SANDIA REPORT

SAND90–3063 • UC–721
Unlimited Release
Printed December 1991

Expert Judgment on Inadvertent Human Intrusion into the Waste Isolation Pilot Plant

Stephen C. Hora, Detlof von Winterfeldt, Kathleen M. Trauth

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
Office of Scientific and Technical Information
PO Box 62
Oak Ridge, TN 37831

Prices available from (615) 576-8401, FTS 626-8401

Available to the public from
National Technical Information Service
US Department of Commerce
5285 Port Royal Rd
Springfield, VA 22161

NTIS price codes
Printed copy: A16
Microfiche copy: A01

SAND90-3063
Unlimited Release
Printed December 1991

Distribution
Category UC-721

EXPERT JUDGMENT ON INADVERTENT HUMAN INTRUSION INTO THE WASTE ISOLATION PILOT PLANT

Stephen C. Hora[1], Detlof von Winterfeldt[2],
Kathleen M. Trauth

Sandia National Laboratories
Albuquerque, NM 87185

ABSTRACT

Four expert-judgment teams have developed analyses delineating possible future societies in the next 10,000 years in the vicinity of the Waste Isolation Pilot Plant (WIPP). Expert-judgment analysis was used to address the question of future societies because neither experimentation, observation, nor modeling can resolve such uncertainties. Each of the four, four-member teams, comprised of individuals with expertise in the physical, social, or political sciences, developed detailed qualitative assessments of possible future societies. These assessments include detailed discussions of the underlying physical and societal factors that would influence society and the likely modes of human-intrusion at the WIPP, as well as the probabilities of intrusion. Technological development, population growth, economic development, conservation of information, persistence of government control, and mitigation of danger from nuclear waste were the factors the teams believed to be most important. Likely modes of human-intrusion were categorized as excavation, disposal/storage, tunneling, drilling, and offsite activities. Each team also developed quantitative assessments by providing probabilities of various alternative futures, of inadvertent human intrusion, and in some cases, of particular modes of intrusion. The information created throughout this study will be used in conjunction with other types of information, including experimental data, calculations from physical principles and computer models, and perhaps other judgments, as input to a "performance assessment." The more qualitative results of this study will be used as input to another expert panel considering markers to deter inadvertent human intrusion at the WIPP.

1 University of Hawaii at Hilo
2 University of Southern California

ACKNOWLEDGMENTS

The authors would like to acknowledge the efforts of many individuals in conducting the expert-judgment process and in producing this report. D. Scott, W. Grant, J. Chapman, and D. Marchand at Tech Reps, Inc. were instrumental in the expert-selection process and in planning for and conducting the panel meetings. D. Anderson (SNL/6342), S. Bertram-Howery (SNL/6621), K. Brinster (SNL/6342), R. Guzowski (Science Applications International Corporation), S. Lambert (SNL/6233), S. Pasztor (Tech Reps, Inc.), P. Swift (Tech Reps, Inc.), and W. Weart (SNL/6340) all presented material to the panel members. R. Guzowski and R. Klett (SNL/6342) provided the internal Sandia review. M. Gruebel and D. Bissell at Tech Reps, Inc. provided editorial support. Thanks also go to D. Rivard and the Word Processing Department and to R. Andree and the Computer Graphics Department at Tech Reps, Inc.

PREFACE

This SAND report was prepared from information presented by a panel of experts expressing judgments about future societies and the possibility that those future societies will inadvertently intrude upon the Waste Isolation Pilot Plant. Appendices C, D, E, and F were written by the panelists and do not necessarily reflect the opinions of the authors of this SAND report or of Sandia National Laboratories. The authors consolidated and utilized these appendices in preparing the body of the report. The members of the expert panel reviewed a draft copy of the report for misstatements of fact.

CONTENTS

FIGURES

TABLES

EXECUTIVE SUMMARY

The information obtained through this study (modes and likelihoods of inadvertent human-intrusion activities) has two purposes. The first purpose is to provide background information for the design of mechanisms to deter future inadvertent human intrusion at the Waste Isolation Pilot Plant (WIPP). These mechanisms include systems of markers to inform and warn future generations, barriers to impede human intrusion, and information systems external to the WIPP repository that provide for the maintenance and communication of knowledge of nuclear waste repositories. The expert panel on future societies can advise on disposal-site markers. The need for the most practical permanent markers to designate disposal sites is specifically mentioned in section 191.14(c) (the Assurance Requirements) of the U.S. Environmental Protection Agency (EPA) regulation 40 CFR 191, referred to as the Standard (U.S. EPA, 1985). As discussed in the preamble to the Standard, the Assurance Requirements were included to counteract the uncertainty inherent in the analyses for the Containment Requirements. Thus, in order "to reduce the potential harm from some aspect of our uncertainty about the future," a set of actions was outlined for implementation. Section 191.14(c) of the Standard states that "[d]isposal sites shall be designated by the most permanent markers, records, and other passive institutional controls practicable to indicate the dangers of the wastes and their location."

A plan for implementation of a marker strategy, including design characteristics, will be necessary for compliance evaluation to show that such markers can be constructed. Part of marker design would be based on the findings from studying past monuments that have stood the test of time, current materials technology, and present understanding of communication methods. A second important input to marker design would be from the expert panel on future societies (called the Futures Panel). This input is about the possible future states of society (including the expected activities and resource needs, and the ability to interpret and heed warning markers) and how future societies might intrude upon a repository. While it was not specifically a part of their statement of work, two of the four teams comprising the Futures Panel recommended that a "no marker" strategy be considered for the WIPP because markers might draw attention to the WIPP.

The second purpose of this study is to provide quantitative estimates of the likelihoods of various types of intrusions. The information created through this study will be used in conjunction with other types of information, including experimental data, calculations from physical principles and computer models, and perhaps other judgments, as input to a "performance assessment." At the time of this study, the Standard is the regulation governing performance assessment for the WIPP. The EPA has defined performance assessment as a probabilistic evaluation of the potential releases of radioactive material to the accessible environment over the period of concern (10,000 years). The performance assessment is conducted using guidelines provided by the Standard, which suggests that "inadvertent and intermittent intrusion by exploratory drilling for resources (other than any provided by the disposal system itself) can be the most severe intrusion scenario assumed..." (Appendix B of the Standard, p. 38089).

The methodology employed in this study is referred to as expert-judgment analysis. For some aspects of performance assessment (human-intrusion in particular), conducting experiments that will provide data to resolve uncertainties is not possible. When such unresolvable uncertainties do exist, the judgments of experts are often used to quantify the uncertainties and express both what is known and what is not known. Expert judgment is pervasive in complex analysis. Judgments about the selection of models, experimental conditions, and data sources must be made. The choice is not whether expert judgment will be used; instead, the choice is whether it will be collected and used in a disciplined, explicit manner or utilized implicitly where its role in the analysis is not as obvious.

The Futures Panel was selected through a formal nomination process. Initial nominations for members of the Futures Panel were made by individuals from professional societies, government agencies, and public interest groups. The initial nominees could nominate themselves and/or others. The nominees came from the disciplines of futures research, law, physics, social science, agriculture, political science, and climatology, among many others. The actual selection of the panel was made by a committee external to Sandia National Laboratories (SNL) according to the following criteria: (1) tangible evidence of expertise; (2) professional reputation; (3) availability and willingness to participate; (4) understanding of the general problem area; (5) impartiality; (6) lack of economic or personal stake in the potential findings; (7) balance among team members so that each team has the needed breadth of expertise; (8) physical proximity to other participants so that teams can work effectively; and (9) balance among all participants so that various constituent groups are represented.

Sixteen experts arranged in four teams of four members each were used in this study. Geographic neighbors were placed on the same team while, at the same time, preserving balance among disciplines on each team. The teams were given the following designations: Boston Team, Southwest Team, Washington A Team, and Washington B Team. The team format was selected because the subject matter, the futures of society, is inherently multidisciplinary. Each team was given the same assignment, as described in the Issue Statement and Task Statement (Appendix G), that was presented and discussed during the first meeting in Albuquerque, New Mexico.

Methodologies

Consideration of the possible types of future human societies is an essential task in studying the potential for inadvertent human intrusion. The methodologies employed by the teams to delineate future societies, along with lists of the factors used in determining the possible futures, and alternative modes of intrusion into the WIPP are described in Chapter III. These methodologies were developed after the panel of four teams visited the WIPP and the surrounding area, and listened to presentations delivered by SNL staff regarding the WIPP, the Standard, performance assessment, the physical and cultural setting of the WIPP, and scenario development. Training in the expert-judgment process was also provided.

BOSTON TEAM

The Boston Team analyzed alternative futures describing future civilizations in two distinct ways. The first way began with the examination of intrusive activities and worked backward to determine the attributes of society that might lead to such intrusions. This "top down" approach led the team to define "generic" alternative futures--alternatives that are broad in scope and lack detail, but are representative of many possible futures. The second way of developing alternative futures that was employed by the Boston Team resulted in the creation of inventive, highly detailed pictures of the future. These futures were termed "point" futures by the team. Both the terms "generic" and "point" futures will be retained to describe the findings of the four teams.

When creating generic alternative futures, the Boston Team followed a consistent approach for each potential intrusion mode. This approach involved first identifying the vulnerability of the WIPP. The specific event or events that would be required to exploit the vulnerability were then analyzed. Next, the activities that could potentially require such events to take place were discussed, and an analysis of the societal and physical conditions necessary for these activities was presented. The team also identified criteria for each specific mode of intrusion that could be used to characterize the intrusion as inadvertent. Finally, initial probability assessments, in qualitative terms, were provided for each of the precursor events and activities defining the path to intrusion.

The point futures developed by the Boston Team provide a thought-provoking view of what future societies could be like. These future societies range from the WIPP becoming the nation's primary nuclear waste site to a society dominated by individuals who do not believe in science as currently practiced. The creation of alternative futures is the product of a highly imaginative process and expands the range of possible futures to consider when designing passive markers and barriers for the WIPP. These futures are not in conflict with the generic futures, but instead provide an alternative, detailed view of the future that, although of low probability because of the level of specificity, is instructive about the variety of futures that should be anticipated.

SOUTHWEST TEAM

The Southwest Team created views of the future through a forward process. This process also produced generic alternative futures. The process began with the establishment of key assumptions about the operations of the WIPP and the scope of the analysis to be provided. The team then identified environmental changes and socioeconomic factors that potentially would impact human intrusion. For each of the socioeconomic factors, a qualitative assessment of its impact on human intrusion was provided.

Five narrative futures were created by the Southwest Team. These futures were identified as

technological knowledge increases,
decline and rebuilding of technological knowledge: seesaw,
technological knowledge decreases,
altered political control of the WIPP area,
stasis (not included in probability elicitation).

These narrative futures are generic in that many possibilities are included within a single future. The probabilities of inadvertent intrusion arise from these futures by considering the probabilities of the persistence of the present political control over the WIPP, the pattern of technological development given the state of political control, and intrusion given both the state of political control and the pattern of technological development.

WASHINGTON A TEAM

The Washington A Team focused its views of the future on the relationship between earth resources and society. These futures were

continuity--continued population growth and current levels of resource consumption, radical increase--massive increases in the consumption of world resources,

radical discontinuity--erosion of conditions in the WIPP area by major war or political change,

steady-state resources--world consumption of resources dramatically reduced through zero population growth and extensive recycling.

The first three of these alternative futures involved population growth and substantial extractive activity. In these futures, the natural environment was thought of as a source of materials and energy rather than as a human habitat. In the fourth future, humans reached an equilibrium with nature. The state of the world became constant, and there was little need for extractive activity.

The Washington A Team allowed that the future may shift among several of these alternatives at various points in time. Thus, these futures should be viewed as snapshots of what the future might be like rather than complete, mutually exclusive paths that society's development might follow. This team also provided an extensive analysis concerning loss of memory about the WIPP and the inability to use existing information.

WASHINGTON B TEAM

The second team from Washington, the B Team, constructed a four-component model of paths leading to human intrusion. The first component of the model was the state of society, both local and worldwide. These views of the future states of society were based upon the climate at the WIPP area (both natural and human-induced changes are allowed), energy and mineral costs, food supply and demand, and governance of the WIPP area. The ensuing components of the model included the level of awareness about nuclear waste, the presence of potentially intrusive activities, and the modes of inadvertent intrusion into WIPP.

The factors that underlie the Washington B Team analysis are levels of resource prices, with higher levels bringing about greater exploration and extraction, modification of the existing climate or water importation, and the ability of the government to retain sufficient control to preclude inadvertent human intrusion. The analysis was based on forming all combinations of the levels of these factors. In this way the team created a potentially exhaustive set of alternative futures.

Catastrophes, which are unfortunate events that occur over a short time and have the potential to change the course of civilization, were also considered by the Washington B Team. These events, both natural and manmade, can cause such a disruption of society that memory of nuclear waste becomes lost, and the potential for inadvertent human intrusion increases.

Underlying Factors

Each of the four teams identified factors thought to be determinants of the activities of coming societies. In some instances these factors are given in tables found in the team reports, while in other cases the factors are identified in the narrative.

The facets of society that most directly impinge upon inadvertent human intrusion include the rate of technological development; population growth; economic developments, including the prices of minerals and energy resources; water availability and production in the WIPP region; and the level of governmental continuity and cognizance of nuclear waste. These factors are related and cannot be treated independently. For example, the level of technological progress may have a profound effect on the world economy's need for resources. Similarly, the world population size will also impact the level of resource exploration and extraction. The relationships among factors can be even more complex. Technology may directly impact both population size and resource utilization, for instance, and population may directly impact resource utilization. Thus, technology will have both direct and indirect (through population) impacts on resource utilization.

TECHNOLOGICAL DEVELOPMENT

Critical to future human activities is the progress that will be made in technological development. Many of the specific human activities that could result in inadvertent intrusion are in some way dependent upon the advance of technology. One type of intrusive activity is excavation for the purposes of construction. The most likely type of construction is a dam to hold water for industrial, energy, agricultural, or residential uses. Resource extraction may also be influenced by technology. New methods of resource exploration, similar to medical CAT scanners, may allow exploration in more nonintrusive manners than currently available. In addition, there may be new and efficient means of drilling, new fluids for solution mining, and new, rapid means of excavating.

It was proposed that both technological innovation and technological stagnation can increase the potential for intrusion. Under technological stagnation, intrusive means would be used for resource exploration. Impacts due to technological innovation include advanced drilling techniques, methods for high-volume water desalting that may make water extraction worthwhile, deep strip-mining techniques that would reduce the cost of resource extraction, the identification of new resources, and the use of autonomous mechanical extraction techniques for minerals.

Technological development that leads to the increased utilization of solar energy resources could lead to the extraction of mineral resources at the WIPP. Solar energy would be used in the processing of the ores. In a future with radically increasing resource exploitation, machines presumably not subject to the same hazards from contact with radiation as human beings would increase the willingness of drillers to take risks. Further, the existence of such technology may lead to overconfidence in the ability of their human directors to employ them without accident.

POPULATION GROWTH

Increases in population will impact the WIPP through a variety of paths. First, increases in world population will translate into increased resource demands. There is also the possibility of increased population density in the WIPP area and increased industrialization. The concept of local population growth was refined to include redistribution of the population by governmental policy and voluntary motivation. Voluntary redistribution might occur because of resource exploitation opportunities, grazing or crop production, or recreation purposes.

ECONOMIC DEVELOPMENT

The role of economic development in alternative futures containing human intrusion into the WIPP is not as sharply defined as that of technological development. One team used a single underlying factor to represent both technological and economic progress. Other teams implicitly included economic development in the alternative futures. For one team, the economic demand for resources and the political control that moderates the use of resources are fundamental in defining alternative futures.

CONSERVATION OF INFORMATION

The persistence of information about the WIPP and the continuity of government control are intertwined. The likelihood of loss of information is apt to increase when there is a discontinuity in governmental control. Despite the close relationship between these two aspects of inadvertent intrusion, they are separated in this discussion.

One team identified inadequate records, inaccessibility of records, inability to understand records, ignoring of information that is understood, and lack of information regarding the effects of nearby activities as contributors to inadvertent-intrusion possibilities. A second team identified the possibility that nuclear energy will be a short-lived phase of our economic development. In this event, some loss of memory is likely. Memory loss was identified as taking several forms. Memory about the facility may be lost, memory may be lost about the danger but not the facility, and local but not institutional memory may be lost. A third team identified four states of memory about WIPP. Memory of the WIPP could be relatively complete, memory of the location but not of the hazards may persist, memory of the WIPP may become a legend or a myth, or all memory may be lost. While complete memory of the WIPP and its attendant dangers will deter intrusion, partial memory can serve to attract potential intruders. Knowing that something is there, but not knowing what it is or what its value may be, may serve to attract investigations such as archaeological digs or salvage operations.

The survival of information may depend upon the survival of our information systems. Changes in the basic forms of communication are likely in the next 10,000 years. Both written and oral forms of communication may be quite different than they are today. Moreover, the means for storing information may be significantly different than the means used today. If this is so, future generations may find it difficult to access the information that we have intended for them.

PERSISTENCE OF GOVERNMENT CONTROL

A recurring perception among the teams is the small likelihood of continued U.S. political control over the WIPP. Governments are seldom stable for long periods of time, certainly not for the periods of time covered by this study. In one alternative future, a separate nation is formed from northern Mexico and the southwestern U.S. at some time in the future. In the chaos of the transition, information about the WIPP may be lost--except, perhaps, for local folklore about buried treasure. Alternatively, the discontinuity of government control could include the erosion of conditions so that New Mexico resembles a less developed nation in the future. The cultural differentiation of the region adds credibility to the hypothesis of a change in government control. A conclusion that may be drawn from the experts' views of political stability is that continued U.S. control of the WIPP for 10,000 years is unlikely. The transition from one government to another may be disruptive and preclude the transferal of information about the WIPP. Even if U.S. control is perpetuated, the application of effective measures to warn potential intruders may not follow.

MITIGATION OF DANGER FROM NUCLEAR WASTE

If nuclear waste is intruded upon at some point in the future, the exposed waste will not necessarily cause harm. Medical technology may have developed to a point where cancer is curable or the consequences of radiation exposure can be greatly reduced. Scientists may determine that low-level radiation is not hazardous, or a technology for safe redisposal may become available.

Modes of Intrusion

The underlying factors that determine the nature of future societies provide the basis for the consideration of alternative modes of intrusion into the WIPP. A summary of the modes of intrusion provided by the teams follows.

Excavation
- archaeological
- mineral
- construction

Disposal/Storage
- underground injection
- petroleum storage
- additional radioactive waste storage

Tunneling
- transportation
- pipeline
- mole mining

Drilling
- hydrocarbons
- water
- research

Offsite Activities
- water impoundment
- explosions
- water well field

Elicitation

Once the teams had developed systems for delineating possible future societies, they returned to Albuquerque to organize them further. These qualitative assessments of underlying societal and physical factors were developed into a framework from which the teams could be elicited as to the probabilities of various alternative futures, of inadvertent human intrusion, and in some cases, the probabilities of particular modes of intrusion. The different methodologies and frameworks developed by the teams resulted in elicited probabilities that took different forms. Two of the teams developed probabilities of a first intrusion for each alternative future, essentially ignoring additional intrusions as unlikely or irrelevant. These probabilities of intrusion over the entire 10,000 years ranged from 0.0095 to 0.07. Probabilities were not assigned to particular modes of intrusion.

The other two teams provided expected numbers of various intrusions over the entire 10,000 years. Both of these teams stated that boreholes drilled for resource extraction would not continue after about 300 to 500 years, with

0.86 and 0.93 boreholes per square mile expected in that initial period. The impact of some of the other modes of intrusion such as storage expansions and scientific investigations should be rather straightforward to assess because material would be brought to the surface. Other modes of intrusion, particularly indirect modes of intrusions, such as weather modification, dams, injection wells, explosions, and water wells, would require further study to determine just how these activities might impact the performance of the WIPP.

Conclusions

Clearly, the future may follow many paths--some more desirable than others. Several themes are so pervasive in the views of the future that they should be singled out for attention. First, in the time scale of nuclear waste decay, the continuity and stability of governments are insufficient to provide any assurance that humans will maintain active control of the repositories or be aware of the existence of buried nuclear waste. A second factor that occurs throughout the alternative futures is the rate of technological development and its persistence or lapse. While the work of any group of experts cannot define all the possible futures, let alone know which future will come to be, the futures envisioned by the experts involved in this project are sufficiently varied to alert us to the need to consider a very wide range of possibilities when designing markers and barriers to prevent human intrusion into radioactive waste repositories.

The intrusions identified through this process are more varied than those previously considered. The planning for this panel involved a conscious decision to solicit opinion on the future states of society and on a variety of modes of intrusion that go beyond what the Standard requires for performance assessment. While the increased variety of threats to the WIPP system will make designing markers and barriers more difficult, it will also make the task more meaningful. The probabilities of various modes of intrusion were elicited from the teams. In some instances, the probability of one or more intrusions is provided, while in other instances a rate per unit of time or time and area is provided. No attempt has been made to combine the intrusion probabilities across teams, nor has an attempt been made to add together the rates of various types of intrusion to obtain a single number. In the first case, combining across teams is unwise because the definitions of the types of intrusions differ--some are more aggregated than others. Aggregating probabilities or rates of intrusion across modes of intrusion is likewise unjustifiable. The severity of the various types of intrusion will vary greatly. It is arguable, for instance, that water impoundments such as dams will not result in the same magnitude or timing of releases of radionuclides to the accessible environment as a borehole would.

Combining an intrusion rate for dams with an intrusion rate for drilling would be meaningless.

The value of the report is that a reasoned approach has been taken in examining the possibility of inadvertent human intrusion. The qualitative findings, including the discussions of government control and the identification of possible modes of intrusion, are perhaps the most valuable contributions of the experts. The quantitative assessments of intrusions, both probabilities and rates, can be used for the performance and safety analyses of the WIPP system. These probabilities and rates reflect the best judgment of sixteen experts drawn from diverse backgrounds and reflect a very uncertain state of knowledge about the future.

I. INTRODUCTION

This study has been conducted to achieve several goals related to the potential for inadvertent human intrusion by future generations into the Waste Isolation Pilot Plant (WIPP). The specific goals are to (1) assemble an expert panel of individuals from a variety of disciplines that are believed to be important in the consideration of future societies; (2) convene the expert panel and provide them with both sufficient background information to perform their assigned task and a clear definition of their task; (3) elicit from the experts their opinions regarding the modes and probabilities of intrusion; (4) organize the elicited opinions for clear presentation to the expert panel studying markers for the WIPP; and (5) document both the process and the elicitation results in a report along with the more qualitative individual team reports.

Inadvertent human intrusion occurs when the integrity of a repository is unintentionally compromised by the activities of humans in the immediate vicinity of the disposal system. The intrusion may or may not result in the release of radioactivity to the environment. Hazards from nuclear waste can be long lived--lasting for many millennia. Over such long time periods, information about the location of nuclear waste and the inherent dangers from releasing the waste may become unclear and even forgotten. Uninformed individuals, corporations, or governments may inadvertently intrude upon radioactive material buried in underground repositories created during our lifetimes. Depending on the type of intrusion and the time in the future when intrusion occurs, there may be releases of radioactivity to the biosphere. The objective of this study is to envision the types of inadvertent intrusions that may take place in the future, to understand the motivations for these intrusions, and to appraise the likelihood these intrusions will occur. The specific repository under study is the WIPP near Carlsbad, New Mexico, which is a facility proposed for the disposal of radioactive waste generated by defense-related activities of the United States government.

Background

An October 23, 1989 memorandum from the Department of Energy, Albuquerque Operations Office (DOE/AL), to both Westinghouse (the DOE contractor responsible for construction of the WIPP repository) and Sandia National Laboratories (SNL) (Appendix A) initiated the process of outlining passive-marker design characteristics for the WIPP. The memorandum stated it was necessary to "define the criteria which will be used to decide what kind of passive markers can be used at the WIPP to significantly mitigate the effects of the human intrusion scenarios on performance assessment." SNL was given the responsibility to lead the effort to develop the criteria. Westinghouse was named as "the lead for the proof of concept and implementation of the passive markers selected."

SNL responded in a February 15, 1990 memorandum to A. E. Hunt at the WIPP Project Office (WPO) in Carlsbad, New Mexico (Appendix B). As part of the research outlined in the memorandum, SNL would conduct a literature review of previous studies regarding (1) repository marker and barrier "longevity," (2) the technological activities and requirements of future societies, and (3) communication to future societies of the location and danger of a repository over time. With the basis provided by the literature search, expert panels could be "organized and utilized" to develop opinions on the above topics, as well as the time to first intrusion, the longevity of passive institutional controls, and the rate of intrusions over the period of regulatory concern. The expected use of the opinions is both in future performance-assessment calculations of probabilistic cumulative radionuclide releases and in defining the criteria for passive-marker and barrier systems. Once the criteria have been established, SNL can work with Westinghouse to develop a plan to construct the marker and barrier systems, and to improve these systems over the operational life of the facility.

The expert group studying future societies has been asked to address a number of issues. These issues are all directed at establishing modes and likelihoods of inadvertent intrusive activities into the WIPP, which provides the foundation for the development of characteristics for markers and obstacles designed to prevent human intrusion. Human intrusion has been identified as the means by which the Standard could be exceeded (undisturbed conditions are expected to provide isolation for beyond that required by the Standard) and, therefore, is central to the performance of the WIPP (Marietta et al., 1989; Guzowski, 1990).

Because the regulatory period for the WIPP spans 10,000 years (based on one part of the applicable regulation), societies different from our own may encounter the buried radioactive waste left by us. Even though the potential risk associated with radioactive waste decreases with time (Klett, 1991), it is still necessary to consider possible future societies when designing markers and obstacles to prevent human intrusion. One approach is to create alternative futures for the development of society. These alternative futures can be constructed by considering alternative projections of basic trends in society. These trends may include population growth, technological development, and the utilization and scarcity of resources, among other factors. Overwhelming these factors in the possible impact on human intrusion are events that interrupt, modify, or reinforce the development of society. Such events may include nuclear war, disease, pestilence, fortuitous discovery of new technologies, climatic changes, and so forth. The creation of a reasonable set of alternative futures provides the first step in evaluating the types and likelihoods of intrusive activities. It is not possible, however, to ensure that all possible futures are considered. It is not even reasonable to assume that humans can conceive of all possible future societies. The farther into the future we delve, the less complete these alternative futures are likely to be.

Each alternative future provides a picture of certain possible characteristics of society at various points in the future. These characteristics, in turn, provide information about those activities that may take place and pose threats to the integrity of the WIPP. Such activities may include extractive industry, such as mining for potash or drilling for oil and gas, and drilling for water for use in agriculture, industry, or for other purposes.

The states of society and the types of potentially intrusive activities suggest modes of intrusion and motivations for these intrusions. The alternative futures and the states of society also provide information about the existence of knowledge concerning underground disposal of nuclear waste, the continued existence of the waste itself, and the availability of means to detect waste prior to, during, or after intrusion.

The products of the expert-judgment group to assess future societies and inadvertent intrusions include alternative futures for the development of society and descriptions of possible futures, along with the rationales supporting the possibilities of these futures. These rationales are conveyed as appendices to this report and serve as documentation of the experts' findings. Quantitative assessments of the likelihoods of various alternative futures have also been obtained. These probabilistic assessments are used to develop probabilities of intrusive activities over time.

The work required to develop the assessments for human intrusion was accomplished through two meetings of the experts and a study period between the two meetings. At the first meeting, the issues to be addressed by the experts, background information on the WIPP, and previous research findings were presented. Other research materials were distributed, training in probability assessment took place, and a tour of the WIPP was provided. All of these activities were carried out by SNL staff.

During the two-month period following the first meeting, the experts studied the issues and background material, and developed methods of creating possible future societies and their activities, with special attention to those activities that may impact the WIPP. It was requested that approximately two weeks of effort be spent by each expert in preparing these analyses.

The second meeting provided a forum for the discussion of possible future societies and the methods used to create them. Following the discussion, the experts participated in a formal probability assessment conducted by specialists in expert-judgment elicitation. The experts were asked to provide assessments of the likelihoods of various alternative futures, and of the frequencies of various types of intrusions given each alternative future. The experts were free to consider all modes of intrusion they deemed appropriate and were not limited to drilling, which was identified by the vacated standard as the worst case that needs to be considered.

Following the second meeting, the elicitation findings of the group were organized and returned to the experts for review, correction, and revision. The reports prepared by the teams discussing human intrusion are reproduced as submitted as Appendices C, D, E, and F.

Purposes of the Study

The information obtained through this study (modes and likelihoods of inadvertent intrusion activities) has two purposes. The first purpose is to provide background information for the design of mechanisms to deter future inadvertent human intrusion. These mechanisms include systems of markers to inform and warn future generations, barriers to impede human intrusion, and information systems external to the WIPP repository that provide for the maintenance and communication of knowledge of nuclear waste repositories.

The second purpose of the study is to provide quantitative estimates of the likelihoods of various types of intrusions. The information created through this study will be used in conjunction with other types of information, including experimental data, calculations from physical principles and computer models, and perhaps other judgments, as input to a "performance assessment." At the time of this study, the regulation governing performance assessment for the WIPP is the U.S. Environmental Protection Agency (EPA) regulation 40 CFR 191, referred to as the Standard (U.S. EPA, 1985). The EPA has defined performance assessment as a probabilistic evaluation of the potential releases of radioactive material to the accessible environment over the period of concern (10,000 years). The performance assessment is conducted using guidelines provided in the Standard.

The Futures Panel (whose work is described in this report) was established as the first part of a planned, multipart, expert-elicitation effort. The following section discusses this panel in the context of the overall expert-judgment effort to comply with the Standard.

The Regulatory Requirement for Evaluating Risks from Inadvertent Human Intrusion

Public Law 96-164 (1979) mandated the construction of the WIPP "for the express purpose of providing a research and development facility to demonstrate the safe disposal of radioactive wastes resulting from the defense activities and programs of the U.S. exempted from regulation by the Nuclear Regulatory Commission...." The WIPP is a deep geologic repository located in southeastern New Mexico, approximately 26 miles east of the city of Carlsbad. The actual disposal area is 2,150 ft (655 m) below the surface in a bedded salt formation. The WIPP has been designed for the disposal of transuranic (TRU) nuclear wastes. TRU wastes are those wastes with an atomic number greater than 92, a half-life greater than 20 years, and a concentration greater than 100 nCi/g, excluding high-level waste and/other specific waste types.

Disposal of TRU wastes is regulated by the EPA Standard. Subpart A of the Standard prescribes the operation of a disposal facility while wastes are being received. Subpart B prescribes how the repository must perform after it is decommissioned. Performance is regulated by four separate sections. Section 191.13, Containment Requirements, outlines the cumulative releases allowed for 10,000 years after disposal, based on the probability of such releases. Section 191.14, Assurance Requirements, describes the activities that must be undertaken in an attempt to improve the ability of the repository to isolate wastes from the accessible environment. Section 191.15, Individual Protection Requirements, limits radiation exposure to members of the public in the accessible environment from the undisturbed performance of the repository for 1,000 years after disposal. Section 191.16, Ground Water Protection Requirements, limits radiation concentrations in special sources of ground water from the undisturbed performance of the repository for 1,000 years after disposal.

Appendix A of Subpart B of the Standard provides the method for determining the allowable release rates of particular radionuclides and in total. Appendix B, Guidance for Implementation of Subpart B, is nonbinding guidance on the assumptions that were used in developing the Standard and on a recommended method of approaching compliance.

The United States Court of Appeals for the First Circuit vacated Subpart B of the Standard in 1987 and remanded it to the EPA for reconsideration. Until the Standard is repromulgated, the DOE and the State of New Mexico have agreed, through the Consultation and Cooperation Agreement (as modified), to undertake investigations based on the vacated Standard (U.S. DOE and State of New Mexico, 1981).

Efforts are under way, based on section 191.13 and the Guidance in Appendix B, to assess whether the WIPP has a "reasonable expectation" of complying with the Standard. Section 191.13(a) is excerpted below:

> Disposal systems for...transuranic radioactive wastes shall be designed to provide a reasonable expectation, based on performance assessments, that cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system.... (p. 38086)

Performance assessment, as defined in the Standard, involves identifying the processes and events that could impact the disposal system; determining the possible impacts of processes and events on the disposal system; and performing calculations to estimate cumulative releases considering "uncertainties" and the significant processes and events.

Significant events and processes for inclusion in the analysis are defined in the Guidance in Appendix B as having at least a 1 in 10,000 chance of occurring over 10,000 years, or as having a significant impact on the cumulative releases. Thus, events and processes with a smaller probability of occurrence can be removed from consideration (regardless of the impact). Other events and processes can be removed from consideration if the removal is not expected to significantly impact cumulative releases (regardless of the probability).

The Guidance also addresses the topic of possible disruptive events, including intrusion:

> Determining compliance with 191.13 will also involve predicting the likelihood of events and processes that may disturb the disposal system. In making these various predictions, it will be appropriate for the implementing agencies to make use of rather complex computational models, analytical theories, and prevalent expert judgment relevant to the numerical predictions. (p. 38088)

The two previous quotes make clear that attention must be paid to identifying those events that could impact the disposal system and estimating their probabilities, with the expectation that expert judgment might be used. The Futures Panel was convened to address these two needs. For performance-assessment calculations, significant events and processes are combined as appropriate to develop scenarios for the condition of the repository throughout the period of regulatory concern. For the purpose of WIPP performance assessment, a scenario is specifically defined as a combination of naturally occurring or human-induced events and processes that represents realistic future changes to the repository, geologic, and geohydrologic systems that could effect the escape of radionuclides from the repository and release to the accessible environment (Guzowski, 1990). Numerous computer codes are used to calculate cumulative releases of radionuclides to the accessible environment. These cumulative releases, when combined with the probabilities of the scenarios, are used to develop a complementary cumulative distribution function (CCDF). A CCDF, which plots cumulative releases of radionuclides to the accessible environment over 10,000 years versus the probability that a particular release will be exceeded, is compared to the limits established in Appendix A of the Standard to assess compliance with the Standard. Thus, expert judgment, through the Futures Panel, can be used to estimate probabilities of scenarios and to ensure that the simulated scenarios encompass a wide variety of alternative futures.

The undisturbed performance of the repository, as mentioned in the Individual Protection Requirements and the Ground Water Protection Requirements, is defined as "predicted behavior of a disposal system, including the consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events." Previous calculations for the WIPP have shown that radionuclides will not migrate out of the undisturbed repository/shaft system for 50,000 years, much longer than the 1,000 years called for in these sections of the Standard (Marietta et al., 1989). After naturally occurring events and processes have been screened out, human-intrusion activities appear to be the events with the potential to be the failure mode of major concern. The impact of human intrusion on repository performance must be examined and included in performance-assessment calculations. The severity of such human intrusion, which must be considered for comparison with the Standard, is limited by the Standard itself.

> However, the Agency assumes that the likelihood of such inadvertent and intermittent drilling need not be taken to be greater than 30 boreholes per square kilometer of repository area per 10,000 years for geologic repositories in proximity to sedimentary rock formations.... Furthermore, the Agency assumes that the consequences of such inadvertent drilling need to be assumed to be more severe than: (1) Direct release to the land surface of all the ground water in the repository horizon that would promptly flow through the newly created borehole to the surface due to natural lithostatic pressure--or (if pumping would be required to raise water to the surface) release of 200 cubic meters of ground water pumped to the surface if that much water is readily available to be pumped.... (p. 38089)

Current performance-assessment calculations are guided by the vacated Standard. The wide-ranging view of possible modes of intrusion by the experts may prove especially useful if the repromulgated Standard requires the consideration of modes other than drilling.

Estimates of human activities far into the future must be based on judgments rather than experimental procedures. This inherent uncertainty, along with the importance of human intrusion in performance-assessment calculations, makes this process subject to close public scrutiny. Expert judgments must be collected in a manner that addresses the need for traceable actions and believable results.

In addition to providing input to performance-assessment activities, an expert panel on future societies can advise on disposal-site markers. The most practical permanent markers to designate disposal sites are specifically mentioned in section 191.14(c) of the Assurance Requirements. As discussed in the preamble to the Standard, the Assurance Requirements were included to counteract the uncertainty inherent in the analyses for the Containment Requirements. Thus, in order "to reduce the potential harm from some aspect of our uncertainty about the future," a set of actions was outlined for implementation. Section 191.14(c) of the Standard states that "[d]isposal sites shall be designated by the most permanent markers, records, and other passive institutional controls practicable to indicate the dangers of the wastes and their location."

A plan for implementation of a marker strategy, including design characteristics, will be necessary for compliance evaluation to show that such markers can be constructed. Part of marker design would be based on the findings from studying past monuments that have stood the test of time, current materials technology, and present understanding of communication methods. A second important input to marker design would be from the Futures Panel about the possible future states of society (including the expected activities and resource needs, and the ability to interpret and heed warning markers) and how future societies might intrude upon a repository.

In addition to being necessary for simple compliance with the Assurance Requirements, the existence of markers may impact inadvertent human intrusion and should therefore be considered in the analysis of cumulative releases. This idea is stated in the following text from the Guidance in Appendix B:

> The Agency assumes that, as long as such passive institutional controls endure and are understood, they: (1) can be effective in deterring systematic or persistent exploitation of these disposal sites; and (2) can reduce the likelihood of inadvertent, intermittent human intrusion to a degree to be determined by the implementing agency.

Thus, the consideration of markers in the analysis for the Containment Requirements can provide evidence supporting a decrease in the total number of intrusions or an increase in the time to the first intrusion. The Guidance states that the implementing agency must determine the extent to which the markers are able to deter inadvertent human intrusion. To accomplish this, marker design characteristics must be developed (given current knowledge of materials, construction techniques, and communication means) and then evaluated to estimate the extent to which markers might deter human intrusion. Again, these activities start from the point of the possible future states of society.

The work of the Futures Panel is thus supported by the Standard and supporting documentation as providing both input to performance assessment in terms of expected events and probabilities and to the marker design effort in terms of the possible future states of society and modes of intrusion.

II. ORGANIZATION OF THE PANEL

The methodology employed in this study is referred to as expert-judgment analysis (Bonano et al., 1990). For some aspects of performance assessment (human-intrusion analyses in particular), conducting experiments that will provide data to resolve uncertainties is not possible. The same problem occurs in many studies involving the assessment of technological risks. When such unresolvable uncertainties do exist, the judgments of experts are often used to quantify the uncertainties and express both what is known and what is not known.

Using Expert Judgment

The formalization of expert-judgment elicitation for nuclear waste repositories is described in Bonano et al. (1990). Expert judgment is pervasive in complex analysis. Judgments about the selection of models, experimental conditions, and data sources must be made. The choice is not whether expert judgment will be used; instead, the choice is whether it will be collected and used in a disciplined, explicit manner or utilized implicitly where its role in the analysis is not as obvious.

Precursor studies have provided a structure for the collection of expert judgment. These studies include, among others, the Electric Power Research Institute (EPRI, 1986) study of seismicity in the eastern United States and the NUREG-1150 study (U.S. NRC, 1990). These studies provide models for the collection of expert judgments--models that are designed to avoid pitfalls that interfere with the collection process.

A formal expert-judgment process should consist of several well-defined activities. Such activities include creating issue statements for the experts to respond to, selecting experts and training them in probability assessment, eliciting probabilities, and processing and presenting findings.

While the NUREG-1150 study was most central in the design of this current effort, there are substantial differences between these two studies that are important to note. The goal of the expert-judgment process in NUREG-1150 was to provide uncertainty distributions for parameters and to judge the likelihood of certain phenomena. The uncertain quantities were relatively well defined and well known. In the present study of future societies, the issues are less well defined, and the experts are required to employ substantial creative effort in structuring their analyses.

Several forms of organization for experts in an elicitation process have been described (Bonano et al., 1990). One of these forms is the organization of experts into teams. A team structure is useful when disparate disciplines need to be brought to bear on a given problem. An added benefit of using teams is that communication among experts is enhanced. In contrast, when experts from different disciplines work on separate, but connected, parts of the same problem, coordination and communication among the experts must be explicitly provided for.

Sixteen experts arranged in four teams of four members each were used in this study. Each team was given the same assignment, as described in the Issue Statement and Task Statement (Appendix G). The team format was selected because the subject matter, the futures of society, is inherently multidisciplinary.

Expert-Judgment Panel

The selection of experts began with the construction of a Task Statement for the expert teams. This statement is included in Appendix G. The tasks outlined in this statement required judgments about a wide variety of possible futures, based on a wide variety of underlying societal and physical factors. The study of these underlying factors indicates that a multidisciplinary approach is needed. Because the teams were to be composed of scientists and scholars from many disciplines, the pool of candidates needed to be sufficiently broad. To achieve this end, a nomination process was employed.

NOMINATIONS

The first stage in the nomination process was the identification of persons believed sufficiently knowledgeable in the disciplines identified by SNL staff as being pertinent to the project to nominate persons to serve on the teams. The disciplines included futures research, law, physics, social science, political science, agriculture, and climatology. The nominators were identified through contacts with professional organizations such as the Society for Mining, Metallurgy, and Exploration and the American Anthropological Association. Governmental organizations such as the National Science Foundation were also contacted, as were public interest organizations such as the Natural Resources Defense Council and Resources for the Future. Simultaneously, literature searches were performed in various areas such as futures research. From these literature searches, prominent authors were identified and contacted. The editors of journals were also contacted concerning nominations.

An initial contact was almost always made by telephone to explain the project to the potential nominator. This contact was done both to determine whether the potential nominator would be able to provide nominations, and to interest the potential nominator in the project so that the likelihood of cooperation was enhanced.

The identification of nominators and the initial contacts took place during the period from April 23 through May 23, 1990. On May 23, a formal request for nominations (Appendix H) was sent to all nominators who had agreed to contribute. This letter outlined the tasks to be accomplished by the experts, provided a tentative schedule, and included a description of the criteria to be used for selection of experts. The letter invited self-nomination if the nominator deemed this to be appropriate.

During the following week, additional letters were sent to those nominators who had not responded. Several potential nominators, who were thought to be sufficiently knowledgeable that their responses were highly desirable but could not be contacted verbally, were also sent letters. In all, 71 letters requesting nominations were sent. The parties to whom these letters were addressed are shown in Appendix I.

From this effort, a total of 126 nominations were obtained. On June 6, 1990, a letter was sent to each of the nominees (Appendix J). This letter outlined the tasks to be accomplished and firm dates for the two meetings to be held in Albuquerque. The nominees, if interested and able to participate in the project, were asked to send a letter describing their interests and any special qualifications relevant to the WIPP human-intrusion study. A curriculum vita was also requested from each nominee. Letters of interest were received from 70 nominees by noon of June 25, 1990. At that time, the selection committee began deliberations, and no further responses were considered.

SELECTION OF EXPERTS

Criteria for the selection of experts were drafted for use by the selection committee. These criteria were similar to the criteria that were distributed to the nominators and nominees but also included criteria related to the balance and geographic location of the teams. The criteria are included as Appendix K.

The selection committee was composed of three university professors: Dr. G. Ross Heath of the University of Washington (oceanography), Dr. Douglas Brookins of the University of New Mexico (geology), and Dr. Stephen Hora of the University of Hawaii (decision analysis). The members of the selection committee were provided with copies of the letters of interest and the curricula vitae several days prior to the selection meeting.

The selection committee first discussed each of the nominees. Each member of the selection committee provided a numerical or categorical evaluation of each nominee. These evaluations had been prepared in advance of the discussion, but the committee members were free to change evaluations during the discussions.

After the discussion of the nominees was completed, members of the selection committee were asked to provide a cutoff value or category for their scales. A rating at or above the cutoff indicated that a nominee should definitely be included on a team. The first screening of candidates was performed by identifying all nominees who were rated above the cutoff by at least two of the selection committee members. The logic for taking this approach was that the pool of nominees was of very high quality, with far more qualified nominees than could be accommodated. The screening rule allowed the committee to identify the best of the best rather than attempting to screen out those not qualified. This process led to the identification of 16 candidates who, fortuitously, were well distributed across disciplines and provided representation across various organizations, including public interest organizations.

The committee then arranged the experts into teams so that geographic neighbors were placed on the same team while, at the same time, preserving balance among disciplines on each team. The resulting teams are shown in Table II-1. Four teams of four experts were thus constructed. In addition, four other nominees were identified as alternates should any team be reduced to less than three members.

TABLE II-1. EXPERT PANEL TEAMS

Team/Names	Organization(s)	Discipline(s)
Boston		
Bell, Wendell	Yale University	Sociology
Baram, Michael	Boston University	Law and Technology
Gordon, Theodore	Futures Group (founder)	Futures Research
Cohen, Bernard	University of Pittsburgh	Physics
Southwest		
Benford, Gregory	University of California at Irvine	Physics, Futures Research
Kirkwood, Craig	Arizona State University	Operations Research
Otway, Harry	Joint Research Center (Ispra), Los Alamos NL	Engineering and Social Sciences
Pasqualetti, Martin	Arizona State University	Geography
Washington (A)		
Chapman, Duane	The World Bank, Cornell University	Resource Economics
Ferkiss, Victor	Georgetown University	Political Science, Futures Research
Reicher, Dan	Natural Resources Defense Council	Environmental Law
Taylor, Theodore	Consultant	Physics
Washington (B)		
Rosenberg, Norman	Resources for the Future	Agriculture, Climatology
Glickman, Theodore	Resources for the Future	Risk Analysis, Geography, Environmental Engineering
Singer, Max	The Potomac Org.	Law, Futures Research
Vinovskis, Maris	University of Michigan	History, Demographics

III. POTENTIAL FUTURE SOCIETIES

An essential task in studying the potential for inadvertent human intrusion into the WIPP is the consideration of the possible types of future human societies. The planning for this panel involved a conscious decision to solicit opinion on the future states of society and on a variety of modes of intrusion that go beyond what the Standard requires for performance assessment. This chapter explains the methodologies employed by the teams to delineate future societies, lists the factors used in determining the possible futures, and considers alternative modes of intrusion into the WIPP.

Methodologies

The activities of future societies and their awareness of the hazards from nuclear waste are important determinants of the likelihoods of intrusion. In studying these futures, the four teams adopted individual methodologies. These methodologies represent what each team believed to be the important underlying factors impacting societal activities and intrusion, the relationships between the factors, and the extent of the impact.

BOSTON TEAM

The Boston Team analyzed alternative futures by describing future civilizations in two distinct ways. The first way began with the examination of intrusive activities and worked backward to determine the attributes of society that might lead to such intrusions. This "top down" approach led the team to define "generic" alternative futures--alternatives that are broad in scope and lack detail, but are representative of many possible futures. The second way of developing alternative futures that was employed by the Boston Team resulted in the creation of inventive, highly detailed pictures of the future. These futures were termed "point" futures by the team. Both the terms "generic" and "point" futures will be retained to describe the findings of the four teams.

When creating generic alternative futures, the Boston Team followed a consistent approach for each potential intrusion mode. This approach involved first identifying the vulnerability of the WIPP. The specific event or events that would be required to exploit the vulnerability were then analyzed. Next, the activities that could potentially require such events to take place were discussed, and an analysis of the societal and physical conditions necessary for these activities was presented. The team also identified criteria for each specific mode of intrusion that could be used to characterize the intrusion as inadvertent. Finally, initial probability assessments, in qualitative terms, were provided for each of the precursor events and activities defining the path to intrusion.

The point futures developed by the Boston Team provide a thought-provoking view of what future societies could be like. These future societies range from the WIPP becoming the nation's primary nuclear waste site to a society dominated by individuals who do not believe in science as currently practiced. The creation of alternative futures is the product of a highly imaginative process and expands the range of possible futures to consider when designing passive markers and barriers for the WIPP. These futures are not in conflict with the generic futures, but instead provide an alternative, detailed view of the future that, although of low probability because of the level of specificity, is instructive about the variety of futures that should be anticipated.

SOUTHWEST TEAM

The Southwest Team created views of the future through a forward process. This process also produced generic alternative futures. The process began with the establishment of key assumptions about the operations of the WIPP and the scope of the analysis to be provided. The team then identified environmental changes and socioeconomic factors that potentially would impact human intrusion. For each of the socioeconomic factors, a qualitative assessment of its impact on human intrusion was provided.

Five narrative futures were created by the Southwest Team. These futures were identified as

technological knowledge increases,
decline and rebuilding of technological knowledge: seesaw,
technological knowledge decreases,
altered political control of the WIPP area,
stasis (not included in probability elicitation).

These narrative futures are generic in that many possibilities are included within a single future. The probabilities of inadvertent intrusion arise from these futures by considering the probabilities of the persistence of the present political control over the WIPP, the pattern of technological development given the state of political control, and intrusion given both the state of political control and the pattern of technological development.

WASHINGTON A TEAM

The Washington A Team focused its views of the future on the relationship between earth resources and society. These futures were

continuity--continued population growth and current levels of resource consumption,

radical increase--massive increases in the consumption of world resources,

radical discontinuity--erosion of conditions in the WIPP area by major war or political change,

steady-state resources--world consumption of resources dramatically reduced through zero population growth and extensive recycling.

The first three of these alternative futures involved population growth and substantial extractive activity. In these futures, the natural environment was thought of as a source of materials and energy rather than as a human habitat. In the fourth future, humans reached an equilibrium with nature. The state of the world became constant, and there was little need for extractive activity.

The Washington A Team allowed that the future may shift among several of these alternatives at various points in time. Thus, these futures should be viewed as snapshots of what the future might be like rather than complete, mutually exclusive paths that society's development might follow. This team also provided an extensive analysis concerning loss of memory about the WIPP and the inability to use existing information.

WASHINGTON B TEAM

The second team from Washington, the B Team, constructed a four-component model of paths leading to human intrusion. The first component of the model was the state of society, both local and worldwide. These views of the future states of society were based upon the climate at the WIPP area (both natural and human-induced changes are allowed), energy and mineral costs, food supply and demand, and governance of the WIPP area. The ensuing components of the model included the level of awareness about nuclear waste, the presence of potentially intrusive activities, and the modes of inadvertent intrusion into WIPP.

The factors that underlie the Washington B Team analysis are levels of resource prices, with higher levels bringing about greater exploration and extraction, modification of the existing climate or water importation, and the ability of the government to retain sufficient control to preclude inadvertent human intrusion. The analysis was based on forming all combinations of the levels of these factors. In this way the team created a potentially exhaustive set of alternative futures.

Catastrophes, which are unfortunate events that occur over a short time and have the potential to change the course of civilization, were also considered by the Washington B Team. These events, both natural and manmade, can cause such a disruption of society that memory of nuclear waste becomes lost, and the potential for inadvertent human intrusion increases.

Underlying Factors

Each of the four teams identified factors thought to be determinants of the activities of coming societies. In some instances these factors are given in tables found in the team reports, while in other cases the factors are identified in the narrative.

Figure 2 of the Boston Team report (Appendix C, p. C-9) and Table 4 of the Southwest Team report (Appendix D, p. D-21) present such information. Neither of the Washington teams provided a table of such determinants. A review of the reports identifies some common themes about the future that seem to be most critical in judging what the future will be like.

The facets of society that most directly impinge upon inadvertent human intrusion include the rate of technological development; population growth; economic developments, including the prices of minerals and energy resources; water availability and production in the WIPP region; and the level of governmental continuity and cognizance of nuclear waste. These factors are related and cannot be treated independently. For example, the level of technological progress may have a profound effect on the world economy's need for resources. Similarly, the world population size will also impact the level of resource exploration and extraction. The relationships among factors can be even more complex. Technology may directly impact both population size and resource utilization, for instance, and population may directly impact resource utilization. Thus, technology will have both direct and indirect (through population) impacts on resource utilization.

TECHNOLOGY

Critical to future human activities is the progress that will be made in technological development. The Boston Team identified a number of specific human activities that could result in inadvertent intrusion. Many of these activities are in some way dependent upon the advancement of technology. One type of intrusive activity is excavation for the purposes of construction.

The most likely type of construction is a dam to hold water for industrial, energy, agricultural, or residential uses. Such a dam would only be constructed if a major water impoundment and supply system were to be developed. The technology to modify weather, then, may play a key role in bringing about dam development.

Resource extraction may be influenced by technology. New methods of resource exploration, similar to medical CAT scanners, may allow exploration in more nonintrusive manners than currently available. In addition, there may be new and efficient means of drilling, new fluids for solution mining, and new, rapid means of excavating.

The Southwest Team proposed that both technological innovation and technological stagnation can increase the potential for intrusion. Under technological stagnation, intrusive means would be used for resource exploration. Impacts due to technological innovation include advanced drilling techniques, methods for high-volume water desalting that may make water extraction worthwhile, deep strip-mining techniques that would reduce the cost of resource extraction, the identification of new resources, and the use of autonomous mechanical extraction techniques for minerals. Biotechnology was also identified as having the potential to develop new means for the extraction of minerals.

The Washington A Team found that the development of solar energy resources could lead to the extraction of mineral resources (both metal and nonmetals) at the WIPP. Solar energy would be used in the processing of the ores. For example, magnesium could be obtained by electrolytic separation of metallic magnesium from the ground waters at the WIPP. This team also envisioned that, in a future with radically increasing resource exploitation, machines presumably not subject to the same hazards from contact with radiation as human beings would increase the willingness of drillers to take risks. Further, the existence of such technology may lead to overconfidence in the ability of their human directors to employ them without accident. Alternatively, the Washington A Team found that technologies useful in recycling resources are necessary to reach a stable-state world. In such a world there would be little motivation for resource development, which may decrease the probability of inadvertent human intrusion.

Economic and technological developments were tied together as a single factor by the Washington B Team. Wealth is both a result of technology and a precursor to technology. Weather modification and desalination of water on a large scale were identified as technological developments having the potential for impact on the WIPP system.

POPULATION GROWTH

Increases in population will impact the WIPP through a variety of paths. First, increases in world population will translate into increased resource demands (Washington A Team). There is also the possibility of increased population density in the WIPP area and increased industrialization (Boston Team).

The Southwest Team refined the concept of local population growth to include redistribution of the population by governmental policy and voluntary motivation. Voluntary redistribution might occur because of resource exploitation opportunities, grazing or crop production, or recreation purposes.

ECONOMIC DEVELOPMENT

The role of economic development in alternative futures containing human intrusion into the repository is not as sharply defined as that of technological development. Economic development was closely tied to technological development by the Washington B Team. In fact, that team used a single underlying factor to represent both technological and economic progress. The Southwest Team appears to have implicitly taken economic development into account in their five alternative futures.

Economic development also appears implicitly in the alternative futures constructed by the Washington A Team. Here, the economic demand for resources and the political control that moderates the use of resources are fundamental in defining alternative futures. Economic development in the WIPP region appears in the assessment structures given by the Boston Team. In the analysis of injection (disposal) wells, the level of industrialization of the WIPP region plays the major role.

CONSERVATION OF INFORMATION

The persistence of information about the WIPP and the continuity of government control are intertwined. The likelihood of loss of information is apt to increase when there is a discontinuity in governmental control. Despite the close relationships between these two aspects of inadvertent intrusion, we will attempt to separate them in this discussion.

The most complete discussion of the preservation and availability of information was provided by the Washington A Team. This team identified inadequate records, inaccessibility of records, inability to understand records, ignoring of information that is understood, and lack of information regarding the effects of nearby activities as contributors to inadvertent-intrusion possibilities. The reader is referred to the Washington A Team report (Appendix E, pp. E-7 - E-10) for elaboration.

The Southwest Team identified the possibility that nuclear energy will be a short-lived phase of our economic development. In this event, some loss of memory is likely. Memory loss was identified as taking several forms. Memory about the facility may be lost, memory may be lost about the danger but not the facility, and local but not institutional memory may be lost.

During the probability elicitation sessions, the Boston Team identified four states of memory about the WIPP. Memory of the WIPP could be relatively complete, memory of the location but not of the hazards may persist, memory of the WIPP may become a legend or a myth, or all memory may be lost. While complete memory of the WIPP and its attendant dangers will deter intrusion, partial memory can serve to attract potential intruders. Knowing that something is there, but not knowing what it is or what its value may be, may serve to attract investigations such as archaeological digs or salvage operations.

The survival of information may depend upon the survival of our information systems. The Southwest Team has noted that changes in basic forms of communication are likely in the next 10,000 years. Both written and oral forms of communication may be quite different than they are today. Moreover, the means for storing information may be significantly different than the means used today. If this is so, future generations may find it difficult to access the information that we have intended for them. In a point future related to communication, the Boston and Southwest Teams identify a world in which reading is performed by machines for humans.

Alternatively, the Washington A Team believed that the probability of hazard awareness (knowledge of the location of the WIPP, the wastes contained therein, how the WIPP could be intruded upon, and the risks of an intrusion) will be high throughout the study period. This probability could be reduced to a low level due to a catastrophe eliminating both markers and barrier systems.

PERSISTENCE OF GOVERNMENT CONTROL

A recurring perception among the teams is the small likelihood of continued U.S. political control over the WIPP. Governments are seldom stable for long periods of time, certainly not for the periods of time covered by this study. In an alternative future provided by the Southwest Team, a separate nation is formed from northern Mexico and the southwestern United States at some time in the future. In a similar future provided by the Boston Team, New Mexico secedes from the United States and joins Mexico. In the chaos of the transition, information about the WIPP may be lost--except, perhaps, for local folklore about buried treasure.

The "radical discontinuity" future provided by the Washington A Team also deals with the discontinuity of governmental control. Two possibilities include erosion of conditions so that New Mexico resembles a third world nation in the future. The Washington B Team also stated that at some points during the period of interest the area around the WIPP may be inhabited "by societies that are not part of the U.S." (Appendix F, p. F-5).

Presentations made by the teams indicated that the cultural differentiation of the region adds credibility to the hypothesis of a change in government control.

A conclusion that may be drawn from the experts' views of political stability is that continued U.S. control of the WIPP for 10,000 years is unlikely. The transformation from one government to another may be disruptive and preclude the transferal of information about the WIPP. Even if U.S. control is perpetuated, the application of effective measures to warn potential intruders may not follow.

MITIGATION OF DANGER FROM NUCLEAR WASTE

If nuclear waste is intruded upon at some point in the future, the exposed waste will not neccessarily cause harm. Medical technology may have developed to a point where cancer is curable. The avoidance of the consequences of radiation could be accomplished once it is recognized that a hazard has been encountered. These points were made by both the Washington A and Washington B Teams.

The Southwest Team specifically allows for this possibility in the analysis of technologically advanced futures. In such a future, the likelihood of the waste being dangerous is very low, and thus the consequences of inadvertent intrusion are greatly mitigated. In an appendix (Appendix C, p. C-77) to the Boston Team report, Dr. Bernard Cohen presents situations where inadvertent intrusion into the WIPP will not be an issue. These situations include the determination that low-level radiation is not hazardous, that medical progress can greatly reduce the consequences of radiation, and that technology for safe redisposal has become available.

Modes of Intrusion

The underlying factors that determine the nature of future societies provide the basis for the consideration of alternative modes of intrusion into the WIPP. A summary of the modes of intrusion provided by the teams is given in Table III-1.

TABLE III-1. INTRUSION MODES

EXCAVATION	DRILLING
Archaeological	Hydrocarbons
Mineral	Water
Construction	Research
DISPOSAL/STORAGE	OFFSITE ACTIVITIES
Underground Injection	Water Impoundment
Petroleum Storage	Explosions
Additional Radioactive Waste Disposal	Water Well Field
TUNNELING	
Transportation	
Pipeline	
Mole Mining	

IV. SUMMARIES OF PROBABILITY ELICITATIONS

A probability elicitation is a formal session during which one or more experts are assisted in representing their beliefs as probability distributions. For this study, each team of four members worked with a normative specialist, an individual familiar with decision analysis and experienced in conducting this type of session. Dr. Stephen C. Hora (University of Hawaii) and Dr. Detlof von Winterfeldt (University of Southern California) were the normative specialists for this study. The sessions were tape recorded for future reference in documenting the results of the sessions. In some cases, it was necessary for the normative specialist to contact the team members for clarification of some aspect of the elicitation results.

It is important to note that the conditional probabilities found in the following tables are used in the calculation of the probabilities of intrusion by various modes. As intermediate values, it is inappropriate to round them off at this stage.

Knowledge of the WIPP was often a factor in estimating intrusion probabilities. If there is knowledge of the WIPP, the intrusion is not strictly inadvertent. The analyses, as presented by the teams, are described below and document the individual treatment of knowledge of the WIPP.

Boston Team

APPROACH AND DECOMPOSITION

The methodology employed by the Boston Team is based upon five underlying factors: the level of technology, the world population, the cost of materials, the persistence of knowledge regarding the WIPP, and the level of industrialization in the WIPP area. These factors were treated in a dependent fashion, with the level of population density and the persistence of knowledge about the WIPP depending upon the level of technology. Six modes of intrusion were considered by the Boston Team--drilling for resources, underground storage of nuclear waste, disposal of wastes through injection wells, archaeological explorations, explosive testing, and the construction of dams for water impoundment.

The frequencies of the various modes of intrusion are related to the four underlying factors through relatively complex structures. These structures are presented and analyzed in the section on the evaluation of intrusion probabilities. Table IV-1 provides a summary of those factors that are related to each mode of intrusion. In the cases of the level of technology

TABLE IV-1. BOSTON TEAM - MODES OF INTRUSION AND UNDERLYING FACTORS

Intrusion Mode	Underlying Factors
Resource Exploration and Extraction (drilling boreholes)	State of Technology Knowledge of the WIPP Value of Materials
Reopening for Storage	State of Technology State of Knowledge
Disposal by Injection Wells	State of Technology Industrial Activities
Archaeological Exploration	State of Technology Knowledge of the WIPP
Explosive Testing	State of Technology Knowledge of the WIPP
Water Impoundment	State of Technology Knowledge of the WIPP Population Density

and the level of population density, the factors appear as conditions in conditional probabilities. In the case of knowledge of the WIPP, the factor appears as a multiplier applied to the intrusion rate. For example, archaeological intrusion is fifty times more likely if knowledge of the WIPP persists as a myth than if all knowledge of the WIPP is lost.

The logical structure for resource exploration and extraction was developed assuming that gas and oil are the primary resources. Drilling activity depends upon the value of materials, which in turn depends upon the state of technology. Moderating the rate of drilling is knowledge of the WIPP, which is, in turn, dependent on the state of technology.

The Boston Team also considered the possibility that the WIPP system would, at some time in the future, be reopened for the storage of additional wastes. During such a reopening, materials may be accidentally released to the biosphere. The likelihood of such an intrusion depends directly upon knowledge of the WIPP. Once again, however, knowledge of the WIPP is dependent on the state of technology.

The frequency with which injection wells will be built depends upon the level of industrial activity and the time period. Industrial activity, in turn, depends on the level of technology.

The rate of archaeological exploration is also dependent upon knowledge of the WIPP and, therefore, indirectly dependent on the state of technology.

The structure for intrusions because of underground weapons explosions is similar to that of reopening the WIPP for additional storage.

The rate of water impoundment is influenced by the population density in the WIPP area. Population density, in turn, is dependent upon the state of technology. The moderating multiplier for the rate of intrusion is dependent on the knowledge of the past.

SUMMARY OF PROBABILITY ELICITATIONS

The assessments from the Boston Team were obtained interactively from the group. Each probability represents a combination of opinions from the individual team members. Each combination of probabilities was obtained using (1) negotiation, (2) arithmetic averaging, (3) geometric averaging, or (4) a combination of these techniques.

Underlying the analysis are the following features of potential future societies:

> technology: low, moderate, or high relative to today's technology (today considered to be moderate);
>
> world population: below 10 billion (low) or above 20 billion (high);
>
> cost of materials: low or high relative to today's cost (today considered to be low);
>
> knowledge of the WIPP: precise knowledge, location known but consequences unknown, a myth, or completely unknown;
>
> level of industrial activity at the WIPP: low or high (today considered to be low).

The probabilities of the various states of society depend upon the time period in the future being considered. While the Boston Team provided the information necessary to compute rates of intrusion at several points in time (100, 1,000, and 10,000 years after closure), the performance-assessment calculations require rates of intrusion during the entire continuum from 100 to 10,000 years after closure. In order to accomplish the interpolation needed to satisfy the performance-assessment requirements, a logarithmic scale has been used. The midpoint of the logarithms of the 100-year and 1,000-year points is approximately 300 years. The midpoint of the logarithms of the 1,000-year and 10,000-year points is approximately 3,000 years.

This scale provides the motivation for using the rates calculated from the assessment at 1,000 years to represent the 2,700-year period from 300 to 3,000 years. Similarly, the 100-year rates are used for the 100- to 300-year period, and the 10,000-year rates are used for the 3,000- to 10,000-year period.

Assessments were made for each of three time periods: 0 to 300 years after the closure of the WIPP, 300 to 3,000 years after the closure of the WIPP, and 3,000 to 10,000 years after the closure of the WIPP. Dependencies also exist between the state of technology and the world population density, and the state of technology and knowledge of the WIPP.

Beginning with the state of technology, the following team probabilities were obtained (Table IV-2).

TABLE IV-2. BOSTON TEAM - STATE OF TECHNOLOGY

State of Technology	Probability of Occurrence		
	100-300 Years	300-3,000 Years	3,000-10,000 Years
High	0.80	0.70	0.80
Moderate	0.15	0.20	0.10
Low	0.05	0.10	0.10

The assessments of probabilities of future population densities were conditional on the state of technology. Probabilities of population densities as a function of the state of technology are presented in Table IV-3.

TABLE IV-3. BOSTON TEAM - PROBABILITIES OF POPULATION DENSITIES AS A FUNCTION OF THE STATE OF TECHNOLOGY

Population Density	Probability of Occurrence		
	100-300 Years	300-3,000 Years	3,000-10,000 Years
		HIGH TECHNOLOGY	
High	0.45	0.40	0.40
Low	0.55	0.60	0.60

TABLE IV-3. BOSTON TEAM - PROBABILITIES OF POPULATION DENSITIES AS A FUNCTION OF THE STATE OF TECHNOLOGY (Continued)

Population Density	Probability of Occurrence 100-300 Years	300-3,000 Years	3,000-10,000 Years
	MODERATE TECHNOLOGY		
High	0.65	0.65	0.50
Low	0.35	0.35	0.50
	LOW TECHNOLOGY		
High	0.40	0.30	0.30
Low	0.60	0.70	0.70

The probabilities provided by the individual team members were fairly consistent for both the state of technology and future population size. This was not the case, however, for the value of materials. Shown in Table IV-4 are the individual and averaged probabilities for high and low materials costs at the three future times.

TABLE IV-4. BOSTON TEAM - PROBABILITY OF VALUE OF MATERIALS

Value of Materials	Probability of Occurrence 100-300 Years	300-3,000 Years	3,000-10,000 Years
HIGH			
Average Probability	0.5125	0.325	0.325
(Individual Probabilities)	(0.7, 0.3, 0.75, 0.3)	(0.6, 0.1, 0.5, 0.1)	(0.6, 0.1, 0.5, 0.1)
LOW			
Average Probability	0.4875	0.675	0.675
(Individual Probabilities)	(0.3, 0.7, 0.25, 0.7)	(0.4, 0.9, 0.5, 0.9)	(0.4, 0.9, 0.5, 0.9)

The persistence of knowledge of the WIPP was assessed as conditional on the time period and the state of technology. The individual judgments about the four potential states of knowledge and the exact averages are shown in Tables IV-5, IV-6, IV-7, and IV-8.

TABLE IV-5. BOSTON TEAM - PROBABILITY OF PRECISE KNOWLEDGE ABOUT THE WIPP AS A FUNCTION OF LEVEL OF TECHNOLOGY

Team Member	Level of Technology	Probability of Occurrence		
		100-300 Years	300-3,000 Years	3,000-10,000 Years
1	High	1.0	0.9	0.85
	Low	0.7	0.5	0.1
2	High	0.9	0.2	0.0
	Low	0.9	0.2	0.0
3	High	0.6	0.4	0.2
	Low	0.6	0.3	0.1
4	High	0.5	0.3	0.2
	Low	0.2	0.1	0.0
Average				
	High	0.75	0.45	0.3125
	Moderate*	0.675	0.3675	0.1812
	Low	0.6	0.275	0.05

* Moderate level of technology is an arithmetic average of the values of the high and low levels.

TABLE IV-6. BOSTON TEAM - PROBABILITY OF LOCATION OF THE WIPP KNOWN BUT CONSEQUENCES UNKNOWN AS A FUNCTION OF LEVEL OF TECHNOLOGY

Team Member	Level of Technology	Probability of Occurrence		
		100-300 Years	300-3,000 Years	3,000-10,000 Years
1	High	0.0	0.0	0.05
	Low	0.2	0.1	0.2
2	High	0.0	0.2	0.0
	Low	0.0	0.2	0.0
3	High	0.2	0.3	0.2
	Low	0.2	0.3	0.1
4	High	0.1	0.3	0.3
	Low	0.2	0.2	0.1
Average				
	High	0.075	0.2	0.1375
	Moderate*	0.1125	0.2	0.1188
	Low	0.150	0.2	0.1

* Moderate level of technology is an arithmetic average of the values of the high and low levels.

TABLE IV-7. BOSTON TEAM - PROBABILITY OF THE WIPP'S EXISTENCE AS A MYTH AS A FUNCTION OF LEVEL OF TECHNOLOGY

Team Member	Level of Technology	Probability of Occurrence		
		100-300 Years	300-3,000 Years	3,000-10,000 Years
1	High	0.0	0.1	0.05
	Low	0.1	0.2	0.5
2	High	0.1	0.2	0.2
	Low	0.1	0.1	0.2
3	High	0.1	0.1	0.2
	Low	0.1	0.1	0.2

TABLE IV-7. BOSTON TEAM - PROBABILITY OF THE WIPP'S EXISTENCE AS A MYTH AS A FUNCTION OF LEVEL OF TECHNOLOGY (Continued)

Team Member	Level of Technology	Probability of Occurrence 100-300 Years	300-3,000 Years	3,000-10,000 Years
4	High	0.0	0.2	0.3
	Low	0.1	0.3	0.3
Average				
	High	0.05	0.15	0.1875
	Moderate*	0.075	0.1625	0.2438
	Low	0.1	0.175	0.3

* Moderate level of technology is an arithmetic average of the values of the high and low levels.

TABLE IV-8. BOSTON TEAM - PROBABILITY OF NO KNOWLEDGE OF THE WIPP AS A FUNCTION OF LEVEL OF TECHNOLOGY

Team Member	Level of Technology	Probability of Occurrence 100-300 Years	300-3,000 Years	3,000-10,000 Years
1	High	0.0	0.0	0.05
	Low	0.0	0.2	0.2
2	High	0.0	0.4	0.8
	Low	0.0	0.5	0.8
3	High	0.1	0.2	0.4
	Low	0.1	0.3	0.6
4	High	0.4	0.2	0.2
	Low	0.5	0.4	0.6
Average				
	High	0.125	0.2	0.3625
	Moderate*	0.1375	0.275	0.4562
	Low	0.15	0.35	0.55

* Moderate level of technology is an arithmetic average of the values of the high and low levels.

ACTIVITIES AND MODES OF INTRUSION

The states of society and the states of knowledge given in the preceding tables provide the conditions for probability assessments about potentially intrusive activities. These activities and their respective conditioning variables are listed below.

Drilling

The frequency of drilling boreholes for the exploration and extraction of resources depends on the value of materials in the ground. The value of the materials depends upon the amount of time that has passed. If material values are high, then in the near future (100 years), the number of boreholes drilled in the WIPP area will be in the range of from 0.25 to 4 times the current rate. If material prices are low, however, the rate will be only 0.1 of the rate for the high material cost case. Beyond the near future, it is unlikely that boreholes will be drilled for materials extraction in the WIPP area. Knowledge of the WIPP will moderate the drilling frequency at the WIPP, as shown in Table IV-9. As before, the multiplier is applied to the rate of intrusion.

TABLE IV-9. BOSTON TEAM - RATE OF ACTIVITY MULTIPLIERS FOR INTRUSIONS INTO THE WIPP[a]

Activities	State of Knowledge			
	Precise Location-Impacts Understood	Precise Location-Impacts Not Understood	Myth	Loss of Memory
Excavation[b]	0.50	0.90	0.70	1.00
Storage (Expand WIPP)	1.00	1.70	0.40	0.00
Boreholes	0.60	0.60	0.60	1.00
Subsurface (Archaeology)	0.25	1.00	1.00	0.02
Explosive Testing	1.00	0.00	0.00	0.00
Construction/ Impoundment	0.40	0.25	0.80	1.00

a The analysis of disposal by injection wells does not include the use of multipliers.
b The multipliers for excavation were not used because this activity was not analyzed in detail.

Storage

Additional storage of hazardous wastes may continue at the WIPP even after the original facility is closed. In the future, if knowledge of the WIPP becomes fuzzy, additional storage facilities may be created there. During the construction of such facilities, inadvertent intrusion in the form of tunneling or boring may occur. The frequency of such intrusions depends, first, upon the WIPP being reopened for expansion. This reopening is only feasible in a moderate or high technology society. Given moderate or high technology, the probability that the WIPP will be reopened in the near future (represented by 0 to 300 years) is 0.5; during the intermediate period (represented by 300 to 3,000 years) the probability is 0.6; and in the far future (represented by 3,000 to 10,000 years) the probability is 0.7. Given that the WIPP is reopened during the near or intermediate future, there will be between 1 and 10 expansions during these periods. Similarly, if the WIPP is opened for expansion in the far future, there will be between 1 and 10 expansions. These rates of intrusion are moderated by the appropriate multipliers shown in Table IV-9.

Disposal by Injection Wells

Disposal refers to the injection of industrial wastes into the ground. While this mode of intrusion involves drilling and boring, it is different from extractive drilling in that materials are injected rather than withdrawn. This difference will require that the consequences of such intrusions be modeled differently than those for drilling for extraction. Disposal activity depends upon the level of industrial activity near the WIPP. If the level of industrial activity is high, injection disposal may occur. On the other hand, if the level of industrial activity is low, it is doubtful that such activity will occur.

The rate of creation of injection wells in the WIPP area is dependent on the level of industrial activity. The level of industrial activity was assigned two levels by the Boston Team--high and low. The present level of industrial activity in the WIPP area is low. Table IV-10 contains the averaged probabilities of high and low industrial activity given the level of technology and the time period.

After the initial elicitation sessions, it was determined that insufficient information had been obtained from the Boston Team to provide a rate of disposal intrusion. The team members were requested by mail to supply rates of disposal well construction per square mile per 1,000 years for each of the three time periods under both high and low industrialization. Three of the experts responded to the request. The fourth expert was out of the country and unable to respond. The results are shown in Table IV-11.

TABLE IV-10. BOSTON TEAM - AVERAGED PROBABILITIES OF INDUSTRIAL ACTIVITY AS A FUNCTION OF THE LEVEL OF TECHNOLOGY

Level of Industrial Activity	Probability of Occurrence		
	100-300 Years	300-3,000 Years	3,000-10,000 Years
	HIGH TECHNOLOGY		
High	0.6	0.65	0.65
Low	0.4	0.35	0.35
	MEDIUM TECHNOLOGY		
High	0.2	0.25	0.25
Low	0.8	0.75	0.75
	LOW TECHNOLOGY		
High	0.15	0.15	0.15
Low	0.85	0.85	0.85

TABLE IV-11. BOSTON TEAM - FREQUENCY OF INJECTION WELLS PER SQUARE MILE PER 1,000 YEARS

Level of Industrialization	Frequency of Occurrence		
	100-300 Years	300-3,000 Years	3,000-10,000 Years
HIGH			
Average Probability	0.4	$1.0\overline{33}$	$4.00\overline{3}$
(Individual Probabilities)	(1, 0.1, 0.1)	(2, 0.1, 1)	(2, 0.01, 10)
LOW			
Average Probability	0.017	0.167	1.667
(Individual Probabilities)	(0, 0.001, 0.05)	(0, 0.001, 0.5)	(0, 0.001, 5)

Archaeological Investigation

In a state of partial knowledge about the WIPP, the facility may become a prime target for archaeological exploration. The rate of such investigation would be in the range of 0.01 to 4 times per 1,000-year period. The frequency would be moderated by the multipliers shown in Table IV-9.

Explosions

The testing of nuclear weapons at the WIPP may take place at some time in the future. Such testing would only take place with precise knowledge of the WIPP's location and purpose. Given that knowledge of the WIPP is precise, the rate of testing could be anywhere between 0.01 tests and 10 tests per 10,000 years. The geometric mean of the assessments provided a value of 0.3 tests near the WIPP per 10,000 years given precise knowledge.

Construction and Impoundment

Construction of dams near the WIPP may result in seepage into the repository. The likelihood of such construction depends directly on the population density, which, in turn, depends upon the state of technology and the time period. The state of knowledge about the WIPP may also moderate the frequency with which dams are built near the WIPP area.

Given a high population density, the team reported that somewhere between 1 and 20 dams might be built in the Nash Draw area adjacent to the WIPP if knowledge of the WIPP is lost. For the low population scenario, the number of dams would be between 0 and 10. Multipliers of 0.4, 0.25, 0.8, and 1.0 were provided for the four states of knowledge of the WIPP, as shown in Table IV-9.

ASSEMBLING THE JUDGMENTS

Drilling

The complexity of the decomposition provided by the Boston Team has required that the recomposition of judgments be done with the assistance of computer software. To aid in this recomposition, the computer program InDia (<u>In</u>fluence <u>Di</u>agram <u>A</u>nalysis) was employed. InDia supports generalized decision trees as described by Shachter (1986). In order to demonstrate how the calculations are performed, a single type of intrusion mode, drilling, has been selected. The manual calculations will be presented for this mode of intrusion in the near future (0-300 years after closure).

Figure IV-1 is the influence diagram for intrusion due to drilling for resources. Three different entities are represented by three symbols in the influence diagrams. The most prevalent symbol is the single oval. The single oval represents a concept that will potentially influence other concepts shown in the diagram and that possesses a probability distribution, perhaps a conditional probability distribution. Probabilities may be assigned to quantities (random variables) or qualitative categories such as myth or high. The distributions are conditional because they depend upon the predecessor concepts. An oval has also been used for the time period as a matter of

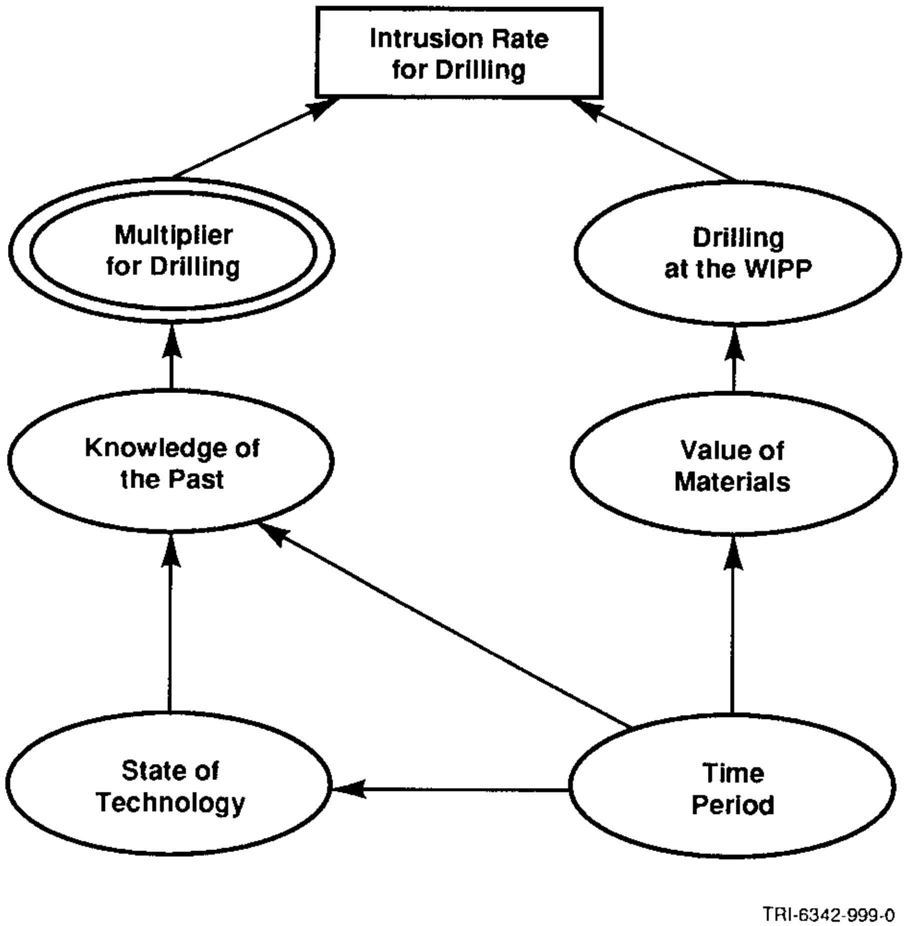


Figure IV-1. Boston Team - Influence Diagram for Resource Drilling Intrusions.

convenience. The double oval represents a deterministic quantity, usually a multiplier that is conditional on a state of knowledge. The arrows in the diagram show the directions of the influence. The third symbol is a rectangle that represents a mathematical function.

The following symbols will be used in the manual analysis of the decomposition shown in the diagram:

T_i = {the ith time period, i=1,2,3}
ST_j = {the jth state of technology, j=1,2,3}
KP_k = {the kth state of knowledge about WIPP, k=1,2,3,4}
VM_l = {the lth state of the value of materials, l=1,2}
$D_m(T_i, VM_l)$ = {a random multiplier for drilling that depends on T_i and VM_l}
$m_d(KP_k)$ = {a deterministic multiplier for drilling that depends on KP_k}
bhr = {the historic borehole rate in the region, a parameter}.

The random variable that is the drilling rate per 10,000 years can be expressed as the product:

$$\text{drilling rate} = bhr * D_m(T_i, VM_l) * m_d(KP_k). \qquad \text{(IV-1)}$$

Because D_m is a random variable and the conditions VM_l and KP_k have probability distributions that are, in turn, dependent on other conditions such as the state of technology, the distribution of D_m is not simple to develop.

As an example, suppose that the value of materials is high (l=1) and knowledge of the WIPP is mythical (k=3). Consider the determination of the drilling rate for given VM_1 and KP_3. The value of $m_d(KP_k)$ is then 0.60. In contrast, $D_m(T_i, VM_l)$ is a random variable that has the distribution shown in Table IV-12 when the value of materials is high. This distribution was created to span the range from 0.25 to 4 and have a mean of 1. The distribution is discrete rather than continuous, so that it can be accommodated by the InDia software.

TABLE IV-12. BOSTON TEAM - RANDOM MULTIPLIER FOR DRILLING

		High Value of Materials			
D_m	0.25	0.50	1.00	2.00	4.00
Prob	0.19	0.19	0.50	0.06	0.06
		Low Value of Materials			
D_m	0.01	0.1	0.25	0.5	
Prob	0.35	0.5	0.075	0.075	

Combining bhr, the historic borehole rate of 83 boreholes per square mile per 10,000 years, with $m_d(KP_k) = 0.6$ and the above distribution for $D_m(T_i, VM_l)$, the conditional distribution for the average number of boreholes per square mile per 10,000 years is obtained, which is shown in Table IV-13.

TABLE IV-13. BOSTON TEAM - CONDITIONAL DISTRIBUTION FOR THE AVERAGE NUMBER OF BOREHOLES PER SQUARE MILE PER 10,000 YEARS (FOR GIVEN EXAMPLE)

$bhr*D_m*m_d$	12.45	24.9	49.8	99.6	199.2
Prob	0.19	0.19	0.5	0.06	0.06

The probability of the conditions of the above distribution is obtained in the following manner. Considering only the near future time period, the probability of both high material values and mythical knowledge of the WIPP is derived from the state of technology in the following manner:

$$P(KP_3, VM_1) = \sum_{j=1}^{3} P(KP_3 | ST_j)\ P(VM_1)\ P(ST_j) \qquad \text{(IV-2)}$$

$$= (0.05)(0.5125)(0.8) + (0.075)(0.5125)(0.15) + (0.1)(0.5125)(0.05)$$
$$= 0.029$$

where KP_3 symbolizes the state of knowledge "myth," VM_1 symbolizes high value of materials, and the three values of ST_j are high, moderate, and low.

For each of the six sets of conditions, a different distribution for the borehole drilling rate is derived. These conditional distributions are then combined using the probabilities of the conditions. For the borehole drilling rate, the combined distribution is given in Table IV-14.

TABLE IV-14. BOSTON TEAM - DISTRIBUTION FOR EXPECTED NUMBER OF BOREHOLES PER SQUARE MILE PER 10,000 YEARS

Number of Boreholes	Probability		
	0-300 Years	300-3,000 Years	3,000-10,000 Years
0.498	0.153	0	0
0.83	0.022	0	0
4.98	0.218	0	0
8.3	0.032	0	0
12.45	0.116	0	0
20.75	0.017	0	0
24.9	0.116	0	0
41.5	0.017	0	0
49.8	0.218	0	0
83	0.032	0	0
99.6	0.026	0	0
166	0.004	0	0
199.2	0.026	0	0
332	0.003	0	0

In the intermediate and far futures, drilling is not apt to occur, and thus the drilling rate is set at zero.

The method of recombining the probability assessments for each of the other modes of intrusion is similar. The underlying factors may vary, however, and the exact form of the decomposition will vary. Influence diagrams for each of the other modes of intrusion are given in Figures IV-2 through IV-6. The recombined distributions for each mode of intrusion and time period are given in the following sections.

Reopening the WIPP for Additional Storage

The structure for intrusions from expansions of the WIPP to increase storage is shown in Figure IV-2. For each of the three time periods, standard conditional probability calculations yield probabilities of no expansion of 0.577, 0.930, and 0.946, respectively. If there are one or more expansions, then the distribution of the number of expansions is given as a uniform distribution on the integers 1 through 10, which is, in turn, modified by the multiplier that reflects the influence of knowledge of the past. Rather than applying the multiplier to each of the integers directly, we have chosen to apply the multiplier to the number 10 and create a uniform distribution on the numbers 1 through 10*multiplier. This relationship retains the integer nature

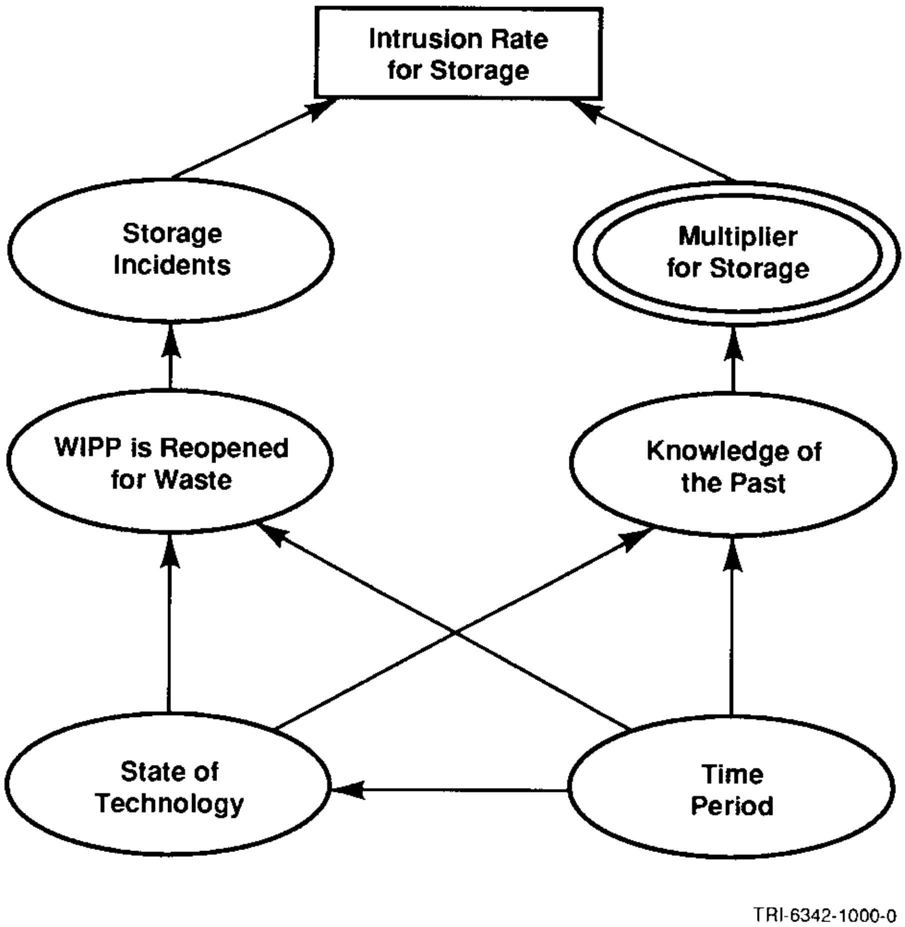


Figure IV-2. Boston Team - Influence Diagram for Expansion of the WIPP.

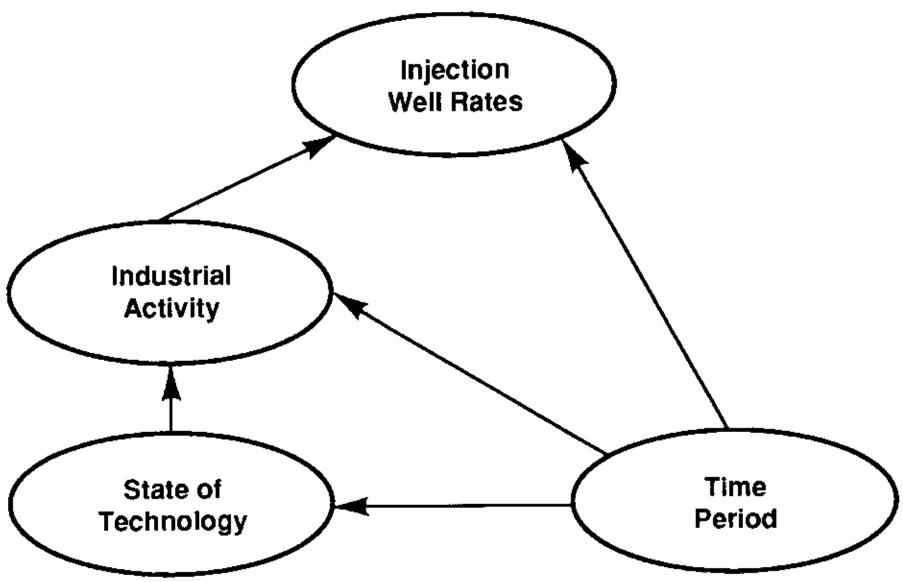
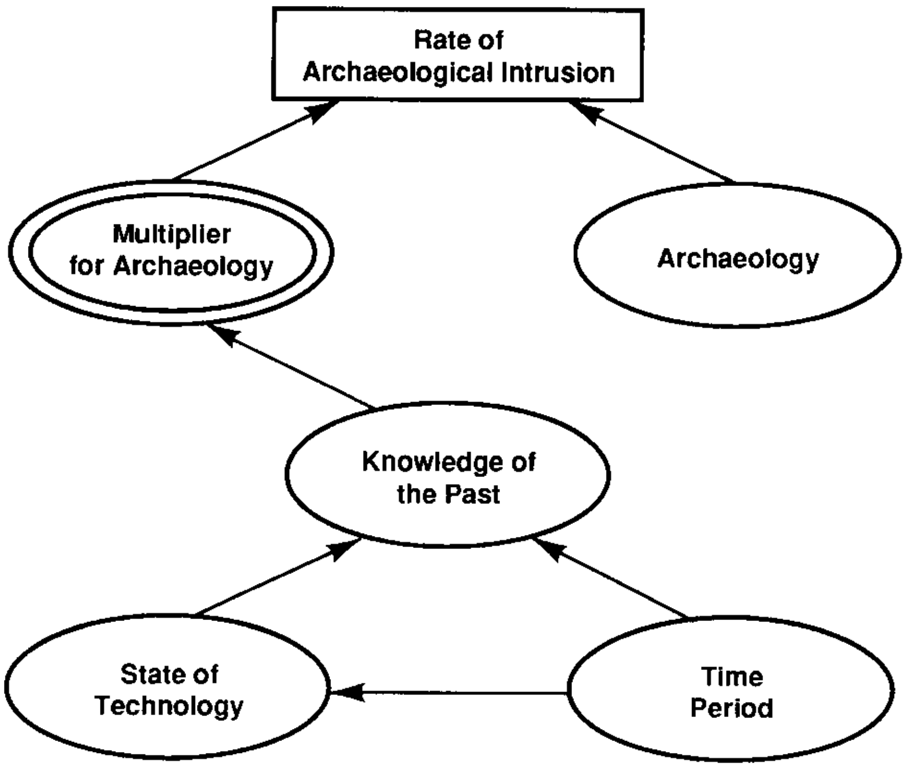


Figure IV-3. Boston Team - Influence Diagram for Disposal by Injection Wells.



TRI-6342-1002-0

Figure IV-4. Boston Team - Influence Diagram for the Rate of Archaeological Investigation.

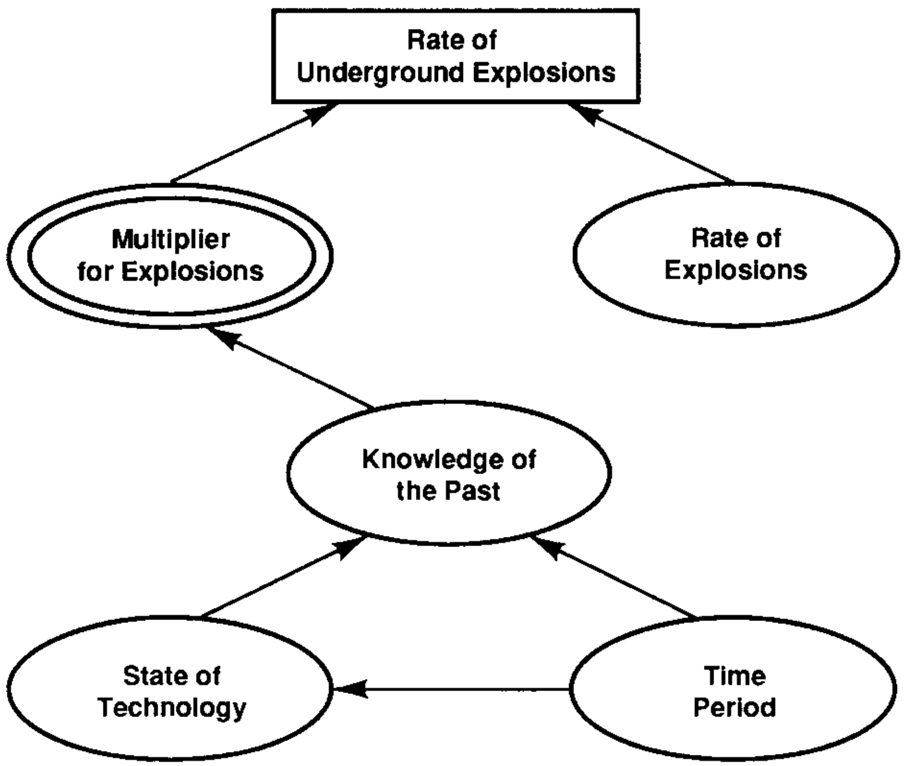


Figure IV-5. Boston Team - Influence Diagram for the Rate of Underground Explosions.

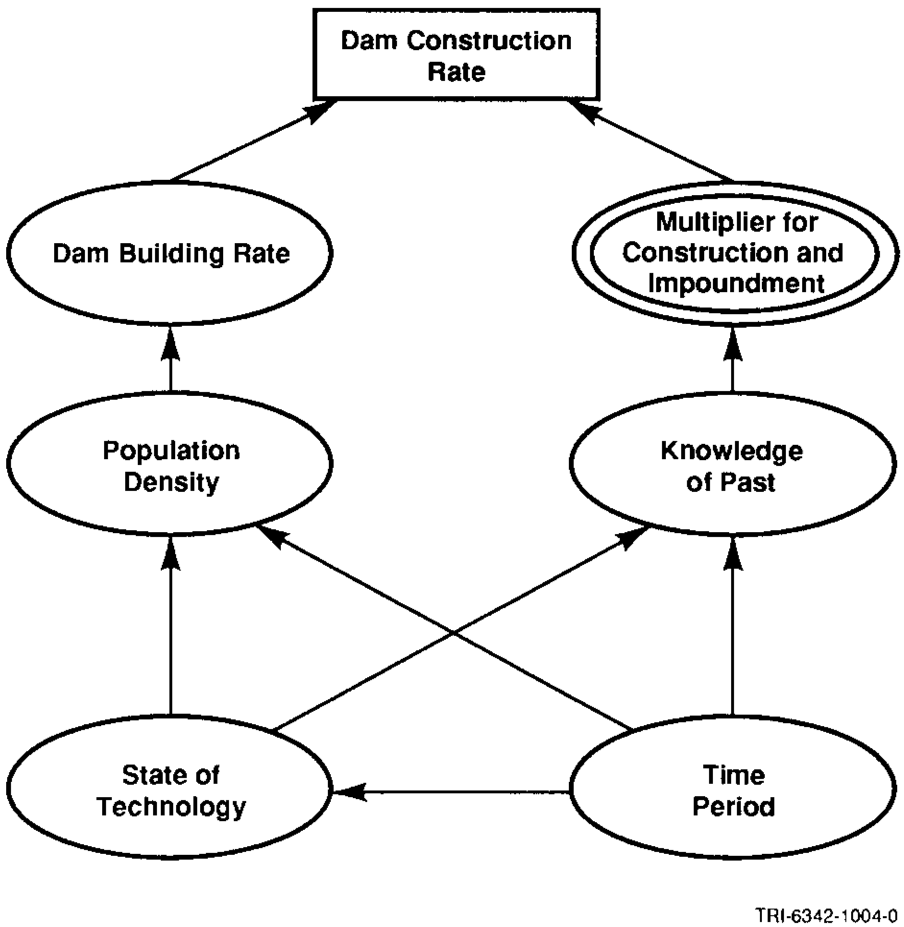


Figure IV-6. Boston Team - Influence Diagram for the Rate of Dam Construction.

of the number of intrusions. For example, if the multiplier is 0.4 (the WIPP is a myth), the distribution of the number of intrusions, given at least one intrusion, is uniform over the integers 1 through 4.

The resulting recompositions for the three time periods are shown in Table IV-15.

TABLE IV-15. BOSTON TEAM - PROBABILITY OF NUMBER OF EXPANSIONS OF THE WIPP WITH RELEASE OF MATERIAL

Number of Expansions	0-300 Years	300-3,000 Years	3,000-10,000 Years
0	0.577	0.930	0.946
1	0.044	0.008	0.008
2	0.044	0.008	0.008
3	0.044	0.008	0.008
4	0.044	0.008	0.008
5	0.037	0.005	0.003
6	0.037	0.005	0.003
7	0.037	0.005	0.003
8	0.037	0.005	0.003
9	0.037	0.005	0.003
10	0.037	0.005	0.003
11	0.002	0.001	0.001
12	0.002	0.001	0.001
13	0.002	0.001	0.001
14	0.002	0.001	0.001
15	0.002	0.001	0.001
16	0.002	0.001	0.001
17	0.002	0.001	0.001

Each expansion does not necessarily generate an intrusion. The assessed probability that any given expansion will generate an intrusion into the previously stored waste is 0.01. If this mode is to be studied further, it will be necessary to generate the number of expansions per time period and then generate binary random variables to determine if each expansion has resulted in an intrusion.

Waste Injection Wells

The rate of creation of waste injection wells is dependent on the time period and the level of industrial activity. In turn, the level of industrial activity is dependent upon both the time period and the state of technology. Three resulting distributions were obtained for the rate of injection well creation per square mile per 1,000 years. The distributions are shown in Table IV-16.

TABLE IV-16. BOSTON TEAM - DISTRIBUTION FOR EXPECTED NUMBER OF INJECTION WELLS PER SQUARE MILE PER 1,000 YEARS

	Probability		
Number of Injection Wells	100-300 Years	300-3,000 Years	3,000-10,000 Years
0	0.161	0.160	0.147
0.001	0.161	0.160	0.147
0.01	0	0	0.186
0.05	0.161	0	0
0.1	0.345	0.173	0
0.5	0	0.160	0
1.0	0.172	0.173	0
2.0	0	0.174	0.186
5.0	0	0	0.147
10.0	0	0	0.187

The means of the three distributions are 0.21, 0.62, and 2.9 wells per square mile per 1,000 years in the near, intermediate, and far periods, respectively.

Archaeological Investigation

The rate of archaeological investigation is tied to knowledge of the WIPP. Total memory and total loss of memory will decrease the rate of investigation, while partial memory or myth will enhance the rate of intrusion. The influence diagram in Figure IV-4 shows the relationship of knowledge of the past to the rate of archaeological investigation. The distribution of the expected number of archaeological intrusions was given to be between 0.1 and 4 with a mean of about 1.0 per 1,000 years. This rate, unmodified by knowledge of WIPP, was modeled as follows:

Expected Intrusions	0.10	0.50	1.00	2.00	4.00
Probability	0.25	0.40	0.20	0.10	0.05

Analysis of the structure yields the following probability distribution for the rate of archaeological investigation at the WIPP. The rate is given in terms of the expected number of investigations per 1,000 years (Table IV-17).

TABLE IV-17. BOSTON TEAM - DISTRIBUTION FOR EXPECTED NUMBER OF ARCHAEOLOGICAL INVESTIGATIONS PER 1,000 YEARS

	Probability		
Expected Number of Investigations	100 to 300 Years	300 to 3000 Years	3000 to 10,000 Years
0.002	0.032	0.058	0.098
0.010	0.051	0.092	0.156
0.020	0.026	0.046	0.078
0.025	0.183	0.104	0.068
0.040	0.013	0.023	0.039
0.080	0.006	0.012	0.020
0.100	0.035	0.089	0.084
0.125	0.293	0.166	0.109
0.250	0.146	0.083	0.055
0.500	0.129	0.183	0.162
1.00	0.065	0.092	0.081
2.00	0.014	0.035	0.034
4.00	0.007	0.018	0.017

The means of the distributions for the intrusion rate for the three periods are 0.27, 0.38, and 0.34 investigations per 1,000 years in the near, intermediate, and far periods, respectively.

Explosions

Weapons testing in the WIPP area might be undertaken in the future presumably because of pre-existing radioactive contamination. This possibility will only occur, however, if precise knowledge of the WIPP is maintained. During the near, intermediate, and far futures, the probabilities of no testing are 0.269, 0.585, and 0.728, respectively. If testing is undertaken, the number of tests per 10,000 years was assessed as being between 0.01 and 10. A log uniform distribution (uniform in the exponents) might be used to generate the testing rate. The rate can be low enough that no tests will occur during a 10,000-year period.

Water Impoundment (Dams)

The elicitation structure for water impoundment is shown in Figure IV-6. The underlying factors include population, knowledge of the past, and, indirectly, the level of technology. Table IV-18 displays the mean dam building rate (mean number of dams per 10,000 years) for each of the three time periods. While a single rate was assessed for the low and high population cases, the application of multipliers increases or decreases the rate, in most cases resulting in different rates for the three time periods. The distribution of the number of dams (per 10,000 years) should be constructed from the mean rate by doubling the mean rate and creating a uniform distribution from zero to twice the mean rate.

TABLE IV-18. BOSTON TEAM - DISTRIBUTION FOR EXPECTED NUMBER OF DAMS CONSTRUCTED PER 10,000 YEARS

	Probability		
Number of Dams	100-300 Years	300-3,000 Years	3,000-10,000 Years
1.25	0.043	0.112	0.079
2.00	0.383	0.234	0.163
2.50	0.041	0.088	0.053
4.00	0.377	0.268	0.234
5.00	0.067	0.128	0.236
8.00	0.027	0.068	0.081
10.00	0.061	0.102	0.155

The expected number of dams in each of the three time periods are 3.6, 4.1, and 4.9 dams per 10,000 years, respectively.

Southwest Team

APPROACH AND DECOMPOSITION

In their own paper, the members of the Southwest Team state: "Our team is varied: An astrophysicist who also writes science fiction, a decision analyst, a physical scientist turned social scientist, and a geographer" (Appendix D, p. D-6). In spite of this diversity, the team members agreed on the basic approach to the problem, the set of futures, and a decomposition that facilitated the assessment of the probabilities in response to the questions raised in the Issue Statement.

The team members examined a variety of environmental and socioeconomic factors that are relevant for distinguishing whether inadvertent intrusion may or may not occur. They considered environmental changes (seismic activity, increased moisture, increased vegetative density, and increased soil fertility) and concluded that these changes would merely be contributing factors either to facilitating intrusion (seismic activity--disrupting the existing geology/hydrology to allow greater transport of radionuclides) or to the consequences of intrusion (increased population due to increased moisture, vegetative density, and soil fertility). They examined in some detail the following socioeconomic factors:

economics,
water availability,
population change,
technological influences,
memory loss,
altered political control,
communication changes,
facility management.

Based on a qualitative assessment of the probabilities of inadvertent intrusion for different states in each of the environmental and socioeconomic factors, the team members concluded that the following alternative futures represent the key factors that would make a difference to the probability of intrusion:

steady increase:	technology continues to increase,
steady decline:	society stagnates and reverses,
seesaw pattern:	technology cycles through declines and upward swings,
alteration of political control:	the U.S. loses control over the WIPP,
stasis:	a future in which everything goes right in terms of WIPP being inviolate--many activities must take place.

The authors describe each of these five alternative futures in rich detail (Appendix D), and thus we need not repeat these descriptions here. Noteworthy, however, is the qualitative description of the stasis future that leads to the conclusion that many things need to go "right" in this future, and that therefore the joint probability of the stasis future is small. This future was not evaluated mathematically. In addition, the authors seem to consider the probability of altered political control to be high, and it is discussed further in this section.

The Southwest Team arranged the five futures presented previously to represent mutually exclusive and exhaustive cases through the use of the event tree in Figure IV-7. The first three futures listed above are basically variants of social and technological development patterns. The fourth is an example of several possible variants (e.g., U.S. maintains control, control is passed back and forth between U.S. and other countries, and a superordinate government containing the U.S. assumes control). The stasis future is a special case of combining the steady-increase and the no-alteration-of-political-control patterns. In Figure IV-7, the first event node is political control, with two possible futures: alteration of political control or U.S. forever. Given the nature of political change and the historical evidence about the longevity of governments, the team members considered the U.S.-forever event to be very unlikely. The team assigned a probability of 0.001 to this alternative future. It is possible that societies could skip among the three technological development patterns and between the two types of political control throughout the study period.

The second event node refers to the state of technological development. The events at this node are the three futures described above: steady increase, steady decline, and seesaw pattern. The team members assigned preliminary conditional probabilities to these three futures as shown. The main difference in these assessments is that the team members considered it more likely that there would be a steady decline if the U.S. maintained political control than if there was altered political control.

By definition, the six resulting futures (paths through the event tree) are mutually exclusive. Also, by interpreting the boundaries of each event broadly, the six futures could be considered as exhaustive for most practical purposes. These conditions facilitated the elicitation of probabilities considerably.

At the end of each path through the event tree, the inadvertent-intrusion node characterizes whether or not there will be an intrusion. The team focused on a single intrusion because they considered more than one intrusion unlikely. The team also assigned probabilities to the events at this node. In general, they considered intrusion most likely in the seesaw pattern and least likely in the case of steady increase and steady decline. The reason for a higher probability in the seesaw pattern was that in this case memory would be lost, but the technology for intrusion is likely to be regained. The reason for the low probabilities in the steady-decline future was that the technology for intrusion would be lost. The reason for the low probability in the steady-increase future was that the ability to detect the wastes and understand their harmfulness would likely exist and prevent inadvertent intrusion.

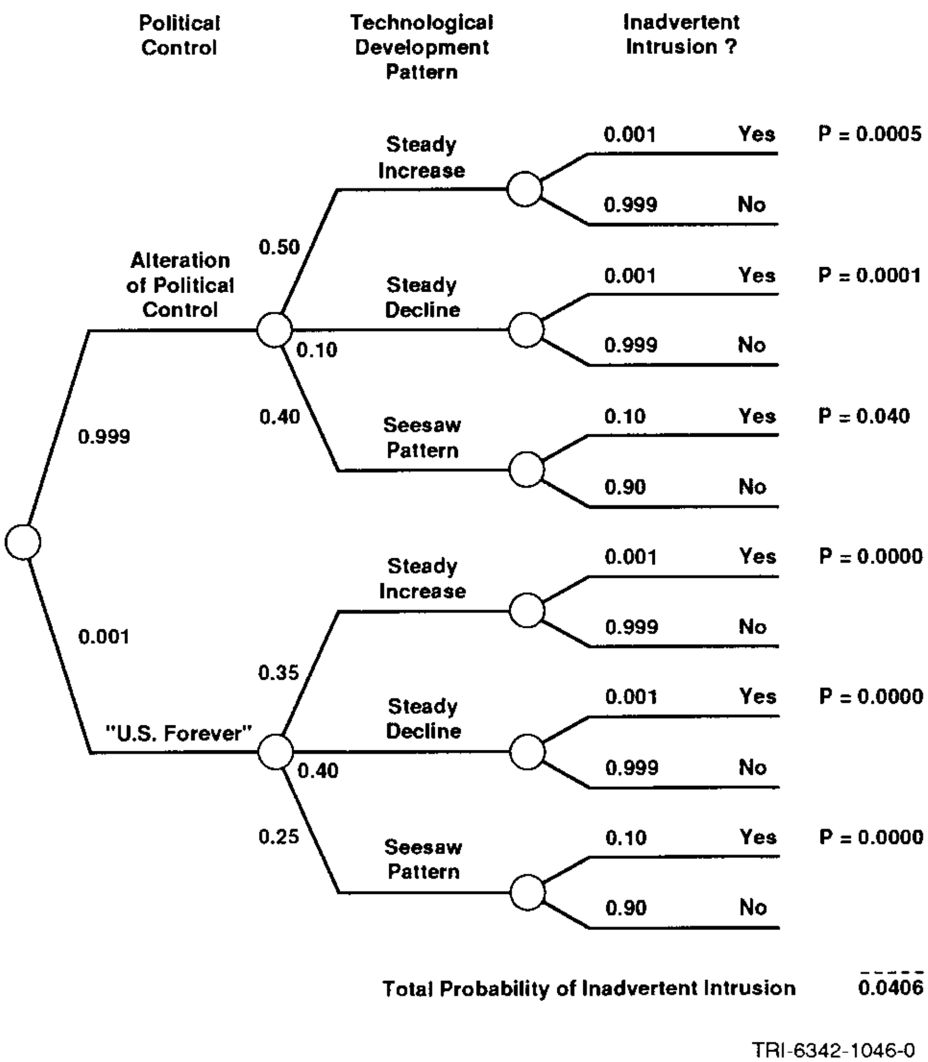


Figure IV-7. Southwest Team - Alternative Futures for Inadvertent Intrusion (Assessments Prior to Elicitation).

Given the structure in Figure IV-7 and their preliminary team assessments, the team arrived at a total probability of inadvertent intrusion of between 1 and 25 percent over the 10,000 years. The actual assessments differed by individual members. By far the largest contributor to this probability was the future that combined altered political control with a seesaw pattern of technological development.

ELICITATION AND RESULTS

The elicitation was fairly straightforward because the team had already defined the alternative futures in the form of an event tree and had assigned preliminary probabilities. The elicitor first discussed the structure of the futures and examined whether the team wanted to be elicited within this structure. After confirming this, he first asked the team members to separately state the 1st, 50th, and 99th fractiles of their subjective probability distribution over the probability of intrusion for the next 10,000 years. The idea was to work backwards from this very intuitive assessment to a more formal one.

Table IV-19 shows the 1st, 50th, and 99th fractiles of the subjective probability distributions over the probability of inadvertent intrusion over 10,000 years for the four team members separately. In addition, the respective group averages are shown. Team member D is the most pessimistic with respect to inadvertent intrusion, giving a median probability of 0.20 and a 99th fractile of 0.80. However, the size of the ranges of the distributions across team members are wide, covering 0.19, 0.27, 0.40, and 0.79, respectively, for the four teams' members.

TABLE IV-19. SOUTHWEST TEAM - INTUITIVE AND CALCULATED OVERALL PROBABILITY JUDGMENTS OF INADVERTENT INTRUSIONS

Team Member	Intuitive			Calculated Median
	1st Fractile	Median	99th Fractile	
A	0.01	0.05	0.20	0.03
B	0.03	0.085	0.30	0.046
C	0.001	0.041	0.40	0.041
D	0.01	0.20	0.80	0.222
Average	0.013	0.094	0.425	0.085

The average for each of the fractiles are shown in the last row of this table. In addition, the last column of the table shows the calculated medians, based on the decomposed judgments described below. The intuitive and calculated medians are compared to ensure that through the decomposition/recomposition process the opinions of the team members are correctly expressed. The first-cut intuitive medians and the calculated medians agree to a considerable extent, both among team members and in the average. This agreement may be due to the fact that team members had previously thought in terms of their decomposition and had made tentative probability judgments as well as calculations within it. Yet, even the team member who deviated from the trend of the others had these deviations clearly represented in the calculated results.

Overall, Table IV-19 indicates probabilities of inadvertent intrusion over the 10,000 years that are large enough that they must be considered in the performance assessment (both the intuitive and the calculated medians just below 0.10). While there is a wide band of uncertainty around this median, none of the team members seemed to think that the chances of intrusion are extremely low.

Next, the elicitor asked each team member separately for the probability of intrusion, given any one of the six possible futures. First, the team members considered the more likely case of altered political control and assigned conditional probabilities of intrusion to each of the three technological development patterns. Subsequently, the same judgments were made for the case of continued U.S. control over the WIPP repository.

Table IV-20 shows the individual results as well as averages. All probabilities should be interpreted as medians of the probability distributions over the probability of intrusion. This table also shows the relative probabilities assigned to the altered-political-control events (0.999) versus the U.S.-political-control event (0.001). These latter probabilities were based on a team consensus and thus were not elicited separately.

To a large extent, the pattern shown in Figure IV-7 (the seesaw technological development pattern contributes the most to the overall probability of intrusion) is repeated here with some interindividual variation. All team members agree that the seesaw future is accompanied by the highest probability of intrusion. There is some disagreement about how much the probability of intrusion decreases for the steady-decline and steady-increase futures, with team member C assuming a considerable reduction in probabilities and the other team members seeing relatively little change. The effect of moving from altered political control to U.S. political control is minor, except for team member D.

TABLE IV-20. SOUTHWEST TEAM - DECOMPOSED JUDGMENTS: PROBABILITY OF INTRUSION GIVEN THE STATE OF POLITICAL CONTROL AND PATTERNS OF TECHNOLOGY

Team Member	Increase	Decline	See-Saw
	Future: Altered Political Control - 0.999		
A	0.010	0.050	0.050
B	0.010	0.100	0.100
C	0.001	0.001	0.100
D	0.060	0.300	0.300
Average	0.020	0.113	0.138
	Future: U.S. Political Control - 0.001		
A	0.010	0.050	0.050
B	0.010	0.120	0.120
C	0.001	0.001	0.100
D	0.020	0.100	0.100
Average	0.010	0.068	0.093

The next task was to assess the probability of occurrence of each of the six mutually exclusive futures. First, the team members each stated the conditional probabilities of each of the three technological development patterns given altered political control. Next, they assigned probabilities to the three technological development patterns given U.S. control. Finally, they assigned probabilities to the two states of political control.

Table IV-21 shows the probabilities of the three technological development futures given the possible states of political control both for each individual and in terms of group averages. The overall pattern, agreed on by all team members, is that the steady-decline future has a relatively lower probability, with the other two futures dividing the major proportion of probability. There is a slight disagreement on which of the two remaining futures (seesaw or steady-increase) is the more likely one. The pattern of responses for the case of U.S. political control is quite similar.

Table IV-22 summarizes the responses to the three questions: When will there be a loss of active controls and markers, what modes of intrusion will occur at what time, and will wastes be rendered harmless? The team was fairly pessimistic with respect to society's ability to maintain active controls and effective markers. Two of the four team members stated that the loss would

TABLE IV-21. SOUTHWEST TEAM - DECOMPOSED JUDGMENTS: PROBABILITY OF PATTERNS OF TECHNOLOGY GIVEN THE STATE OF POLITICAL CONTROL

Team Member	Increase	Decline	See-Saw
	Future: Altered Political Control - 0.999		
A	0.50	0.10	0.40
B	0.60	0.05	0.35
C	0.50	0.10	0.40
D	0.30	0.10	0.60
Average	0.475	0.0875	0.4375
	Future: U.S. Political Control - 0.001		
A	0.67	0.13	0.20
B	0.35	0.40	0.25
C	0.35	0.40	0.25
D	0.30	0.10	0.60
Average	0.4175	0.2575	0.325

TABLE IV-22. SOUTHWEST TEAM - OTHER ASSUMPTIONS AND ESTIMATES

Loss of Active Controls and Markers (All Futures)

A	1,000 years
B	100s years
C	100s years
D	<100 years

Modes and Timing of Intrusion (Consensus)

Increase	Moles; Deep Strip Mining; Nanotech	1,000-2,000 Years
Decline	Conventional Drilling + Excavation	100-500 Years
See-Saw	Conventional Drilling + Excavation	Cycles of 1,000 Years

Wastes Rendered Harmless?

Increase	Yes (0.95-0.99)
Decline	No
See-Saw	No

likely occur within hundreds of years. One team member (A) stated that the controls and markers may last as long as 1,000 years, and one member (D) thought that the loss would occur in less than 100 years. It is probably fair to say that team member A based his judgment on an optimistic view of technology, while team member D based his judgment on a pessimistic assessment of society's cultural and social ability to maintain active control and effective markers at the WIPP. While there was no clear group consensus, it appears that any further analysis should consider the assumption that markers and active controls might be lost in about 100 years. A base case for this group might be 500 years.

ANALYSIS AND AGGREGATION

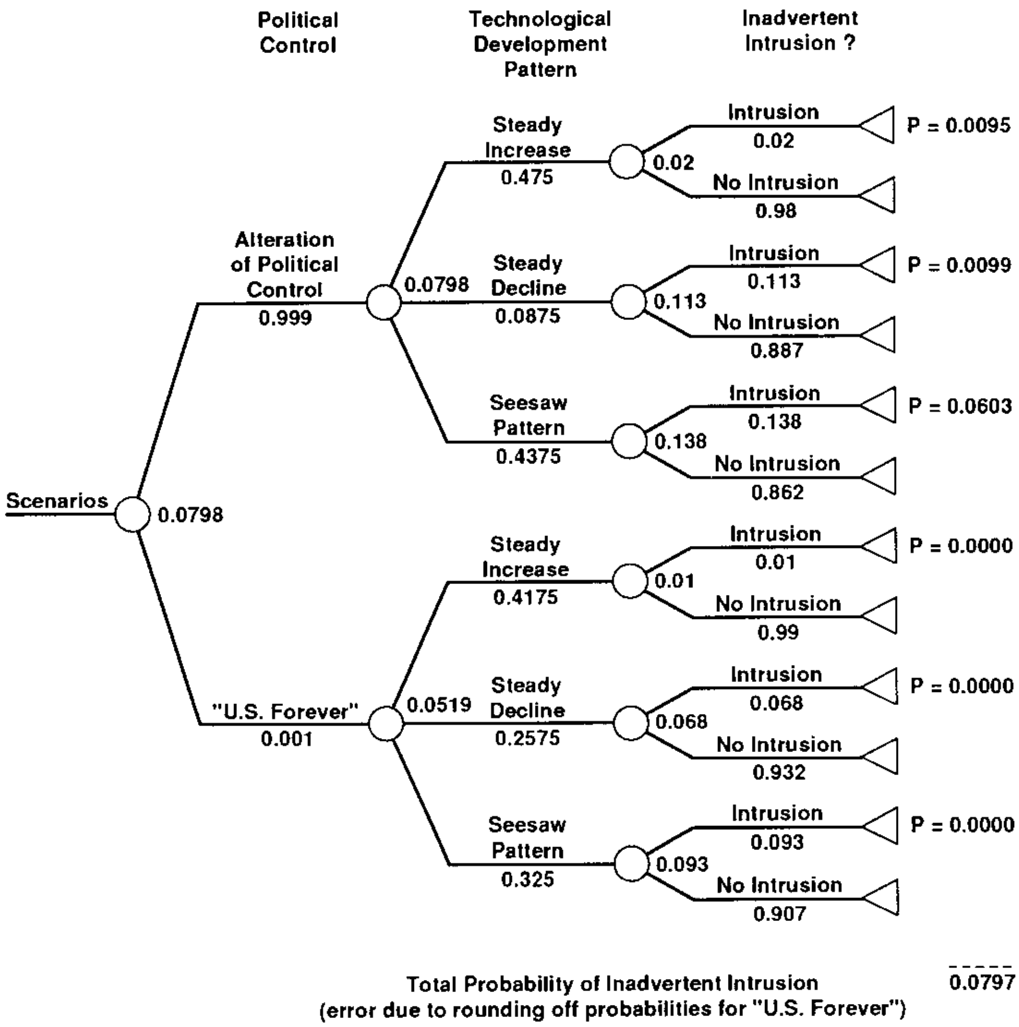
Figure IV-8 reproduces Figure IV-7 with probabilities that were calculated from the decomposed judgments described in Tables IV-20 and IV-21. In all cases, we have inserted the averaged group probabilities and conditional probabilities. As in Figure IV-7, the major contributor to the overall intrusion probability is the seesaw future assuming alteration of political control.

Group consensus was obtained on all other ancillary questions. For the steady-increase future, moles, deep strip-mining, and exotic technologies were considered the prevalent modes of intrusion, and these modes were assumed to lead to intrusion sometime between 500 and 2,000 years. For the steady-decline future, the intrusion modes were thought to be drilling and excavation, with a time frame of 100 to 500 years. For the seesaw future, the modes were again conventional drilling and excavation, occurring in cycles of about 1,000 years.

The team also agreed on the conditional probabilities that the wastes will be rendered harmless (through early detection, treatment, or other mechanisms). This possibility was considered high (0.95-0.99) for the steady-increase future and essentially zero for the other two futures.

CONCLUSIONS

From examining both the team members' intuitive probability judgments and their calculated ones, it is clear that all members consider it moderately likely (medians of 0.03-0.22) that inadvertent intrusion will occur at some time during the 10,000 period after closure of the WIPP repository. While



TRI-6342-1069-0

Figure IV-8. Southwest Team - Alternative Futures and Probabilities for Inadvertent Intrusion (Assessments from Decomposed Judgments). The probabilities are calculated by multiplying the numbers from left to right. The intermediate probabilities located at the circles are calculated by multiplying and summing from right to left.

team members disagreed to some extent (about a factor of 7 in their respective medians), this disagreement was not of orders of magnitude as is often found in this type of probability elicitation.

All team members considered the probability of the U.S. maintaining political control of the WIPP over the long term to be very small (0.001). The results are therefore strongly shaped by their (implicit and--in the decomposition--explicit) assumption that the U.S. loses political control as described, for example, in the alternative future of a "Free State of Chihuahua" (Appendix D, p. D-31). The following comments can therefore concentrate on the case where political control changes.

The main contributor to the overall probability of intrusion is the seesaw future. The reason for the dangers in this future is the belief that memory, markers, and control are lost, while the technology may be regained to intrude. The steady-increase future contributes a small probability, but the potential danger resulting from intrusion is negated by the team's assessment of a high probability that the waste will be rendered harmless by the time this intrusion will occur. The steady-decline future itself is the least probable and carries with it only a one-time possibility for intrusion, presumably after memory and control are lost but while the technology still exists for intrusion. This analysis indicates a total probability of intrusion of about 8 percent over 10,000 years.

As a conclusion, the team itself writes: "The probability of inadvertent intrusion into the WIPP repository over the next ten thousand years lies between one and twenty five percent" (Appendix D, p. D-43). They also observe that there is a high likelihood of altered political control over the next 200 years. Further, following their description of the possible exotic modes of intrusion, they warn of intrusions from all sides of the repository. They point out the possibility that members of future generations may not speak any presently known language.

The team recommends that markers be developed that address these issues, and that a "no-marker" strategy at least be considered as a possibility to deter curiosity seekers. They also recommend that a standing group devoted to further alternative futures analysis and marker development be established.

Washington A Team

APPROACH AND DECOMPOSITION

The Washington A Team began by listing factors that affect the likelihood of human intrusion and subsequently defined several alternative futures that are distinguished with respect to these factors (Appendix E). The list of factors that affect the likelihood of human intrusion includes

(in)-sufficiency of information:
- records that are inadequate,
- records that are inaccessible,
- records that are not understandable,
- records that are ignored,
- lack of understanding of the side effects of activities in spite of records;

ability to intrude;

interactions with the WIPP:
- search for resources,
- unrelated activities near the WIPP (e.g., tunnels, dams).

The team members developed a detailed argument regarding the insufficiency of information about the existence and danger of the WIPP wastes. Essentially they make the point that information inherent in markers or records needs to satisfy many criteria besides physical survivability to be an effective deterrent against intrusion. The information has to maintain its message value (e.g., not deteriorate), remain accessible (e.g., not shelved away in obscure libraries), and be understandable (e.g., readable by generations who may not speak any language known to current civilizations). But even if all these conditions are met, the team members felt that the records may be ignored or their implications for some activities may not be understood. Overall, the team argues that records are very unlikely to be an effective means of discouraging intrusion.

The ability to directly intrude the WIPP repository by technical means such as excavation or drilling is certainly an important factor for assessing the likelihood of intrusion. The team felt that, while there exists a possibility that a future society may lack the ability to intrude the repository, there is a history of society's ability to do so. Moreover, the team members felt that intrusion could also occur by indirect means (e.g., water withdrawal or explosions) that could occur in spite of effective information about the WIPP (Appendix E, p. E-10).

Exploration and development of resources is the most likely type of human interaction with the WIPP, according to this team. However, the team stresses, and the elicitation confirms, the importance of indirect interactions with the WIPP, based on inadequate understanding of how the indirect activity interacts with the wastes in the repository. The team lists several possible interactions: construction of a deep tunnel on route from Texas to California, building a dam, drilling a field of wells, and setting off large explosions (Appendix E, pp. E-11 - E-12).

Knowledge, ability, and type of interactions formed the backdrop against which the team created four alternative futures that, for practical purposes, are considered mutually exclusive and exhaustive. They are listed below and discussed in the following text:

continuity,
radical increase,
discontinuity,
steady-state resources.

The authors note that the future does not necessarily need to follow any of these alternatives exclusively, but may shift among them, perhaps even several times during the 10,000 years considered (Appendix E, p. E-18). For the purpose of the elicitation, the alternative futures were assumed to be mutually exclusive and exhaustive.

The continuity future is essentially an extrapolation of today's growth patterns. Population growth, technology development, and resource exploration and extraction are to grow roughly at a rate that continues past trends. The modes of intrusion would be conventional drilling and excavation. In this future, intrusion could happen at any time, with a greater chance of occurring in the next 200 years.

The radical-increase future assumes that society's willingness and ability to extract resources will grow at a much higher rate than what current extrapolations suggest. The modes of intrusion would include unintentional intrusion by machines that would take over the tasks of exploration and extraction of resources, accidentally drilling tunnels or pipeline ducts through the repository, and conventional drilling and excavation. Intrusion under this future is likely to occur within the next 200 years as the rate and effectiveness of resource extraction increases.

The discontinuity future consists of two sub-futures. One assumes a major war that leads to a demise of western civilization as we know it. The other involves radical political changes, leading to substantial reconfigurations of political power and socioeconomic development in the southwestern region of the United States. In both sub-futures, the main path to intrusion is the loss of knowledge about the WIPP coupled with eventual resource exploration and extraction. The time frame of intrusion would be about 200 years after the major changes (through war or political upheaval) occurred.

The fourth future assumes a reversal in the current trends of resource extraction and consumption. The emphasis of resource development is on steady state rather than growth. Population shows no growth or even negative growth, and energy is produced primarily by use of renewable resources. The authors state that "under such a scenario there would be little pressure to drill for gas or oil at or near the WIPP site, and almost certainly less interest in other possible resources. As long as such values prevailed, the likelihood of inadvertent intrusion at WIPP would be minimized" (Appendix E, pp. E-29 - E-30). However, intrusion by indirect means (a dam or well field for example) could still occur.

With the exception of the discontinuity future, these alternative futures are largely driven by the prevailing societal value system regarding growth and resource use and the political will to implement these values. The continuity future is characterized by a "value system which postulates that the resources of the earth exist to be developed by man as soon and as completely as possible with relatively little respect paid to environmental constraints" (Appendix E, p. E-19). The radical-increase future "postulates a massive increase in our current willingness to use all the earth's resources for human material needs..." (Appendix E, p. E-25). The steady-state future "involves a future in which current attitudes toward the control of nature through technology have been radically altered.... Growth for growth's sake, regardless of the ecological consequences, has been repudiated as a dominant societal ideal" (Appendix E, pp. E-28 - E-29). Thus, the assessment of alternative future probabilities becomes, to some extent, an assessment of future societal values and political will--an exceedingly difficult task.

The Washington A Team had not developed a particular decomposition prior to elicitation, but they had stated modes and timing of intrusion for each future. In the first three alternative futures, a crucial time period was the first 200 years. In the steady-state future, there would be a fairly low probability of intrusion, distributed over the whole time period of 10,000 years. Further, in the continuity and discontinuity futures, the main modes of intrusion would be conventional drilling and excavation for the purposes of resource exploration and extraction. In the radical-increase future, more exotic modes of intrusions like machine intrusion, tunnels, and deep pipelines would be added to conventional drilling and exploration. In the steady-state future, the intrusion would likely come from activities near the WIPP but unrelated to the repository (e.g., from building a dam or from irrigation).

Knowledge of the WIPP and existence of active controls are another important aspect of decomposition. The team members made an important point that knowledge, while perhaps existing somewhere, may not be effective in deterring intruders. Thus, existence of effective knowledge was a major conditioning factor that could radically change the assessed probabilities of intrusion. Three of the four team members were also quite pessimistic about the possibility of maintaining active controls for any period of time, even for 100 years. One member was much more optimistic in this regard, although he felt that this opportunity for long-term active control had to be bought at substantial human costs, possibly affecting human rights and other aspects of the culture and value system of society.

A decomposition that captures the conditioning variables above is shown in Figure IV-9. Clearly, the main variable that determines the probability of intrusion is the nature of society. The four alternative futures were described by the team as time independent, even though they acknowledge that futures can alter and several futures could occur in sequence during the 10,000 years. For simplification, this decomposition as well as the subsequent elicitation will ignore such sequential aspects and assume that these futures are mutually exclusive and exhaustive.

The probabilities of all other events are a function of time. The first event node is characterized by either existence or nonexistence of effective active controls. If active controls exist at a given time, there will be no intrusion. The second event node defines whether effective information about the WIPP exists. If there are no active controls, but if there is effective information, there still may be some chance of intrusion, though this chance would be lower than if there is no effective information. Finally, a chance node defines whether there is intrusion or not given no active controls and effective or no effective information. This decomposition suggests first to assess probabilities for the four futures and subsequently to assess probabilities of active controls, effective information, and intrusion as a function of time and conditional on each future.

The team chose not to address the issue of whether at any given time the wastes might be detected or rendered harmless (e.g., by medical cures of cancer or by processing them on contact). The team members considered this task not to be part of their charter and referred this assessment to the analysis addressing issues related to consequence assessment.

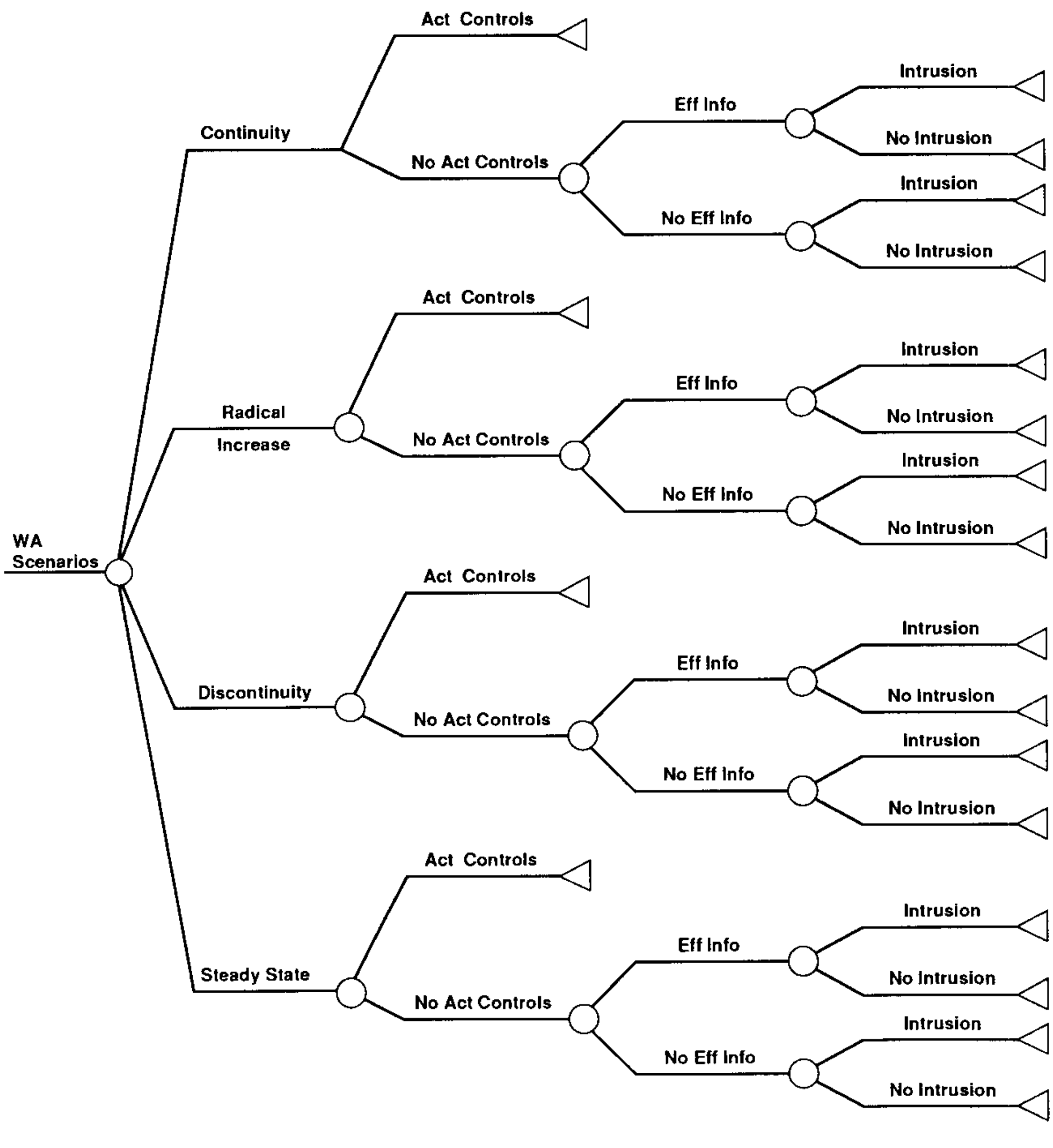


Figure IV-9. Decomposition of the Washington A Team.

ELICITATION AND RESULTS

The decomposition in Figure IV-9 was not available at the beginning of the elicitation session, and the structure represented in that figure only emerged during the elicitation. The main idea of the elicitation was first to obtain rough estimates of the probability of one or more intrusions during the 10,000 years and then to back up these rough estimates with successively detailed decomposed estimates.

The team members first presented their reasoning for the four alternative futures, and they stated individually and separately their rough guesses of the intrusion probability. One member (C) gave the 5th and 95th fractiles in addition to the median. Another member (D) specified the functional form (log-normal) in addition to these two fractiles. Analysis of the data showed that team member D apparently thought that intrusion was much less likely to occur than the other three team members did. Discussion revealed that this team member felt that there was a substantial chance of maintaining active control over the repository for a significant period of time and that his more optimistic view of the low probability of intrusion was based on that assumption.

Table IV-23 shows the team members' elicitation results for the first-cut intuitive judgments of the probability of intrusion over the 10,000-year period. The last column shows the calculated median intrusion probabilities based on the decomposed probability judgments p(future) and p(intrusion|future). The intuitive and calculated medians are compared to ensure that through the decomposition/recomposition process, the opinions of the team members are correctly expressed. This table shows a considerable amount of agreement among team members. Team member D, however, has a distinctly lower median. As he stated, this result was influenced by the fact that he gave significant credence to the effectiveness of active controls. In his decomposed judgments, he had explicitly assumed no active controls, and, therefore, his calculated intrusion probability is much higher.

The first layer of decomposition consisted of determining the probability of intrusion conditional on each future as a function of time, intuitively averaging out other contingencies such as the existence of active controls and effective information. In terms of Figure IV-9, this determination is equivalent to assessing p(intrusion at t|future). Because of the overall sense of the team that most of the intrusions would occur during the first 200 years, this probability was not assessed as a continuous function of time but rather for two time periods: the first 200 years and the following 9,800 years. Each team member gave his judgment separately.

TABLE IV-23. WASHINGTON A TEAM - INTUITIVE AND CALCULATED OVERALL PROBABILITY JUDGMENTS OF INADVERTENT INTRUSIONS

	Intuitive			Calculated Median
Team Member	5th Fractile	Median	95th Fractile	
A	n.a.	0.30-0.50	n.a.	0.37
B	n.a.	almost 0.50	n.a.	0.37
C	0.01	0.30	0.50	0.40
D	0.01	0.07	0.50	0.70

Table IV-24 shows the results of the probability judgments at this layer of decomposition. The probabilities of intrusion over the entire 10,000-year period are the sum of the probabilities of the near and far future and are not time averaged (i.e., there is not a probability per year). For a number of reasons, team member D felt uncomfortable answering the questions regarding the time dependency of futures 1-3, and this lack of response is indicated by a "n.a." Overall, the agreement among the other three members is very good. Clearly, the continuity and the discontinuity futures are responsible for the largest probabilities of intrusion averaged over the entire 10,000 years. These futures are the ones with a high probability of intrusion in the 200-10,000-year time period. The steady-state future has the lowest overall probability and only a 0.01 probability of intrusion within the first 200 years.

Next was the elicitation of the probability of futures, p(future). These probabilities were again assessed individually. First, the elicitor asked for a rank order of the alternative futures and for an estimate of the distribution of the probabilities among the various futures. Subsequently, he asked for point estimates of the probabilities. Table IV-25 shows the elicited probabilities of the four alternative futures, both separately for each team member and for the average. The trend, with the exception of team member D, was to assign higher probabilities to the continuity and steady-state futures and relatively lower probabilities to the other two futures. The main difference was in terms of the degree of optimism about the possibility of achieving a steady-state future. Team members A and B agreed that this possibility was as likely to happen as not (0.50), while the other two team members were increasingly pessimistic.

TABLE IV-24. WASHINGTON A TEAM - DECOMPOSED JUDGMENTS: PROBABILITY OF INTRUSION GIVEN THE ALTERNATIVE FUTURES

Team Member	Continuity	Radical Increase	Discontinuity	Steady State
		Over the Entire 10,000 Years*		
A	0.30	0.89	0.85	0.10
B	0.30	0.89	0.85	0.10
C	0.30	0.60	0.85	0.10
D**	0.50	1.00	0.85	0.10
Average	0.35	0.85	0.85	0.10
		Split up by Time Periods		
0-200 Years***				
A	0.09	0.80	0.43	0.01
B	0.09	0.80	0.43	0.01
C	0.09	0.54	0.43	0.01
D	n.a.	n.a.	n.a.	0.01
200-10,000 Years***				
A	0.21	0.09	0.42	0.09
B	0.21	0.09	0.42	0.09
C	0.21	0.06	0.42	0.09
D	n.a.	n.a.	n.a.	0.09

* The probabilities are the sum of the probabilities from the two time periods and are not time averaged (i.e., there is not a probability per year)

** With no active controls; otherwise much smaller

*** Uniform distribution over years

TABLE IV-25. WASHINGTON A TEAM - DECOMPOSED JUDGMENTS: PROBABILITY OF ALTERNATIVE FUTURES

Team Member	Continuity	Radical Increase	Discontinuity	Steady State
A	0.21	0.18	0.11	0.50
B	0.21	0.18	0.11	0.50
C	0.30	0.25	0.15	0.30
D	0.30	0.30	0.30	0.10
Average	0.255	0.2275	0.1675	0.35

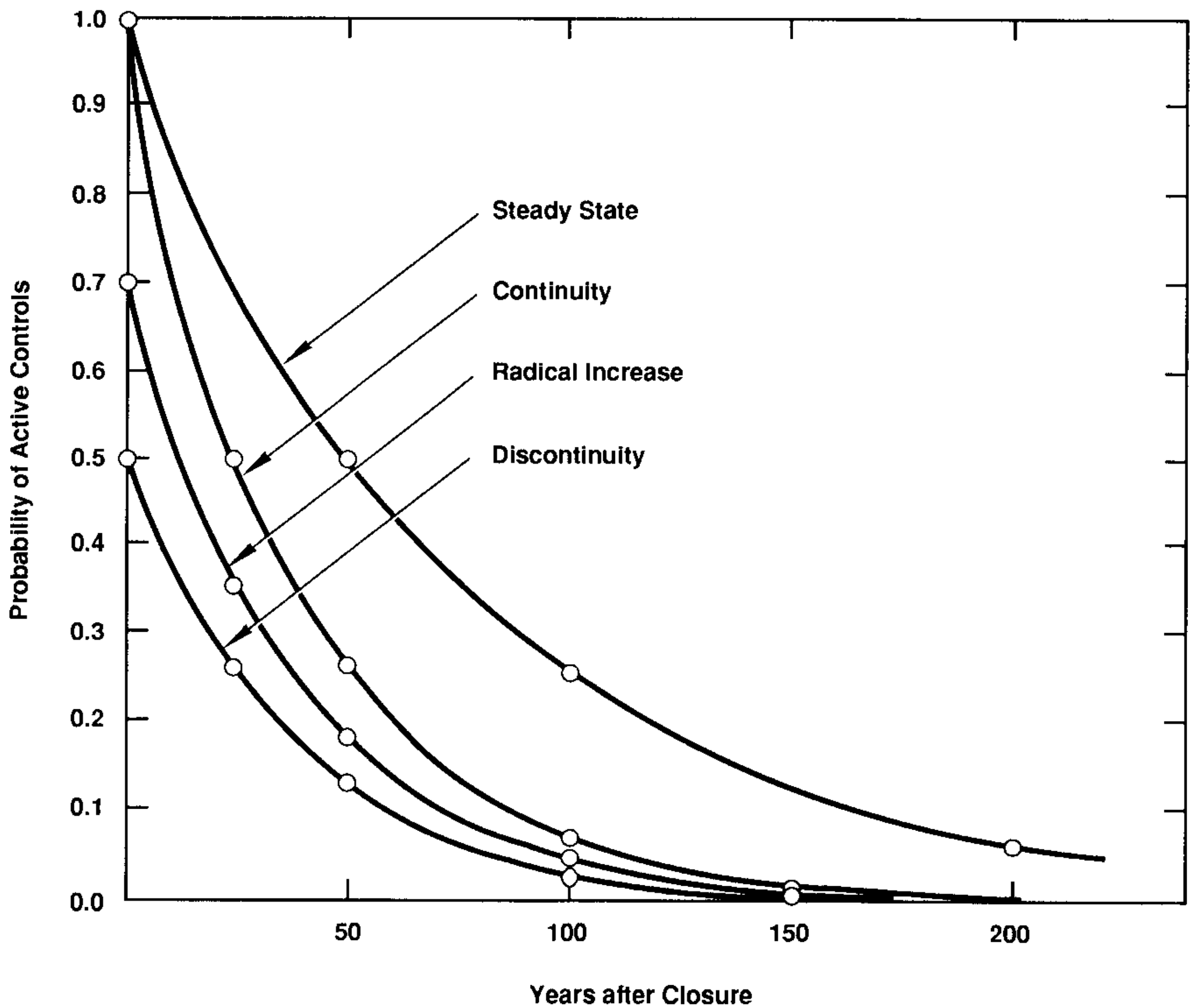
The next task was to estimate the probability of the existence of active controls (AC) as a function of time and the particular alternative future. In other words, the team members individually estimated p(AC at time t|future). All four team members directly stated a functional form that related probability to time. Figure IV-10 shows the plots of probabilities of the existence of effective controls as a function of time and future. The plot labelled continuity indicates the consensus opinion of team members A, B, and C about the probability of the existence of active controls given the continuity future as a function of time. Specifically, the team members felt that this function should be exponentially decreasing, with a halving period of 25 years between 0 and 200 years. They also asked the elicitor to fit the curve to go through about 0.03 at year 200. Applying the rule of "halving" the function yielded a functional form of $y=(0.5)^{x/25}$, which has an ordinate of 0.004 at 200 years. Because this was close enough to the intended value (indicating that at 200 years the probability was extremely small), we used this function for analytical purposes.

These three team members also stated that the shape of the function would remain the same for the radical-increase future but with the effectiveness of the controls reduced by 0.3, as shown in Figure IV-10. Further, they indicated that the probability of active controls would be even less than that in the discontinuity future but did not specify how much less.

The three team members also reached a consensus regarding the steady-state future. They agreed that in this future in 200 years there would be a 0.10 chance of still having active controls. An exponentially decreasing curve was fitted to go through the 0.10 point and has a halving period of 50 years.

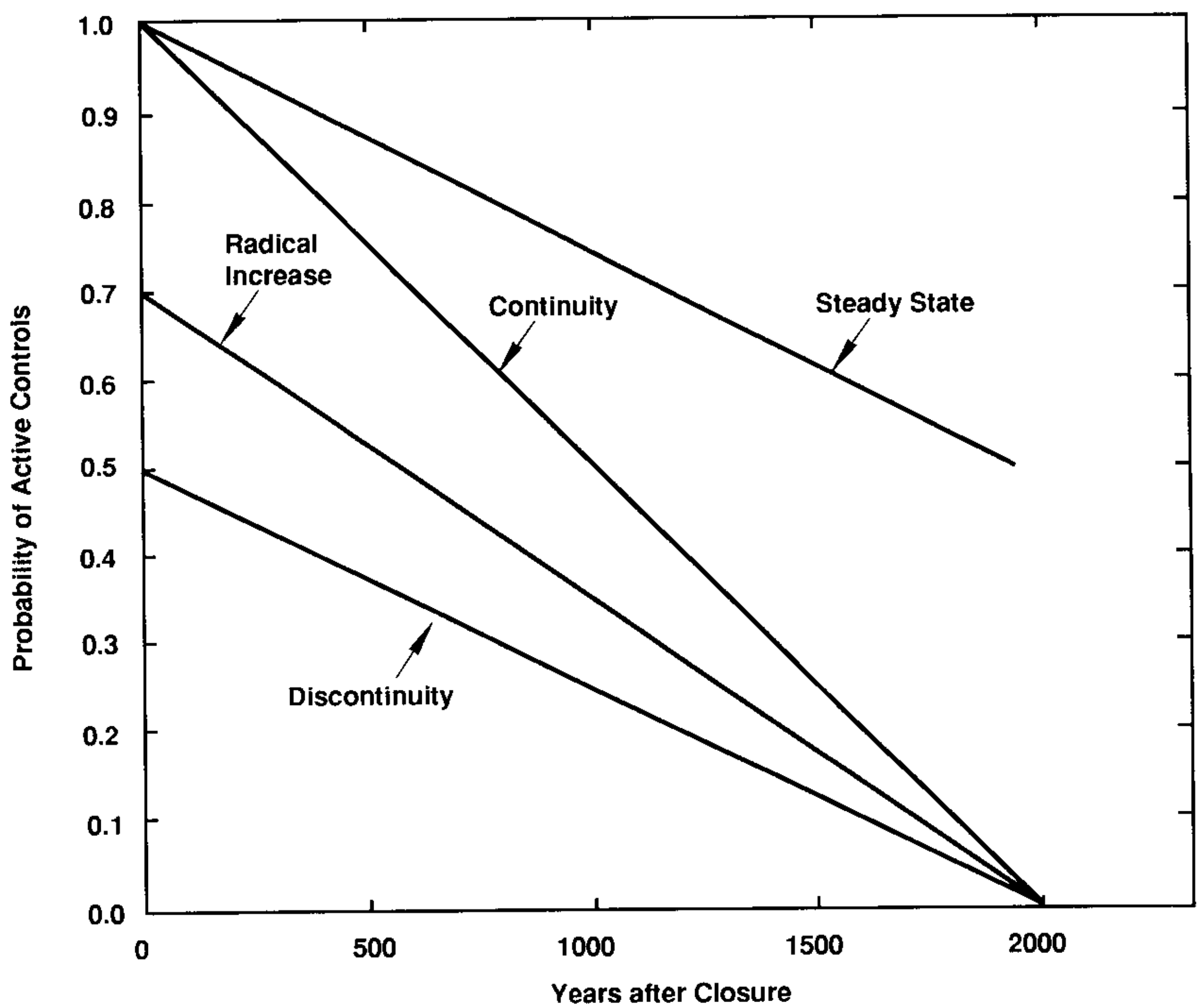
Team member D had a minority opinion, which is shown in Figure IV-11. He felt that the probability of maintaining effective active controls would decrease linearly (rather than exponentially), beginning for the continuity future with 1.00 and going to 0.90 in 200 years and to 0 in 2,000 years (Figure IV-11). He agreed that, in the radical-increase future, the effectiveness part of the active controls curve would be depressed by about 0.30 (Figure IV-11). He also indicated that, in the case of the discontinuity future, the probabilities of maintaining active controls would be even lower. He did not provide any statements regarding the steady-state future, but he obviously considered the chances of maintaining control to be fairly high for this future.

The final task was to estimate the probability of the availability of effective information about the WIPP as a function of future and time. This information was elicited for the first 200 years only because the team members considered it extremely unlikely that such information would exist and be effective in preventing intrusion after 200 years.



TRI-6342-1039-0

Figure IV-10. Washington A Team - Probability of Existing Active Controls as a Function of Time and Future (Team Members A-C).



TRI-6342-1040-0

Figure IV-11. Washington A Team - Probability of Existence of Active Controls as a Function of Time and Future (Team Member D).

The Washington A Team also discussed the existence of effective information about the WIPP as a function of time. The team members felt that, for the continuity and radical-increase futures, the probability is high that the information would exist somewhere during the first 200 years, but much lower that it would be effective in preventing accidental intrusion. For the discontinuity future, the team members indicated that the probability is high that effective information will not survive. For the steady-state future, the team felt that it would be very likely that effective information would remain available throughout the relevant time period. The team members also indicated that, if information exists and is effective, the probability of intrusion would be about half of that without information.

At the end of the session, the team members discussed modes of intrusion and means to prevent it. The team members were in consensus that the main modes of intrusion would be conventional drilling, excavation, and indirect effects. In the steady-state future, the main mode would be indirect effects because there would be much less need for drilling or excavation. For the other possible futures, the main modes would be drilling and excavation.

ANALYSIS AND AGGREGATION

Because the team members did not provide all the information needed for re-composing the tree in Figure IV-9, we made several assumptions for analysis purposes. These results were distributed to the team members and they were asked to review them and report any misstatements. No such comments were received. First, they had only given the exact shapes of the function relating probability of active controls and time for the continuity and radical-increase futures (Figures IV-10 and IV-11). We interpreted their qualitative judgments about the relationship of that curve to the curves for other futures as shown by the remaining plots. When calculating the probability of active controls for the first 200 years, we used the average probability of the respective function. For team members A-C, we assumed that this probability would be essentially zero after the first 200 years.

Similarly, we interpreted the qualitative judgments about the effectiveness of information as a function of time as follows. For the continuity and radical-increase futures, we assumed that the probability of effective information would be 0.5 during the first 200 years and 0 for the remaining 9,800 years. For the discontinuity future, we assumed that the probability of effective information would be 0.10 for the first 200 years and 0 for the remaining 9,800 years. For the steady-state future, we assumed that the probability of effective information would be 0.99 during the first 200 years and 0 thereafter.

Using this information, we could piece together the relevant probabilities required to analyze the tree in Figure IV-9 by using the average probabilities of team members A-C. An analysis was done separately for the first 200 years and for the 9,800 years thereafter because, for team members A-C, the first 200 years had special significance. Figure IV-12 shows the results for the first 200 years. Because the team members were not asked to provide all the conditional probabilities of intrusion, given the possible states of active controls on information, we inferred these conditional intrusion probabilities from their judgments about p(Intrusion|future) and from their statement that the probability of intrusion is twice as high in the case of no effective information compared to the case of effective information. If F is the possible future, AC and NAC stand for active and no active controls respectively, EI and NEI stand for effective and no effective information, and I and NI stand for intrusion and no intrusion, the team members' statements and judgments translate into the following equations:

$$p(I|F) = p(NAC|F)\ p(EI|NAC,F)\ p(I|EI,NAC,F) + p(NAC|F)\ p(NEI|NAC,F)\ p(I|NEI,NAC,F) \qquad \text{(IV-3)}$$

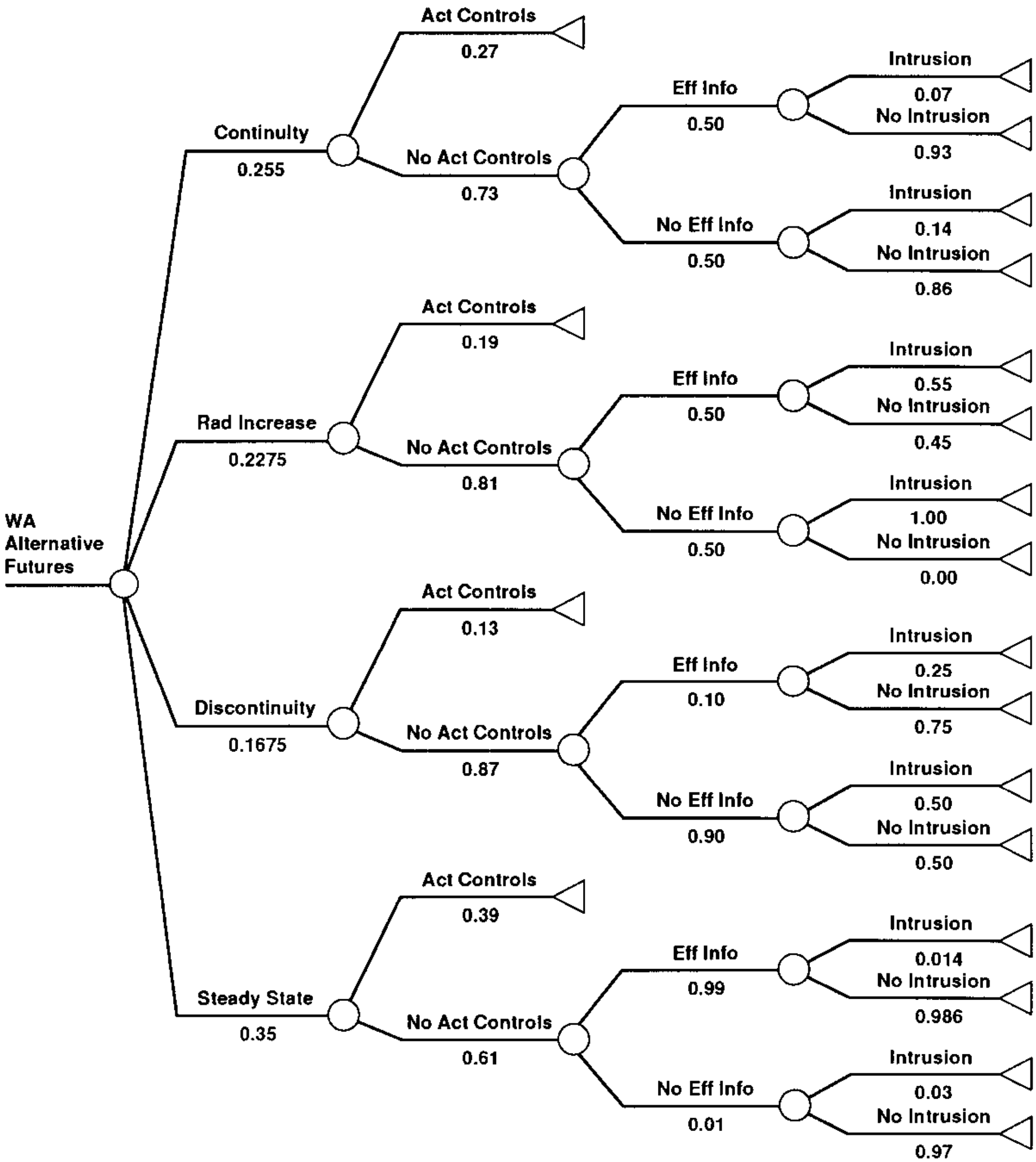
and

$$2p(I|EI,NAC,F) = P(I|NEI,NAC,F). \qquad \text{(IV-4)}$$

Because we have all but the two terms p(I|EI,NAC,F) and p(I|NEI,NAC,F), these two terms can be calculated from the two equations, as shown at the intrusion/no intrusion branches of Figure IV-12.

Figure IV-13 shows the "rolled back" version (showing the intermediate probabilities of intrusion working from intrusion/no intrusion back to the alternative futures) of the tree in Figure IV-12. In it, we designated all intrusion states with a value of 1 and all nonintrusion states with a value of 0. By taking expected values at each node going up the tree, we can determine the probability of intrusion, once that node is reached. Overall, the probability of intrusion during the first 200 years is 0.2346 (the sum of all the intrusion branches). The highest contributors are the radical-increase and the discontinuity futures, with the steady-state future being by far the smallest contributor.

A similar analysis is shown for the following 9,800 years, assuming that the respective probabilities of active controls and of effective information are essentially zero through most of that period (Figures IV-14 and IV-15). The overall probability of intrusion during the later time periods is 0.1736, and the main contributors are the continuity and discontinuity futures.



TRI-6342-1041-0

Figure IV-12. Washington A Team - Decomposed Assessments, Averages of Team Members A-C, First 200 Years.

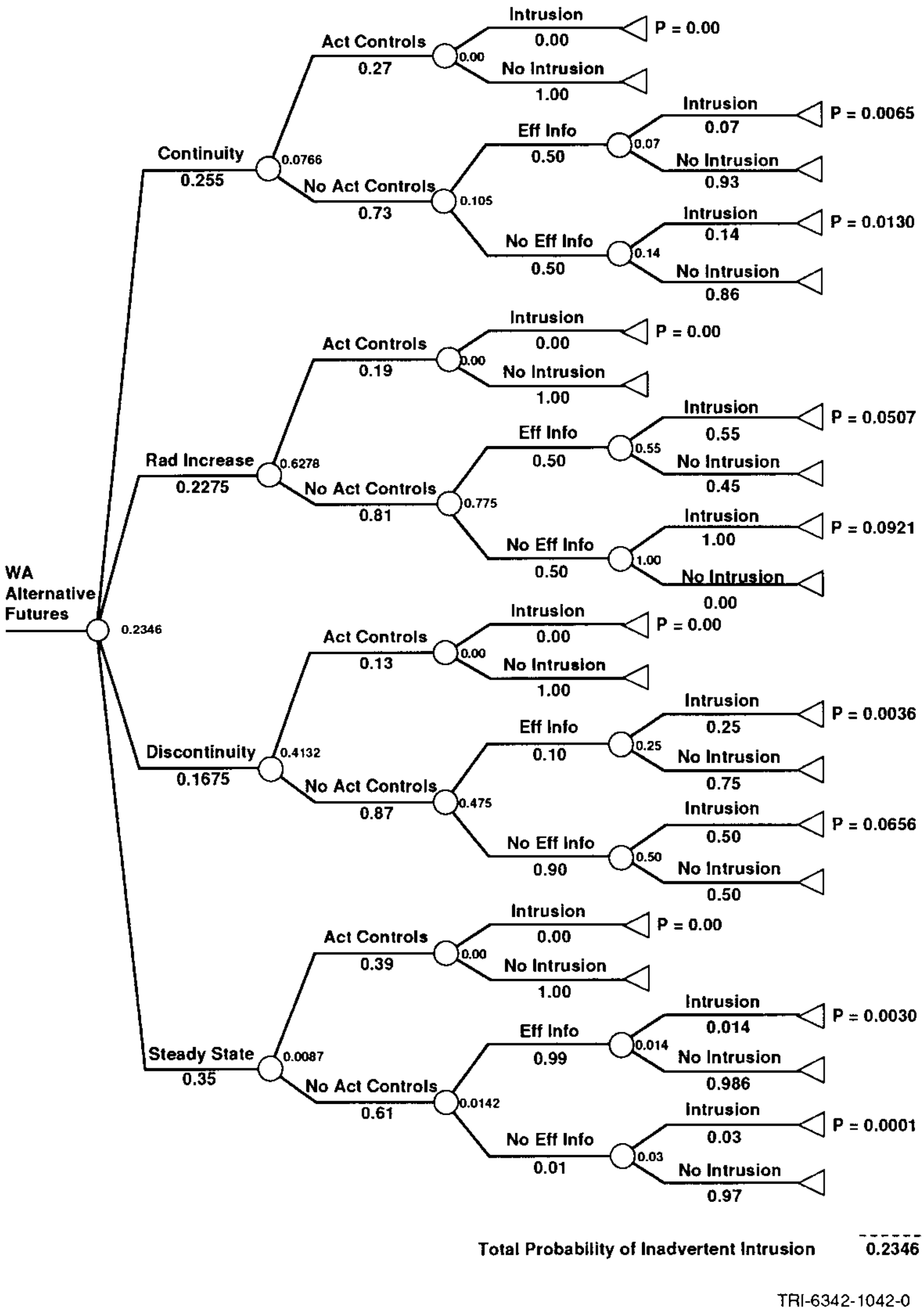


Figure IV-13. Washington A Team - Rolled-back Decomposed Assessments, Averages of Team Members A-C, First 200 Years.

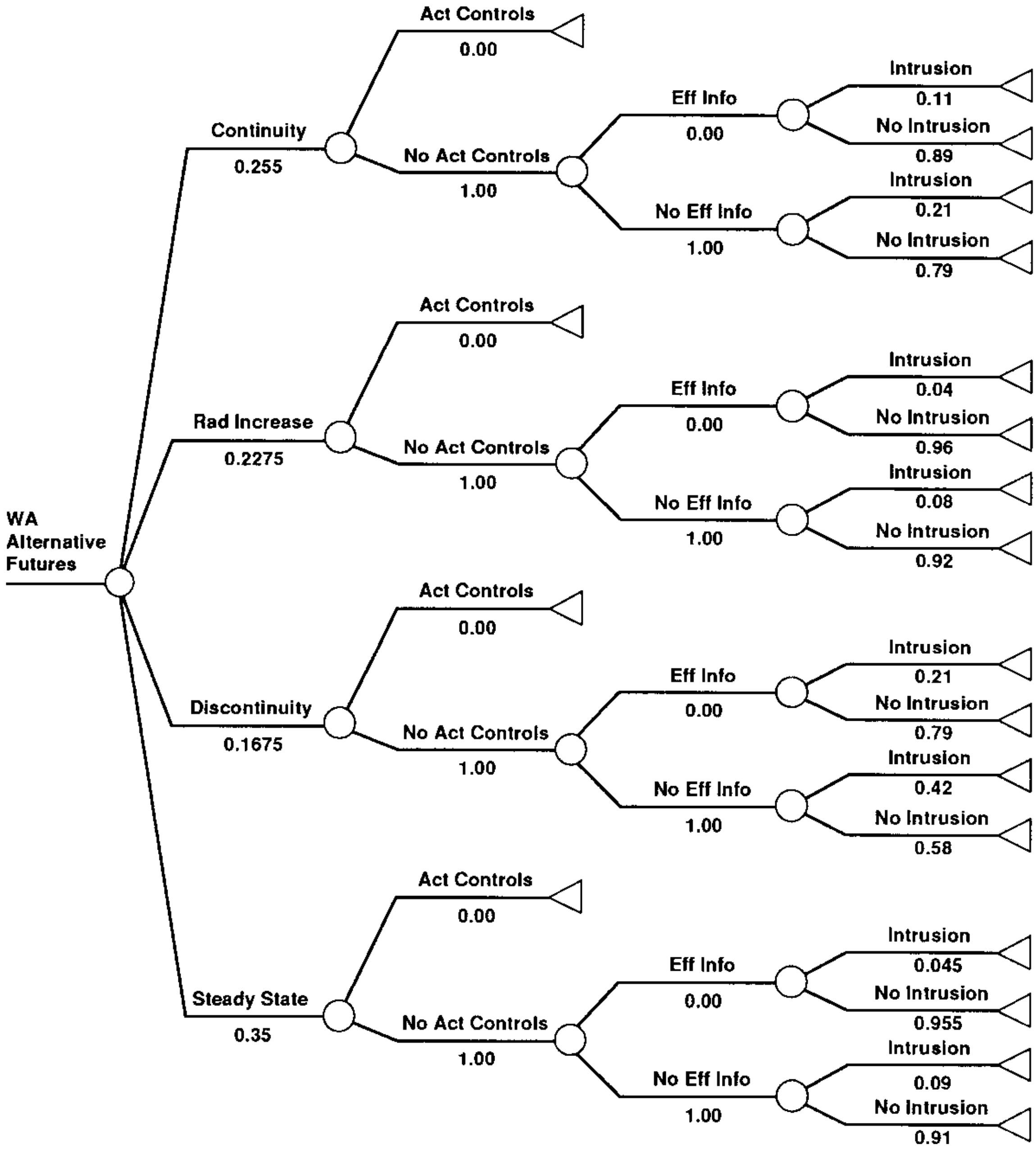


Figure IV-14. Washington A Team - Decomposed Assessments, Averages of Team Members A-C, Next 9,800 Years.

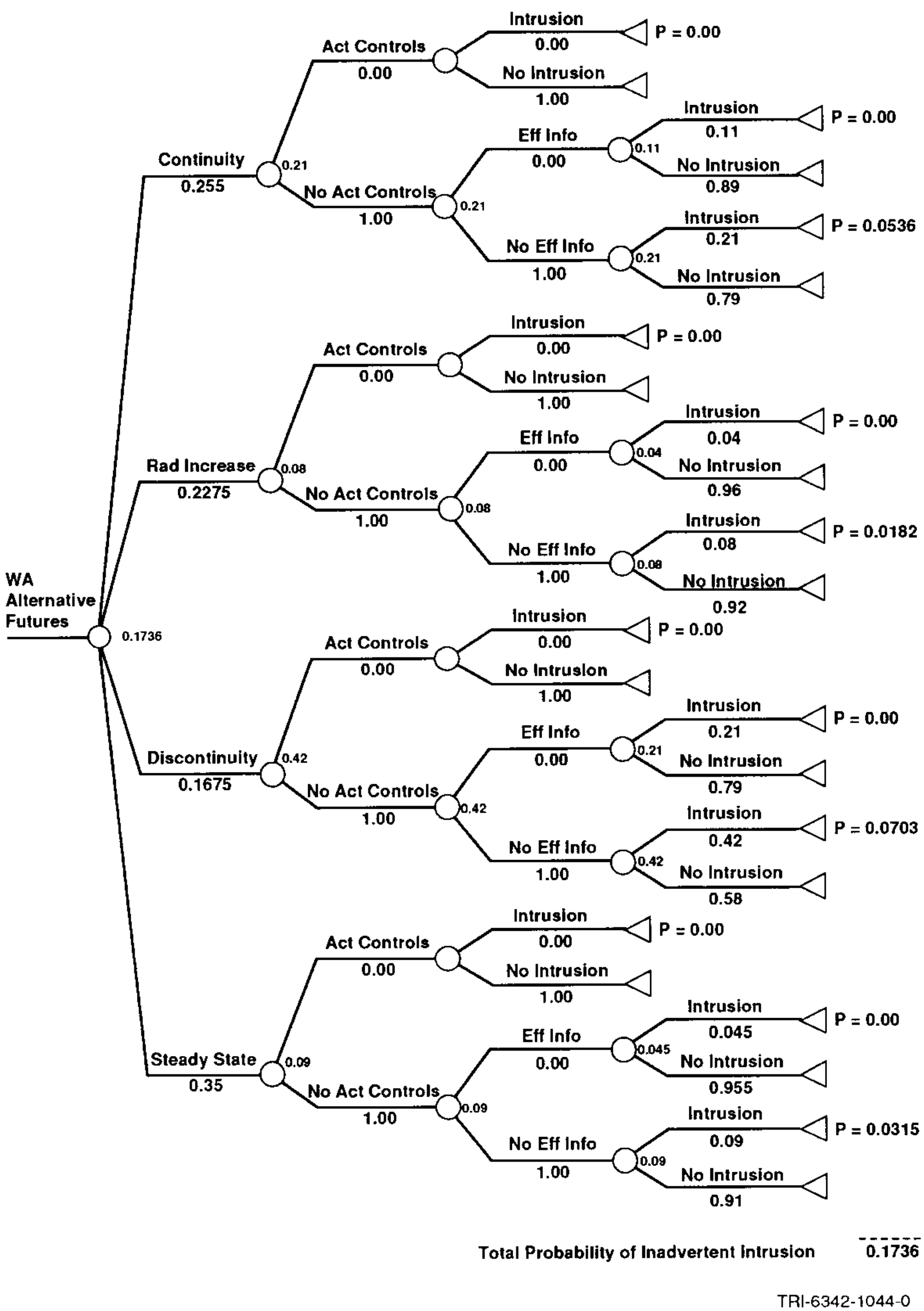


Figure IV-15. Washington A Team - Rolled-back Decomposed Assessments, Averages of Team Members A-C, Next 9,800 Years.

We did not carry out a similar time-dependent analysis for team member D because he did not provide time-dependent information of the probabilities of intrusion. However, it should be clear from his optimistic assessments of the probability of active controls during the first 200 years that he would consider it unlikely that intrusion would occur during those years. Thus, most of his initially assessed probability of intrusion of 0.07 should be attributed to the later years (year 2,000 and after), when he considers it very unlikely that active controls or effective information would exist any more.

CONCLUSIONS

Based on both their intuitive probability judgments and their calculated ones, the team members obviously consider the probability of intrusion moderately likely (0.07-0.50). Three teams members were in agreement that most of this probability is due to events that occur in the non-steady-state futures during the first 200 years after closure (0.2346). Given the nature of these alternative futures and the relative shortness of time to intrusion, the most likely modes considered were conventional drilling, excavation, and indirect effects.

The team members disagreed significantly regarding the probability of the effectiveness of active controls. Three team members (A-C) thought this effectiveness to be very unlikely after 200 years. The other team member gave it a fairly high probability, declining linearly over 2,000 years from 1 to 0. He realized that maintaining active controls would take a significant effort, with possible human and social costs, but he hoped that such control could be achieved as he considered this effort about the only way to avoid intrusion. In fact, without active controls, intrusion became almost an absolute for him under all alternative futures. Because of his optimism about maintaining active controls during the first 200 years, however, he disagreed in his intuitive judgment with the majority of the team by providing a rather low probability of intrusion during that period.

All team members agreed that maintaining active controls would be highly desirable, but they were uncertain about how to achieve that maintenance. They discussed alternative means of preventing intrusion without use of paramilitary controls. One idea was to create long-lived activities above the repository that would maintain effective knowledge as well as physically deter intrusion. Mention was made of a museum about the WIPP and nuclear waste issues.

All members agreed that the best chance to avoid intrusion would be by moving society to the steady-state future. In this future, the probability of intrusion is only about 0.03 in the far future, and the intrusions are most likely to occur from indirect effects rather than from drilling and excavation.

Washington B Team

APPROACH AND DECOMPOSITION

The Washington B Team employed four underlying factors that govern what the future may be like. These factors are the overall level of wealth and technology, the continuance of government control relative to the WIPP system, the climate, and future resource prices. Various levels of each of these four underlying factors were used to develop probabilities for each of the identified modes of intrusion. These modes of intrusion include resource exploration and extraction, drilling of wells for water, scientific investigation, and weather modification. The major factors governing the likelihood of each of the several modes of intrusion are shown in Table IV-26.

TABLE IV-26. WASHINGTON B TEAM - MODES OF INTRUSION AND UNDERLYING FACTORS

Intrusion Mode	Underlying Factors
Resource Exploration and Extraction	Prudent and Effective Government Control Resource Prices
Development of Water Wells	Prudent and Effective Government Control State of Wealth and Technology Climate
Scientific Investigation	Prudent and Effective Government Control
Weather Modification	Prudent and Effective Government Control State of Wealth and Technology Climate

The Washington B Team also considered catastrophic events that might interfere with the development of society and the persistence of knowledge that the likelihood of intrusion could be greatly increased. Such catastrophes include global nuclear war, almost runaway global warming, volcanic eruptions leading to long-term cooling, large-scale meteoric activity, the spread of unknown deadly diseases, and extraterrestrial attack. While each of these catastrophes might profoundly affect the course of society's development, each catastrophe is sufficiently unlikely to occur as to be overshadowed, in a probabilistic sense, by more mundane developments. Thus, although interesting, these events contribute little to the overall probabilities of inadvertent human intrusion.

Resource exploration and extraction was thought to be a relatively near-term phenomena, being completed during the first 500 years if undertaken in the study area at all. Two underlying factors were thought to control the likelihood of such exploration: the continuance of prudent and effective government control and the future level of resource prices. Probability assessments for two periods--the first 200 years after closure and the ensuing 300 years--were obtained under the conditions of rising resource prices and resource prices that are not rising.

The development of water wells in the WIPP area was thought to be possible if the government fails to exercise prudent and effective control, if the state of wealth and technology is high, and if the requisite technology for desalination is available.

Scientific investigation, including archaeological exploration, was treated holistically by the Washington B Team. The probability distribution for the number of attempted intrusions and the probability that an attempt would actually reach the material were both assessed.

The fourth mode of intrusion, the intentional modification of weather to augment rainfall, was assigned probabilities conditional on four factors. The two underlying factors that are shared with some other modes of intrusion are the level of wealth and technology and the presence of prudent and effective government control. In addition, the technology must have been developed for weather modification, and the technology must have been deployed in the WIPP area. Moreover, if the climate in the WIPP region becomes more humid and rainfall increases, there will be no need for weather modification.

PROBABILITY ASSESSMENTS

The Washington B Team provided probability assessments for two time periods, 0-200 years after closure and 200-10,000 years after closure. These time periods are referred to as the near future and far future, respectively. For resource exploration and extraction only, the far future was considered to be 200-500 years after closure, with no boreholes thereafter. The assessments are based on combinations of four underlying factors: a combined factor for wealth and technology, government control, climate, and resource prices.

Wealth and technology takes on one of three levels: high, moderate, or low. The definitions are relative, with today's level of wealth and technology considered to be moderate. In the near future, the probability of low wealth and technology is negligible, while the probabilities of moderate and high wealth and technology are equal. The assessed probabilities for the level of wealth and technology in the near future are shown in Table IV-27, along with probabilities of levels of the other underlying factors.

TABLE IV-27. WASHINGTON B TEAM - PROBABILITIES OF UNDERLYING FACTORS (TABLE IV-26)-NEAR FUTURE (0-200 YEARS)

Factor	Probability
WEALTH AND TECHNOLOGY	
High	0.5
Moderate	0.5
Low	0.0
GOVERNMENT CONTROL	
Prudent and Effective	0.8
Other	0.2
CLIMATE	
Hot and Drier	0.3
Unchanged	0.6
Humid	0.1
RESOURCE PRICES	
Rising	0.7
Not Rising	0.3

Government control is categorized as being either prudent and effective with regard to nuclear waste or not prudent and effective. The third factor, climate, takes on the levels hot and drier, unchanged (similar to today's weather), or humid. The fourth factor, resource prices, can take on one of two levels, rising (meaning more than doubling current levels) or not rising.

Table IV-28 shows the probability assessments for the far future. The descriptions of the factor levels in the far future are similar to those in the near future. The high level of wealth and technology in the far future is akin to the high plus moderate levels in the near future. The "not humid" level for climate in the far future encompasses both hot and drier and unchanged from today as used in the near future.

TABLE IV-28. WASHINGTON B TEAM - PROBABILITIES OF UNDERLYING FACTORS (TABLE IV-26)-FAR FUTURE (200-10,000 YEARS)

Factor	Probability
WEALTH AND TECHNOLOGY	
High	0.9
Not High	0.1
GOVERNMENT CONTROL	
Prudent and Effective	0.33
Other	0.67
CLIMATE	
Humid	0.6
Not Humid	0.4
RESOURCE PRICES	
Rising	0.67
Not Rising	0.33

Resource Exploration and Extraction

The exploration and extraction of resources in the near future is limited to drilling, primarily drilling for natural gas. Other resources are 0.2 to 0.1 times as likely to be exploited, and thus gas exploration dominates in the near future. Other modes of extraction are unlikely to intrude into the repository. Resource exploration and extraction depends upon mineral prices that are most likely to be high during the first 200-year period. Government control, if prudent and effective, will deter mineral exploration within the WIPP land-withdrawal area. This area is defined as the sixteen contiguous sections proposed to be withdrawn from public access.

In the absence of prudent and effective government control, and in the presence of rising resource prices, the probability of drilling for gas is 0.4. If resource prices are not rising, the probability of drilling is 0.2.

Given that drilling is undertaken, the distribution of the average number of wells per square mile was assessed as a triangular distribution on the interval from 0 to 4 with a mean of 2.

In the far future, drilling will not be undertaken if resources have already been removed. Thus, calculation of probability of drilling in the far future requires first calculating the probability that resources are removed during the first 200 years. If resources have not been removed during the first 200 years and there is not prudent and effective government control, the probability of drilling given rising resource prices is 0.4, while the probability of drilling given that resource prices are not rising is 0.2.

If exploration and extraction are undertaken, the average number of wells per square mile is once again represented by a triangular distribution with a mean of 2. Exploration and extraction of minerals will be essentially complete within 500 years.

Water Wells

Agricultural/water development is synonymous with drilling water wells. The drilling of water wells will only occur in the short run if wealth and technology are high, if there is demand for water at the WIPP, and if the technology exists for cost-effective desalination of the ground water. The drilling of water wells over the WIPP repository will occur only if there is a lack of prudent and effective government control. The joint probability that economically viable technology for desalination will be developed in the next 200 years and that demand will exist for water in the WIPP region was assessed as between 0.0001 and 0.001. If water wells are drilled, they will be drilled at a rate sufficient to keep four wells producing per square mile. The team did not have sufficient expertise to assess how often wells would need to be rehabilitated or new wells drilled. For this reason, the team suggested that the technical staff devise an estimate of the drilling rate using the information provided by the team and using other sources.

In the far future, 200 years after closure and beyond, the probability of developing water wells was deemed to be ten times as great as during the near-future period.

Scientific Investigation

The possibility of intrusive scientific inquiry into the WIPP repository in the near future was judged to be negligible. In the far future, with the absence of prudent and effective government control, the rate at which intrusion attempts might occur was assessed. Three team members responded that inadvertent intrusion attempts such as archaeological inquiry would occur at the rate of 1 to 2 attempts per 1,000 years (0.5 probability of 1 attempt and 0.5 probability of 2 attempts). The fourth team member responded that the rate would be 0.5 attempts (probability of 1.0) per 1,000 years. Using this input and assigning 3/4 of the weight to the joint estimates from the three team members, the distributions of probabilities were added to obtain an overall probability distribution of 0.25, 0.375, and 0.375 for intrusion rates of 0.5, 1, and 2 intrusion attempts per 1,000 years.

Each intrusion attempt need not result in reaching the material. The four team members provided a probability of 0.01 to 0.05 that any given attempt will actually reach the material.

Weather Modification

The Washington B Team also identified human modification of the climate as a potential mode of intrusion. Such a modification could result in a 20 to 30 percent increase in rainfall in the WIPP area. The circumstances under which weather modification would occur include high technology and lack of prudent government control. In the near future, the probability that the requisite technology will be developed is 0.2. Moreover, the probability that the technology would be applied at the WIPP is 0.5. In the far future, the probability of developing the technology to modify the climate is between 0.6 and 0.7. Weather modification will not occur, however, if the climate at the WIPP becomes more humid for natural reasons.

EVALUATION OF INTRUSION PROBABILITIES

The probability assessments provided by the Washington B Team were assembled into distributions for various modes of intrusion. For each mode of intrusion, the logic of the assembly and the resulting intrusion distribution are given.

Resource Exploration and Extraction

Resource drilling and exploration in the near future was assumed to depend exclusively upon resource prices. Moreover, drilling above and into the WIPP will not occur if the government retains prudent and effective control.

The probability of drilling is calculated as

$$P(\text{drilling}) = P(\text{drilling}|\text{rising prices})P(\text{rising prices}) + P(\text{drilling}|\text{not rising prices})P(\text{not rising prices}). \quad \text{(IV-5)}$$

Evaluating the above equation gives

$$(0.4)(0.7) + (0.2)(0.3) = 0.34.$$

Drilling above the WIPP can only occur, however, if the government fails to be prudent and effective. The probability of potential intrusion drilling is then

$$P(\text{drilling}) = P(\text{drilling})P(\text{not effective and prudent}) \qquad \text{(IV-6)}$$

$$= (0.34)(0.2) = 0.068.$$

Thus, the probability of no drilling is 1-0.068, or 0.932.

If drilling is undertaken, the average number of wells per square mile per 10,000 years was assessed as a triangular distribution with a mean of 2 and endpoints of 0 and 4. The probability density function for the average number of wells, given there is drilling, is

$$f(x) = \begin{cases} \frac{x}{4} & 0 \le x \le 2 \\ 1 - \frac{x}{4} & 2 < x \le 4. \end{cases}$$

The cumulative probability function, the cdf, is obtained by combining the 0.728 probability of no drilling and the above density. For $x = 0$, where x is the average number of boreholes, $F(0) = 0.932$. For $0 \le x \le 2$, the cumulative probability is

$$0.932 + (1 - 0.932) \int_0^x \frac{y}{4}\, dy \quad 0 \le x \le 2$$

$$= 0.932 + 0.068 \frac{x^2}{8}$$

For $2 < x \le 4$, the cumulative probability is

$$F(x) = 0.932 + (1 - 0.932) \left[\int_0^2 \frac{y}{4}\, dy + \int_2^x 1 - \frac{y}{4}\, dy \right]$$

$$= 0.932 + 0.068 \left[\frac{1}{2} + (x - \frac{x^2}{8} - 2 + \frac{1}{2})\right]$$

$$= 0.932 + 0.068 \left[x - (\frac{x^2}{8}) - 1\right] \quad 2 < x \le 4.$$

The resulting cumulative distribution function (cdf) for the average number of boreholes per square mile, taking into account the probabilities of resource prices and government control, is shown in Table IV-29.

TABLE IV-29. WASHINGTON B TEAM - CUMULATIVE DISTRIBUTION FUNCTION FOR THE AVERAGE NUMBER OF BOREHOLES PER SQUARE MILE PER 10,000 YEARS IN THE NEAR FUTURE (0-200 YEARS)

F(x)	x
0	$x<0$
0.932	$x=0$
$0.932+0.0085x^2$	$0<x\leq 2$
$0.932+0.068[x-(x^2/8)-1]$	$2<x\leq 4$
1	$4<x$

The cdf given above is found by combining a 0.728 probability of no potential intrusion drilling with the triangular distribution for the average number of wells. The mean of this distribution is

$$\text{mean} = (0)(0.728) + (2)(0.272) = 0.544 \text{ boreholes/mile}^2.$$

The probability assessments do not provide the spatial distribution of wells, nor do they provide the temporal distribution other than the drilling is accomplished in the first 200 years after closure.

In the period from 200 to 500 years, drilling will be undertaken only if drilling was not accomplished during the first 200 years. Thus, there is a 1-0.272 = 0.728 probability that the resources are still in the ground. The probability that drilling will be undertaken is then

$$P(\text{drilling}) = P(\text{resource remains})[P(\text{drilling}|\text{rising prices})P(\text{rising prices}) + P(\text{drilling}|\text{not rising prices})P(\text{not rising prices})]. \quad \text{(IV-7)}$$

Evaluating the above equation gives

$$(0.728)[(0.4)(0.67) + (0.2)(0.33)] = 0.243.$$

Once again, drilling above the WIPP will only occur if the government's control is not prudent and effective. Thus, the probability of potentially intrusive drilling is (0.243)(0.2) = 0.0486. As in the case of the near future, if drilling commences, the uncertainty distribution for the average number of boreholes per square mile is triangular with a mean of 2. The resulting cdf is shown in Table IV-30.

As in the near future assessments, the spatial distribution of boreholes is not provided, nor is the temporal distribution other than the drilling is accomplished in the period from 200 to 500 years after closure.

TABLE IV-30. WASHINGTON B TEAM - CUMULATIVE DISTRIBUTION FUNCTION FOR THE AVERAGE NUMBER OF BOREHOLES PER SQUARE MILE PER 10,000 YEARS (200-500 YEARS)

F(x)	x
0	$x<0$
0.9514	$x=0$
$0.9514+0.006075x^2$	$0<x\leq 2$
$0.9514+0.0486[x-(x^2/8)-1]$	$2<x\leq 4$
1	$4<x$

Water Wells

In the near future, the assessment of drilling rates for water wells is based upon the alternative future of economic desalination of water in the WIPP area. Combining the probabilities of high technology, absence of government control, and a continuing dry climate with the probability of economically viable desalination yields

$$\text{P(drilling)} = \text{P(high technology)P(government control not effective and prudent)} \\ \text{P(not humid)P(economically viable)}. \qquad \text{(IV-8)}$$

The last term was assessed by the team as a range of probabilities. Because this quantity is the probability of a single event rather than the probabilities of various frequencies of an event, it will be treated as a single value rather that a range of values. The value chosen is the geometric mean of the endpoints of the range (0.001 and 0.0001). Thus, the probability of drilling is

$$(0.5)(0.2)(0.9)[(0.001)(0.0001)]^{.5} = 0.0000285.$$

The probability of developing water wells is, then, very small. If wells are developed, the Washington B team stated that drilling rate should be assessed as the number of boreholes required to maintain an average of four operating water wells per square mile. The team did not provide such a drilling rate.

It is impossible to complete the cdf for water well development without additional information or assumptions about how long water wells will last, the likelihood of rehabilitating wells, and the need to drill new wells.

In the far future, the team estimated that the development of water wells, given high technology, is ten times more likely than in the near future. Thus,

$$P(\text{drilling}) = P(\text{high technology})P(\text{not effective and prudent})\,P(\text{not humid})P(\text{economically viable}) \qquad \text{(IV-8)}$$

or

$$(0.9)(0.67)(0.4)[(0.01)(0.001)]^{.5} = 0.0007627.$$

Once again, the cdf cannot be obtained without supplementary information. What was provided is an average of four operating wells per square mile as in the case of the near future. Additionally, because the far future extends for nearly 10,000 years, the water resource may become completely extracted at some point in time, and drilling would halt.

Scientific Investigation

Scientific investigation has a very small probability in the near future, which increases in the far future. The rates of intrusion given by the four experts were used to create the following cdf for the average number of attempted intrusions per 1,000 years in the far future (Table IV-31).

TABLE IV-31. WASHINGTON B TEAM - CUMULATIVE DISTRIBUTION FUNCTION FOR THE AVERAGE NUMBER OF ATTEMPTED INVESTIGATIONS PER 1,000 YEARS IN THE FAR FUTURE (200-10,000 YEARS)

F(x)	x
0	$x<0$
0.33	$x=0$
0.5	$0.5 \le x < 1.0$
0.75	$1.0 \le x < 2$
1.0	$2 \le x$

This cdf is equivalent to a 1/3 chance of no intrusions because of prudent and effective government control, a 1/6 chance of a 0.5/1,000-year intrusion rate, a 1/4 chance of a 1/1,000-year intrusion rate, and a 1/4 chance of a 2/1,000-year intrusion rate. Any given attempted intrusion may or may not result in the material being reached. The frequency of intrusion attempts reaching the material was assigned a uniform distribution on the interval [0.01,0.05].

The simulation of intrusions caused by scientific investigation (including archaeological studies) should be accomplished in the following manner. First, generate a uniform random variable on the interval [0.01,0.05]. Denote this random variable by the symbol Y. Next, draw an observation from the distribution F(x) given above. Denote this random variable by X. Using the value of X as the mean of an exponential distribution, generate the times of intrusion attempts from an exponential distribution with a mean of 9.8X. The 9.8 represents the number of millennia in the far future. Denote the intrusion times by $T_1,\ldots,T_M$, where M, the number of intrusion attempts is, itself, a random variable. Finally, generate M values of an indicator (zero-one) variable from a Bernoulli distribution with mean Y. These values are placed in correspondence with the intrusion times. A successful intrusion (one that reaches the material) occurs at each time T_i having a corresponding value of 1.

Weather Modification

The last mode of intrusion identified by the Washington B Team is weather modification. Weather modification can occur under either high or moderate technology. The probability that weather modification technology will be developed during the 200 years after closure is 0.2. Moreover, the probability that the technology will be deployed in the WIPP area is 0.5. The technology will be employed only if government control is not prudent and effective and the climate does not become more humid. The probability of weather modification affecting the WIPP during the next 200 years is then

$$\begin{aligned} &P(\text{weather modification}) = P(\text{high or moderate technology}) \\ &P(\text{not prudent and effective})P(\text{not humid})P(\text{technology is developed}) \\ &P(\text{technology is deployed}) \qquad \text{(IV-9)} \\ &= (1.0)(0.2)(0.9)(0.2)(0.5) = 0.018. \end{aligned}$$

Thus, there is a 0.018 probability that weather modification will be deployed and cause a 20 to 30 percent increase in rainfall at the WIPP during the 200 years after closure.

The analysis for the far future is similar to that for the near future with the exception that if the climate is more humid, weather modification will not be needed. Thus, the probability of weather modification for the far future is calculated as

$$\begin{aligned} &P(\text{weather modification}) = P(\text{not humid})P(\text{high or moderate technology}) \\ &P(\text{not prudent and effective})P(\text{technology is developed}) \\ &P(\text{technology is deployed}) \qquad \text{(IV-10)} \\ &= (0.4)(0.9)(0.67)(0.65)(0.5) = 0.078 \end{aligned}$$

V. CONCLUSIONS

The goals outlined in Chapter I have been achieved through the use of the expert-judgment procedure documented in this report. A nationwide search was undertaken to locate qualified candidates for the expert panel. Government agencies, professional societies, and public interest organizations were solicited for nominations. An established selection criteria based on professional qualifications and diversity of disciplines was used to assemble the final panel. The panel was convened for three days of background information, expert-judgment training, discussion of the issue statement, and a tour of the WIPP. Background information included the topics of the history of the WIPP, the Standard, the performance-assessment process and scenario development, as well as the physical and cultural setting for the WIPP. After a working period, the teams were brought back together to be elicited for their judgments on the modes and probabilities of inadvertent human intrusion into the WIPP. This report documents the collection of these team judgments into coherent statements about future societies, the modes by which they might intrude upon the WIPP, and the probabilities of these intrusions. This report also contains the individual team reports to provide a complete explanation of the results.

The effort undertaken to assess the possible futures of society and how these futures may lead to inadvertent intrusion into radioactive waste repositories has produced a variety of findings--some of which are very speculative. The purpose of the report is to provide an overview of the process and provide quantitative assessments of the likelihoods of various types of inadvertent human intrusion. The report cannot convey the richness and variety of all the findings. Only a careful reading of the four team reports (Appendices C through F) will reveal the many astute thoughts that the sixteen authors have provided. The qualitative appreciations of the future that the team reports provide are, perhaps, the most important contributions of the project.

Clearly, the future may follow many paths--some more desirable than others. Several themes are so pervasive in the views of the future that they should be singled out for attention. First, in the time scale of nuclear waste decay, the continuity and stability of governments are insufficient to provide any assurance that humans will maintain active control of the repositories or be aware of the existence of buried nuclear waste. A second factor that recurs throughout the alternative futures is the rate of technological development and its persistence or lapse. While some may be confident that technology will increase, knowing what path it will follow is difficult. Will cancer be curable and thus nuclear waste less hazardous? Will autonomous robots perform mineral exploration? Will technology replace the human need to read the printed word? While the work of any group of experts cannot possibly define all the possible futures, let alone know which future will come to be, the futures envisioned by the experts involved in this project are sufficiently varied to alert us to the need to consider a very wide range of possibilities when designing markers and barriers to prevent human intrusion into radioactive waste repositories.

The findings of this study have several uses. First, the findings frame the work of the expert group assembled to design and evaluate marker systems for the WIPP. Both qualitative and quantitative aspects of the findings will be useful in the markers endeavor. While it was not specifically a part of their statement of work, two of the four teams comprising the Futures Panel recommended that a "no marker" strategy be considered for the WIPP because markers might draw attention to the WIPP. Second, the findings can be used in the performance and safety assessments for the WIPP. In the performance and safety assessments, the various modes of intrusion and their frequencies of occurrence will be useful. In the following sections, several important aspects of the findings are highlighted and interpreted.

While predicting what the future will be is folly, it is useful to consider what futures are possible. In particular, what might future societies be like in terms of technology, resource utilization and prices, and government control? Because each of the four teams used a different approach in developing their views of the future, it is not possible to provide a simple summary of each of these aspects averaged, in some sense, across the four teams. In the following discussion, the findings of each of the various teams will be emphasized at different times because their contributions bear more directly on each of these aspects of the future.

Technology in Future Societies

Each of the four teams treated technological progress in a somewhat different manner. The Boston Team used technological progress as a fundamental underlying determinant of what the future may be like. Therefore, direct assessments of the future can be found in their analysis. This analysis shows that the most likely future is one where technology is significantly more advanced than today's technology. Roughly speaking, more advanced technology is four times more likely than technology that is not more advanced than today's technology.

The Southwest Team was less sanguine about the future of technology. This team assigned probabilities indicating that growth in technology is as likely as not. In their view, while a continuing decline in technology was unlikely (a 1 in 10 chance), it is possible that technology might be lost and then regained at some time in the future (a 0.4 probability).

Technology was not directly considered by the Washington A Team. Underlying their analysis was resource utilization characterized by either an extrapolation of the increase of today's utilization rates, a radical increase beyond today's utilization rates, a discontinuity in the future, or an environmentally sound world where recycling and renewable resources dominate. In the scenario of abrupt discontinuity, caused either by war or political upheaval and change, it is possible that some technological capability might be lost. This scenario was viewed as relatively less likely and was given approximately a 1 in 6 chance.

Wealth and technology were combined into a single underlying factor by the Washington B Team. Beyond 200 years after closure, significantly greater wealth and more advanced technology are 10 times more likely than not.

Overall, the judgment of the four teams is that continued development of technology is most likely. The probabilities assigned by the various teams to a more advanced technology ranged from 0.5 to 0.9. Excluding the Washington A Team, which did not address technology in a direct manner, the average of the three remaining teams probabilities of more advanced technology in the future is slightly greater than 0.7 in the far future.

Resource Utilization and Resource Prices

Another key factor in human intrusion is the demand for resources in the future. Scenarios with high demand for resources, and resulting higher prices, lead to greater exploration and extraction and, consequently, larger probabilities of inadvertent intrusion. The Boston Team considered resource demand through resource prices that were treated as either being high compared to current prices or low, the same as today's prices or lower. In the near future, 0-300 years after closure, the probabilities of high resource prices assigned by the Boston Team members ranged from 0.3 to 0.75 with an average near 0.5. In the more distant future, the probability of high resource prices assigned by the members ranged from 0.1 to 0.6 with an average of 0.325.

The Southwest Team did not consider resource demand directly in their elicited probabilities, although there is some discussion of resource scarcity in the representative scenarios described in their report. In contrast, the Washington A Team's analysis puts resource demand in a central position. As mentioned in the discussion of technology, the future may bring greater resource extraction rates than those of the current era. The Washington A Team's radical increase scenario was given probabilities ranging from 0.18 to 0.3 while the continuity scenario (extrapolation of current resource extraction activity) was given probabilities ranging from 0.21 to 0.30. Significantly lower resource utilization rates were visualized in the "steady-state" scenario. Probabilities assigned to this scenario range from 0.1 to 0.5 with an average of 0.35, the highest among the four scenarios. The discontinuity scenario, which describes war or political disruption, does not provide specific information about resource utilization patterns. This scenario was judged the least likely by the Washington A Team (probability 0.1675).

The Washington B Team dealt directly with resource prices. A probability of 0.7 was assigned to significantly higher resource prices in the near future and a similar probability, 0.67, was assigned to higher resource prices in the further future.

In summary, the assignments of probabilities to various levels of resource prices suggest that higher prices (or demand as the case may be) are approximately as likely as stable prices. There is, however, substantial variation in the probabilities assigned both by individual team members within teams and average probabilties between teams.

Government Control

Another finding of the four teams is that continued government control of the WIPP system cannot be guaranteed. Again, each team treated the subject in a somewhat different manner. The Boston Team provided probabilities that precise knowledge of the WIPP would be retained, that the location would be known but the purpose of the WIPP unknown, that the WIPP would become a myth, and that all knowledge of the WIPP would be lost. In the far future, the probability assigned to retaining precise knowledge of the WIPP ranges from 0.05 to 0.3125 depending on the level of technology. Societies with high technology are thought to be more likely to retain knowledge of the WIPP.

In contrast, the Southwest Team assessed probabilities of continued U.S. control over the WIPP. The probability assigned to continued U.S. control throughout the performance period was only 0.001. The Washington A Team also was pessimistic about the ability to maintain active control over the WIPP. This team gave the probability of continued control over the WIPP as a decreasing function of time since closure. Three team members believed that continued control was very unlikely after 200 years while the fourth team member believed that control was possible for 2,000 years.

The Washington B Team assigned probabilities that the government would continue to maintain prudent and effective control over the WIPP. The probability of prudent and effective control in the near future was given as 0.8 while in the far future the probability of prudent and effective control falls to 1/3.

Probabilities of Inadvertent Human Intrusion

Summarizing and making comparisons among teams and modes of intrusion is not simple because of the different response modes (probabilities versus rates) and categories of intrusion. In order to make better comparisons of inadvertent human intrusion, Table V-I was constructed using the elicited probabilities and rates of intrusion. Both the Southwest Team and the Washington A Team have provided probabilities of one or more intrusions. In contrast, the Boston Team and the Washington B Team provided probability distributions for rates of intrusion in most cases. Putting these assessments in a form comparable to those of the Southwest and Washington A Teams requires some mathematical manipulation which will be explained.

For example, the Boston Team has provided a probability distribution for the drilling density for hydrocarbon exploration and extraction. This probability distribution is given in Table IV-14. The mean of the expected number of boreholes per square mile per 10,000 years is 28.67 so that during the first 300 years after active controls are relinquished, the expected number of boreholes is 0.86 per square mile. Since the WIPP site has a footprint of approximately 0.2 square miles and 22 percent of the footprint will contain radioactive waste, the expected number of boreholes penetrating radioactive material (a room or drift) is (0.86)(0.2)(0.22) = 0.03784. Assuming that boreholes are drilled in a random manner, both spatially and temporally, the Poisson probability of <u>no</u> boreholes penetrating waste is $e^{-.03784} = 0.963$. The probability of one or more boreholes penetrating waste is then 1-0.963 = 0.037.

Some modes of intrusion may occur in both the near future and the far future. For example, the Washington A Team provides a probability of 0.089 for intrusion through resource exploration and extraction in the near future and a probability of 0.124 in the far future. The probability of one or more intrusions cannot be directly calculated without knowing the joint probability of intrusions in both time periods. If the intrusion in the near future excludes intrusion in the far time period, the probability of one or more intrusions is simply the sum of the probabilities. If, on the other hand, intrusions in the two time periods are independent, then the probability of one or more intrusions is the sum of the probabilities less the product of the probabilities. If intrusions in the two time periods are highly dependent in a positive manner, then the probability of one or more intrusions may be as low as the larger of the two probabilities corresponding to the two time periods.

In Table V-I, we have chosen to give the probability of at least one intrusion over both time periods as though events in the two time periods were independent. This presentation was chosen since it yields values between the

TABLE V-1. APPROXIMATE PROBABILITIES OF ONE OR MORE INTRUSIONS

Team and Mode of Intrusion	Near Future	Far Future	Both Near and Far Future (Union)
Boston			
Drilling			
Hydrocarbons	0.037	0.000	0.037
Injection Wells (3 experts)	(0.003, 0.0004, 0.0006)	(0.288, 0.011, 0.823)	(0.290, 0.011, 0.823)
Archaeology[a,e]	0.002	0.030	0.032
Expansion[b,e]	0.423	0.120	0.492
Underground Tests[b,e]	0.007	0.091	0.097
Dams[c]	0.102	0.989	0.990
Southwest			
Mining[e]	0.000	0.009	0.009
Drilling and Excavation	0.010	0.060	0.069
Washington A			
Resource Exploration and Extraction	0.089	0.124	0.202
Machine Intrusion, Tunneling, etc.[e]	0.143	0.018	0.158
Indirect modes[c]	0.0001	0.031	0.031
Washington B			
Drilling			
Hydrocarbons	0.010	0.000	0.010
Water wells[d]	0.00003	0.0008	0.00083
Archaeological and Scientific[e]	0.000	0.030	0.030
Weather Modification[c]	0.018	0.078	0.095

Footnotes:

a Incomplete information was provided. It is assumed that each intrusion attempt has a .03 chance of reaching radioactive material as per the Washington B Team assessment.

b This mode of intrusion is not considered to be inadvertent.

c This activity does not result in a release to the biosphere.

d Incomplete information was provided. The values provided are upper bounds to the probability of intrusion.

e This mode of intrusion may be more severe than drilling. Modes of intrusion more severe than drilling need not be considered under the guidelines for performance assessment provided in 40 CFR 191.

possible extremes. The time periods shown in Table V-I have varying definitions for the several teams. For the Boston Team, the near future is 0-300 years after the lapse of active controls (100 years after closure.) The Southwest Team used a 100-500 year period after closure for the near future while the Washington A Team used the first 200 years after the lapse of active controls. The Washington B Team also adopted a 200-year definition for the near future.

Several of the modes of intrusion identified by the expert teams are not appropriate for use in the performance assessment for the WIPP. First, some modes of intrusion do not result in releases to the biosphere. Dams, irrigation, and weather modification are examples of human activities that are believed not to affect the WIPP system sufficiently to result in releases to the accessible environment during the 10,000-year performance period. Other activities, such as mining may result in releases that are more severe than those caused by drilling. However, 40 CFR Part 191 specifically provides that intrusion modes more severe than drilling need not be considered in the performance assessment.

The assessment for injection wells was not completed during the elicitation sessions with the Boston Team members. This has resulted in some difficulties in interpreting the results. A letter was sent to the four team members asking them to provide the rate of injection-well drilling in the near-, intermediate-, and far-future time periods. Three team members responded, the fourth was unable to respond due to extended travel. There is great variability among the rates provided and there is an absence of rationales for the judgments. It may be that the drilling rates are conditional on some disposal well activity being present. Moreover, no adjustments were provided for various information states as were provided for other intrusion modes by this team. With these ambivalences in mind, a probability of one or more intrusions into the waste has been calculated for each of the three responding team members. There is less than full confidence that these assessments are of the same quality as other assessments provided by this team, however.

The findings of this report are speculative in nature and provide a view of what <u>may</u> be rather than what <u>will</u> be. While the experts participating in this study have identified many possible modes of intrusion, conceiving of all modes that could occur in the future is not possible. Thus, the analysis is incomplete and must remain so.

The value of the report is that a reasoned approach has been taken in examining the possibility of inadvertent human intrusion. The qualitative findings, including the discussions of government control and the identification of possible modes of intrusion, are perhaps the most valuable contributions of the experts.

The quantitative assessments of intrusions, both probabilities and rates, can be used for the performance and safety analyses of the WIPP system. These probabilities and rates reflect the best judgment of sixteen experts drawn from diverse backgrounds and reflect a very uncertain state of knowledge about the future.

REFERENCES

Bonano, E.J., S.C. Hora, R.L. Keeney, and D. von Winterfeldt. 1990. *Elicitation and Use of Expert Judgment in Performance Assessment for High-Level Radioactive Waste Repositories.* NUREG/CR-5411, SAND89-1821. Albuquerque, NM: Sandia National Laboratories.

EPRI (Electric Power Research Institute). 1986. *Seismic Hazard Methodology for the Central and Eastern United States, Vol. 1, Methodology.* NP-4/26.

Guzowski, R. V. 1990. *Preliminary Identification of Scenarios That May Affect the Escape and Transport of Radionuclides From the Waste Isolation Pilot Plant, Southeastern New Mexico.* SAND89-7149. Albuquerque, NM: Sandia National Laboratories.

Klett, R. D. 1991. *Proposed Extensions of United States Fundamental and Derived Standards for High-Level and Transuranic Radioactive Waste Disposal.* SAND91-0211. Albuquerque, NM: Sandia National Laboratories.

Marietta, M.G., S.G. Bertram-Howery, D.R. Anderson, K. Brinster, R. Guzowski, H. Iuzzolino, and R.P. Rechard. 1989. *Performance Assessment Methodology Demonstration: Methodology Development for Purposes of Evaluating Compliance with EPA 40 CFR Part 191, Subpart B, for the Waste Isolation Pilot Plant.* SAND89-2027. Albuquerque, NM: Sandia National Laboratories.

Public Law 96-164. 1979. *Department of Energy National Security and Military Applications of Nuclear Energy Authorization Act of 1980.*

Shachter. 1986. "Solving Influence Diagrams." *Operations Research* 34: 871-882.

U.S. DOE (Department of Energy) and the State of New Mexico. 1981, as modified. "Agreement for Consultation and Cooperation" on WIPP by the State of New Mexico and U.S. Department of Energy, modified 11/30/84 and 8/4/87.

U.S. EPA (Environmental Protection Agency). 1985. "Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes; Final Rule." 40 CFR Part 191. *Federal Register 50:* 38066-38089.

U.S. NRC (Nuclear Regulatory Commission). 1990. *Severe Accident Risks: An Assessment of Five U.S. Nuclear Power Plants.* Summary Report of NUREG 1150. Washington D.C.: U. S. Nuclear Regulatory Commission.