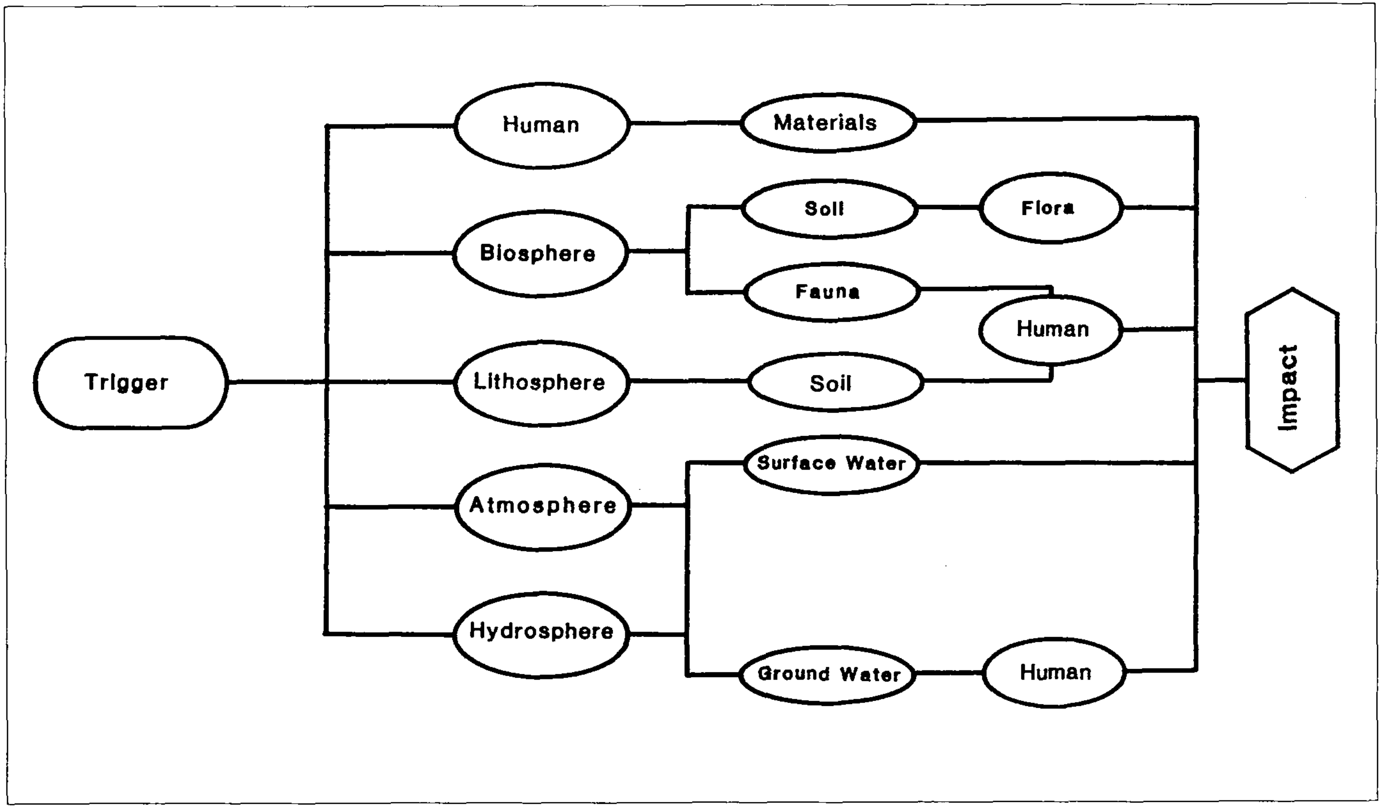

Figure 1. Simplified event diagram.

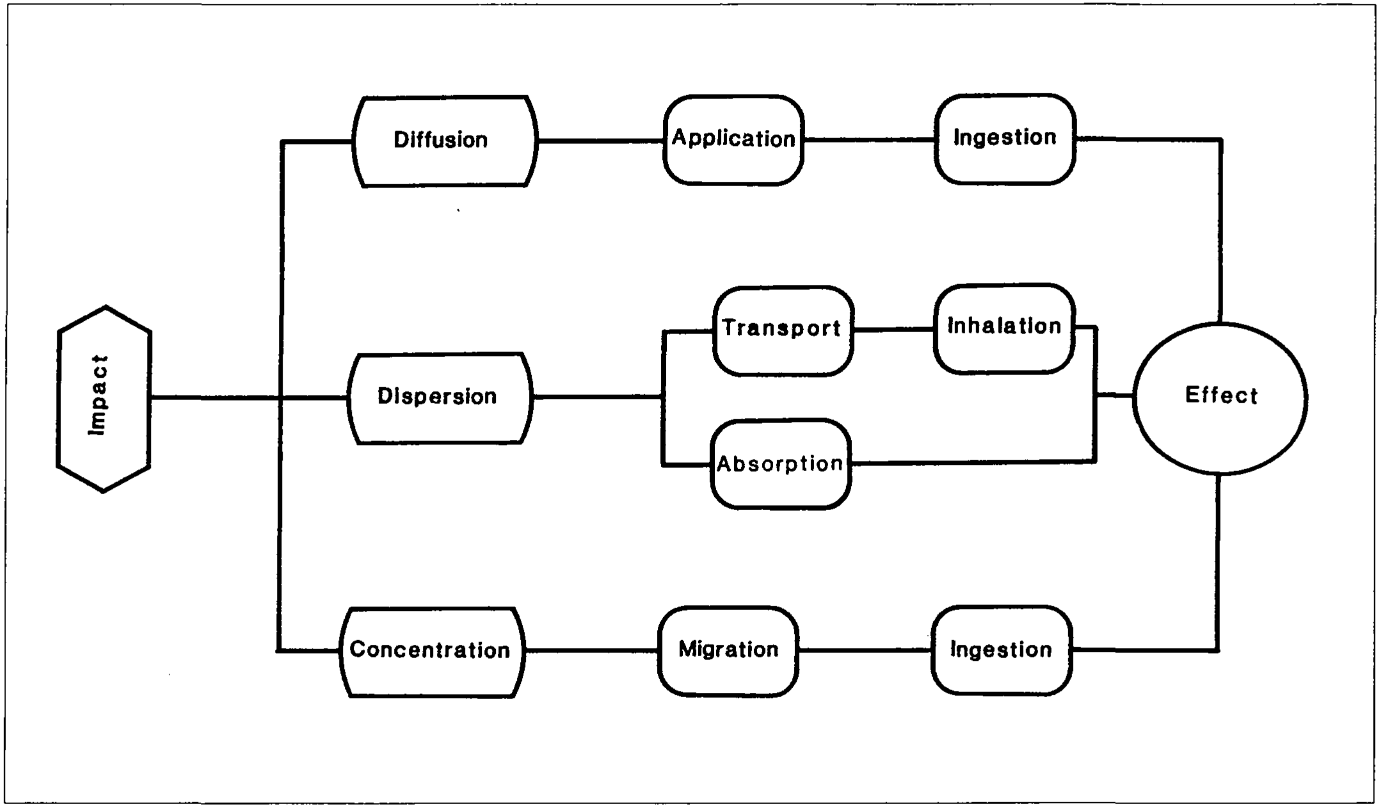

Figure 2. Simplified consequence diagram.

Table 1. General Approaches to Scenario Development and Selection

Six Stage Procedure	Five Stage Procedure
1. Initial identification of events, features, and processes	1. Identification of pertinent system performance measures
2. Classification of events into natural, system-induced, and man-induced	2. Development of event trees
3. Initial screening based on likelihood estimates	3. Identification of pathways defining significant events
4. Development of scenarios based on most probable events	4. Combination of event pathways into scenarios
5. Initial screening based on classification of probable events	5. Identification of pathways that require extensive analysis
6. Final selection using detailed description of consequence	

expert judgment to achieve a more parsimonious collection of scenarios to analyze. However, the results of the selection process may be overly dependent on the opinions of arbitrarily selected individuals [18]. To help overcome the potential problems introduced by human subjectivity, Bertram-Howery, *et al.*, suggest the use of certain screening criteria to assist the selection process [27]. Screening criteria can include factors such as the "reasonableness" of the scenario, its probability as described, and the magnitude of the consequence, to help direct and support a judgment. However, assessing these factors is also very subjective. Effective approaches to these dilemmas remain elusive.

EXPERT JUDGMENT AND EXPERT SYSTEMS

The role of expert judgment is critical in designing an expert system that can assist the performance assessment process. Full understanding of environmental processes is often frustrated by the complexity of system interactions. The relevant phenomena are often imprecise, defined only in qualitative terms, and uncertain as to their very nature. Nevertheless, because expert judgment permeates scientific inquiry and decision making, the question is not whether to use expert judgment, but whether to use it in an explicit, disciplined manner in an *ad hoc* fashion [23]. As noted, expert judgment is used to develop and screen scenarios, estimate probabilities, simulate environmental systems, and interpret data. While expert judgment need not always be formalized, a decision must eventually be made about the "quality" of a given judgment and whether it affects the solution to the problem under review.

An expert system is a computer program in which the facts, relationships, and heuristics of a specialized problem area have been coded in the form of rules and assembled into a decision tree that enables the computer to apply this knowledge toward a solution [28, 29].

Expert systems are under development for a range of environmental application areas [30]. Advocates hope that such systems can help document uncertainties and promote scientific consensus concerning various environmental processes.

An expert system that can assist in the analysis (for example) of the consequences of a breaching event at a geologic repository will have to incorporate information regarding:

- The nature of the breaching event;
- The transport medium involved;
- Characteristics of land use/land cover at the surface;
- Assumptions regarding the level of human activity in and around the site;
- The seasonal conditions descriptive of the surface; and
- Characteristics of the radionuclides.

With this information analysis can focus on characterizing the breaching event, tracing the radionuclide pathway to and through the biosphere, describing the characteristics of biosphere (including climate, vegetation, human activity, and topographic conditions), and estimating health consequences to human populations many thousands of years from now, when some component of the engineered barriers should have failed, leaving natural geologic barriers as the principal shields to the biosphere.

Attempting to simulate the future environment over a 10,000- to 1-million-year time horizon clearly introduces a range of conceptual bottlenecks, particularly when the goal is to couple human and natural system processes in a numerical model. A consequence analysis model would require a description of the geologic regime and hydrologic regime, as well as detailed descriptions of climate, and ecosystem process at the site and in the region. This last would have to include guesses about the evolution of the region's human landscape, and how radionuclide exposure pathways might be affected (see Table 2). Any simulations of remove future human population change, land use activity, and regional spatial patterns would be conjecture, if not outright science fiction. Coupling the human system with the natural system would only compound the uncertainty. However, it is possible that characteristics of the natural environment, as described by the model, could imply boundary conditions for possible exposure pathways resulting from radionuclide release [31-33].

Since any qualitative model reflects current levels of knowledge about the relevant processes and causal chains, using that knowledge heuristically rather

Table 2. Primary Radionuclide Pathways to Humans

- Direct contamination of individuals in general proximity to waste source.
- Inhalation of emissions dispersed into atmosphere.
- Direct ingestion of contaminated surface or ground water.
- Ingestion of contaminated vegetation.
- Ingestion of fauna in the food chain concentrating radionuclides from lower trophic levels.

than algorithmically might simplify the modeling task and more realistically incorporate the effects of uncertainty and subjectivity on the descriptions of consequences. This approach to knowledge-based modeling attempts to capture the logical sequence of event using variables known or hypothesized to control the process under investigation, and employs subjective judgment to provide heuristic quantifiers for processes that cannot be measured using conventional statistical techniques. While the application of heuristics might suggest a lack of mathematical rigor, a developing body of literature suggests that qualitative estimates of environmental process can yield insightful results in the absence of measured values [34].

In this context, simulation unfolds using the facts and relations embedded in the knowledge-base of an expert system to form an event tree guided by "intelligence." Because the expert system describes a knowledge-intensive program, it can search and apply larger bodies of knowledge than the algorithmic approach of conventional computer program, which represents the same knowledge in each iteration. This type of flexibility enables the expert system to consider a wider range of facts that can be applied once, several times, or not at all, given the inputs supplied by the user of the system.

Developing a knowledge-based modeling approach to consequence analysis requires expressing the causal mechanisms and their effects in terms of assumptions about future climate, geology, land use and land cover, radionuclide pathways, plant uptake rates, human and animal ingestion or inhalation, and health consequence. Each rule comprising the knowledge-base expresses a specific environmental condition that ends with a conclusion explaining the health effects that can be attributed to that release scenario. Given the present debate surrounding the treatment of uncertainty in performance assessment [8, 18, 35, 36], a consensus opinion is forming in the literature that the data used in numerical models are statistically meaningless, and that the models themselves are largely unprovable because the natural phenomena involved are so poorly understood. In light of the limitations that presently confront environmental performance assessment, the expert system introduces a mechanism to collect, formalize, and clarify knowledge in this complex, multi-disciplinary domain. It also offers a means to test the logic of the overall modeling problem. To explore the potential of this approach, a simple demonstration expert system for the Yucca Mountain High Level Waste Repository project is described.

AN EXPERT SYSTEM APPLICATION

A program is currently underway to develop a deep geologic repository for high level nuclear waste in the vicinity of Yucca Mountain, Nevada [37]. To produce an expert system for radiological consequence analysis for the Yucca Mountain site, present knowledge of the site and its regional setting, and knowledge pertaining to future environments that might describe the area, is required. Characterizing present site conditions is relatively straightforward, but future environment of Yucca Mountain over the 10,000- to 1-million-year analytic time horizon is unknown. One method of addressing this initial source of uncertainty is to study "natural analogue" environments as a means of understanding and quantifying natural and human landscape processes [19, 37]. Thus, rather than attempting to simulate environmental processes over the site for the period of analysis, knowledge-base development can focus instead on capturing the characteristics of the world's major terrestrial ecosystems, utilizing them as the foundation over which consequence scenarios can be played out. These descriptions, coupled with varying assumptions about human activity, climate, and geologic processes, permit a more comprehensive assessment of environmental impacts for possible futures [38]. Within this framework it is also possible to include a judgment expressing the degree of belief that any of these conditions may in fact be a feature of the Yucca Mountain landscape at some time in the future.

A simple example helps clarify the knowledge-based approach. In this example an event scenario culminates in the release of radionuclides into the hydrogeologic environment. The consequence of this event can be evaluated by constructing a series of rules that establish the environmental setting, contamination pathways, and the biological and ecological effects. One line of reasoning could be structured as follows (using the IF-THEN convention common in expert system design):

```
Rule 1A
    IF breach is hydrologic,
        AND human activity is cropping,
        AND irrigation is "yes,"
        AND source is aquifer,
        AND crop type is α,
        AND uptake rate is χ,
    THEN concentration is β.
```

Rule 1B
    IF concentration is β,
    THEN contamination probability is Z.

Rule 1C
    IF crop type is α,
        AND human food source is yes,
        AND contamination probability is Z,
        AND diet intake is ϕ,
        AND pathway is ingestion,
    THEN consequence is γ health effects per year.

In this example, the release scenario that ended with the breaching event is continued, following the assumption that the radionuclides migrate to an aquifer. The consequence unfolds beginning with rule 1A that establishes land use, and radionuclide entry to the biosphere. With this information rule 1B provides a qualitative estimate of the likelihood or severity of contamination. This information is then available to rule 1C which evaluates the consequence given human ingestion of the contaminated food source.

Rules governing more complex relations can also be constructed. Such rules could evaluate detailed interactions between biosphere components, variations in spatial scale, contrasting geographic environments, or contrasting temporal scales. Rules of this variety might take the form:

Rule 2A
    IF breach is seal fracture
        AND climate is cold midlatitude steppe
        AND season is winter
    THEN transport is cyclonic system.

Rule 2B
    IF transport is cyclonic
        AND landscape is urban settlement,
        AND pathway is inhalation,
        AND settlement density is Ω,
        AND building density is low,
    THEN consequence is K health effects per year.

The condition described by Rule 2A presented above explains the role played by season in establishing a possible transport mechanism for a given release event. That transport mechanism is then carried to the next rule (2B) and the consequence, assuming certain land use, density, and pathway characteristics, is evaluated.

While the examples are hypothetical, they illustrate how a rule-based expert system might capture the detail and processes of interrelated environmental factors. The success of this method, however, rests heavily on the quality of knowledge used to construct the rules. In the examples given above, each rule can be refined to include other pertinent facts that would affect the consequence, such as decay rates, deposition parameters, dispersion characteristics, orographic conditions, and interception and shielding effects. Ideally, the knowledge-base should contain rules covering all possible or reasonable combinations of factors that stand to influence the analysis of consequence.

Another important feature of the expert system is its capacity for handling uncertainty in the knowledge it manipulates and the conclusions it derives. Several methods of handling uncertainty have been introduced [39]. One that is easily applied to the examples given above involves the use of certainty factors (CF). A certainty factor is a numerical estimate of the validity or applicability of the expertise used by the system – in effect, an indication of degree of confidence in the rules in question. Typically, certainty factors are rated on a scale of 0 to 100, with 0 as the lowest and 100 as the highest possible certainty. Because certainty factors are not probabilities, but rather likelihoods or beliefs, they facilitate the use of expert judgment and subjective probabilities, as currently used in performance assessment.

Employing certainty factors to control for uncertainty in consequence analysis can be accomplished in two ways. In one example certainty factors can be input by the user in response to the questions presented by the system. A line of questioning to elicit certainty factors might run:

> Is cropping the dominant human activity occurring at the site (yes/no)?

A reply of yes would trigger the next question;

> How certain are you of this assumption?

to which the user responds with the appropriate value in the range 0 to 100. Certainty factors can also be built directly into each rule. Including certainty factors in Rule 1A, for example, would produce:

```
Rule 1A
    IF breach is hydrologic, 70,
        AND human activity is cropping, 90,
        AND irrigation is yes, 100,
        AND source is aquifer, 80
        AND crop type is $\alpha$, 90,
        AND uptake rate is $\chi$, 30,
    THEN concentration is $\beta$, 60.
```

permitting the certainty factor expressed in the conclusion of the rule (60), defining the overall confidence in the rule, to be amended with a value derived from the values associated with each premise according to the relation:

CF (premise 1 and premise 2 and . . . premise n) = Minimum [CF (premise 1), CF (premise 2), . . . , CF (premise n))] = [CF (conclusion) * CF (min(premise))] / 100.

Thus, in the example given above the certainty of the conclusion would be:

(30 * 60)/100 = 18,

assuming that a chain of reasoning using conjunctions is only as strong as its weakest link. With uncertainty expressed in this way, the system can communicate the degree of expert belief that the consequence will be produced by the associated premises. That degree of belief can then be used by the analyst to rank or evaluate consequence estimates derived from a series of release scenarios.

CONCLUSION

As the demands of modern society introduce new potential risks to environmental stability, the need to evaluate the impact of human activity over the long term has become more apparent. Recent concerns surrounding anthropogenic climate change, deforestation and species extinction, as well as perhaps more immediate issues concerning hazardous waste and high level nuclear waste disposal, suggest that some of the present methods employed to assess environmental impact may not be able to adequately address environmental risks. To overcome some of the conceptual and practical limitations of environmental impact assessment, an intermediate step in the analysis procedure has been proposed. This developing methodology, referred to as environmental performance assessment, permits a more focused and critical evaluation of human activities, engineerings, and policies that stand to influence the environmental system at time scales beyond the planning horizons used in resource management.

In this article a general procedure for conducting an environmental performance assessment was outlined and extended to include an analysis of consequence. A central feature of this approach was its use of an expert system to structure the knowledge and facts of the assessment problem into an "intelligent" event tree. Some features of an expert system design for a consequence analysis were described for the case of high-level nuclear waste disposal. With the expert system, environmental processes can be integrated with the critical features of an event scenario so as to characterize consequences. While moving from this theoretical sketch to a working, fully developed practical models presents many challenges, the present analysis suggests that knowledge modeling can play an important role in evaluating complex environmental relationships under conditions of uncertainty, and suggests that expert systems can usefully address complex environmental problems. As this methodology is refined, and as environmental knowledge improves, the development of a demonstration expert system for consequence analysis will be greatly enhanced.

REFERENCES

1. C. Malone, Environmental Performance Assessment: A Case Study of an Emerging Methodology, *Journal of Environmental Systems, 19*:2, pp. 171-184, 1989-90.
2. L. Canter, Environmental Impact Studies in the United States, in *Perspectives on Environmental Impact Assessment*, B. Clark (ed.), pp. 15-24, 1984.
3. J. Lein, An Expert System Approach to Environmental Impact Assessment, *International Journal of Environmental Studies, 33*, pp. 13-27, 1989.
4. V. Coates and J. Coates, Making Technology Assessment an Effective Tool to Influence Policy, in *Policy through Impact Assessment*, R. Bartlett (ed.), Greenwood Press, New York, pp. 17-25, 1989.
5. E. Hyman and B. Stiftel, *Combining Facts and Values in Environmental Impact Assessment*, Westview Press, Boulder, Colorado, 1988.
6. J. Culhane, H. Friesema, and J. Beecher, *Forecasts and Environmental Decisionmaking: The Content and Predictive Accuracy of Environmental Impact Statements*, Westview Press, Boulder, Colorado, 1989.
7. P. Duinker and G. Baskerville, A Systematic Approach to Forecasting in Environmental Impact Assessment, *Journal of Environmental Management, 23*, pp. 271-290, 1986.
8. A. Brandstetter and B. Buxton, The Role of Geostatistical, Sensitivity, and Uncertainty Analysis in Performance Assessment, in *Geostatistical, Sensitivity, and Uncertainty Methods for Ground-Water Flow and Radionuclide Transport Modeling*, B. Buxton (ed.), Battelle Press, Columbus, Ohio, pp. 89-110, 1989.
9. N. Chapman and I. McKinley, *The Geologic Disposal of Nuclear Waste*, John Wiley and Sons, Chichester, England, 1987.
10. C. Mann and R. Hunter, Probabilities of Geologic Events and Processes in Natural Hazards, *Zeitschrift fur Geomorphologie, 67*, pp. 39-52, 1988.
11. J. Lieberman and W. Lee, Mathematical Modeling of Waste Repository Performance, in *High-Level Nuclear Waste Disposal*, H. Burkholder (ed.), Battelle Press, Columbus, Ohio, pp. 749-758, 1986.
12. C. Malone, Geologic and Hydrologic Issues Related to Siting a Repository for High-Level Nuclear Waste at Yucca Mountain, Nevada, USA, *Journal of Environmental Management, 30*, pp. 914-929, 1990.
13. C. McCombie, T. Papp, and S. Coplan, *The Development Status of Performance Assessment in Radioactive Waste Disposal*, International Symposium on the Safety Assessment of Radioactive Waste Repositories, Paris, 1989.
14. J. Lemons and C. Malone, Siting America's Geologic Repository for High-Level Nuclear Waste, *Environmental Management, 13*, pp. 435-441, 1989.
15. I. Wilson, Scenarios, in *Handbook of Futures Research*, J. Fowels (ed.), Greenwood Press, New York, 1978.
16. C. Kopick, M. Kaplan, and B. Ross, The Safety of Repositories for Highly Radioactive Wastes, *Reviews of Modern Physics, 54*:1, pp. 93-117, 1982.
17. R. Hunter, The Importance of Scenario Development in Meeting 40 CFR Part 191, in *Waste Management '88: Proceedings of the Symposium on Waste Management*, R. Post (ed.), University of Arizona, Tucson, Vol. 2, pp. 643-646, 1988.
18. B. Ross, Scenarios for Repository Safety Analysis, *Engineering Geology, 26*, pp. 285-299, 1989.

19. D. Hodgkinson and T. Sumerling, *A Review of Approaches to Scenario Analysis for Repository Safety Assessment*, International Symposium on the Safety Assessment of Radioactive Waste Repositories, Paris, 1989.
20. M. Thorne, *The Biosphere: Current Status*, Nirex, Ltd., Harwell, United Kingdom (NNS/G106), 1988.
21. E. Bonano and R. Cranwell, Treatment of Uncertainty in the Performance Assessment of Geologic High-Level Radioactive Waste Repositories, *Journal of the International Association for Mathematical Geology, 20*, pp. 543-565, 1988.
22. B. Ross, Disruption Scenarios for a High-Level Waste Repository at Yucca Mountain, Nevada, in *Waste Management '86: Proceedings of the Symposium on Waste Management*, R. Post (ed.), University of Arizona, Tucson, Vol. 2, pp. 403-409, 1986.
23. E. Bonano, S. Hora, R. Keeney, and D. vonWinterfeldt, *The Use of Expert Judgments in Performance Assessment of High-Level Waste Repositories*, Sandia National Laboratories, Albuquerque, New Mexico (SAND89-0495C), 1989.
24. F. Bingham and G. Barr, *Scenarios for Long-Term Release of Radionuclides from a Nuclear Waste Repository*, Sandia National Laboratories, Albuquerque, New Mexico (SAND78-1730), 1979.
25. R. Cranwell, R. Guzowski, J. Campbell, and N. Ortiz, *Risk Methodology for Geologic Disposal of Radioactive Waste: Scenario Selection Procedure*, Sandia National Laboratories, Albuquerque, New Mexico (SAND80-1429), 1982.
26. W. Roberds, R. Plum, and P. Visca, *Proposed Methodology for Completion of Scenario Analysis for the Basalt Waste Isolation Project*, Rockwell Hanford Operations Report, RHO-BW-CR-147P, 1984.
27. S. Bertram-Howery and M. Marietta, *Draft Forecast of the Final Report for the Comparison to 40 CFR Part 191*, Sandia National Laboratories, Albuquerque, New Mexico (SAND88-1452), 1989.
28. B. Buchanan and E. Shortliffe, *Rule-Based Expert Systems*, Addison-Wesley, New York, 1985.
29. K. Parsaye and M. Chignell, *Expert systems for Experts*, John Wiley and Sons, New York, 1988.
30. J. Davis and J. Clark, A Selective Bibliography of Expert Systems in Natural Resource Management, *AL Applications in Natural Resource Management, 3*:3, pp. 1-18, 1989.
31. C. Malbrain and R. Lester, An Improved Environmental Pathway Model for Assessing High-Level Waste Repository Risks, *Health Physics, 53*:5, pp. 473-486, 1987.
32. F. Whicker and T. Kirchner, PATHWAY: A Dynamic Food-Chain Model to Predict Rationuclide Ingestion after Fallout Disposition, *Health Physics, 52*:6, pp. 717-737, 1987.
33. J. Smith, T. Fowler, and A. Goldin, *Environmental Pathway Models for Estimating Population Health Effects from Disposal of High-Level Radioactive Wastes in Geologic Repositories*, U. S. Environmental Protection Agency, EPA 520/5-80-002 (Draft), National Technical Information Service, Springfield, Virginia, 1985.
34. A. Starfield and A. Bleloch, Expert Systems: An Approach to Problems in Ecological Management that are Difficult to Quantify, *Journal of Environmental Management, 16*, pp. 261-268, 1983.
35. R. Hunter and C. Mann, *Techniques for Determining Probabilities of Events and Processes Affecting the Performance of Geologic Repositories*, U. S. Nuclear Regulatory Commission, Washington, D.C., NUREG/CR-3964, 1989.

36. N. Chapman and B. Come, *Long-Term Predictions: Making Proper Use of Geologic Evidence*, International Symposium on the Safety Assessment of Radioactive Waste Repositories, Paris, 1989.
37. U. S. Department of Energy, *Site Characterization Plan, Yucca Mountain Site*, Washington, D.C., DOE/RW-0199, 1988.
38. R. Wilmot, A. Chadwick, and P. Ringrose, Modeling Environmental Change in Support of Assessments of Radioactive Waste Disposal in the U. K., *Radioactive Waste Management, 2*, pp. 145-152, 1989.
39. J. Giarrantano and G. Riley, *Expert Systems: Principles and Programming*, PWS-Kent Publishing Co., Boston, Massachusetts, 1989.

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