A PROBABILISTIC DERIVATION OF WASTE CONCENTRATION LIMITS FOR THE RADIOACTIVE WASTE MANAGEMENT SITES AT THE NEVADA TEST SITE

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ABSTRACT

A probabilistic approach to performance assessment was used to derive waste concentration limits for the Area 5 and Area 3 Radioactive Waste Management Sites at the Nevada Test Site (NTS). Probabilistic techniques employed in the performance assessments include probabilistic treatment of parameter uncertainty, the occurrence of inadvertent human intrusion scenarios, and the longevity of institutional controls. Site-specific and probabilistic treatment of the intruder at NTS is appropriate given the location of the low-level waste disposal facilities in a remote desert environment.

The probability of intrusion and the length of the institutional control period was estimated from the elicitation of a panel of subject matter experts (SMEs). The SMEs concluded that the probability of future inadvertent human intrusion and human settlement would be very low in the remote arid valleys of the NTS. Moreover, the SMEs believed that institutional controls were likely to be effective beyond 100 years at the NTS.

The NTS SMEs estimated the probabilities of inadvertent human intrusion for a 10,000-year compliance period and a 0.8-hectare disposal site footprint. Application of elicitation-derived intruder probabilities to the disposal facilities was a three-step process: 1) adjust probabilities to a 1,000-year performance assessment compliance period based on new regulatory guidance; 2) adjust probabilities to the actual footprint of the waste cell; and 3) adjust for an elicitation-derived institutional control period of 250 years. The probability-weighted dose, or expected dose to an intruder for a disposal cell at the NTS, was determined by multiplying the dose by the probability of a well-drilling intruder scenario. When the intruder performance objectives were found to be limiting, waste concentration limits were derived for select radionuclides using the probability-weighted intruder dose.

The paper explores the benefits of the NTS probabilistic approach on waste concentration limits:

- accounting for site-specific conditions at the waste disposal facility allows full credit to be taken for the advantages offered by a remote, arid site

- providing a means to compare the merits of disposal facilities for large volumes of Department of Energy legacy waste by providing a realistic and quantitative assessment of the options
- providing a defensible technical basis for increased waste concentration limits, thereby reducing the potential inventory of performance assessment limited waste

INTRODUCTION

The U.S. Department of Energy, Nevada Operations Office (DOE/NV) operates, oversees, and has responsibility for future closure of Radioactive Waste Management Sites (RWMSs) located in Area 5 in Frenchman Flat and Area 3 in Yucca Flat at the Nevada Test Site (NTS; Figs. 1 and 2). The DOE/NV Waste Management Program provides low-level radioactive waste disposal capability for NTS-generated waste and other DOE-approved waste generators. Disposal of low-level radioactive waste began at the Area 5 RWMS in 1960 and at the Area 3 RWMS in 1968. Low-level radioactive, transuranic, mixed, and classified wastes have been disposed in shallow, unlined trenches and greater confinement disposal boreholes.

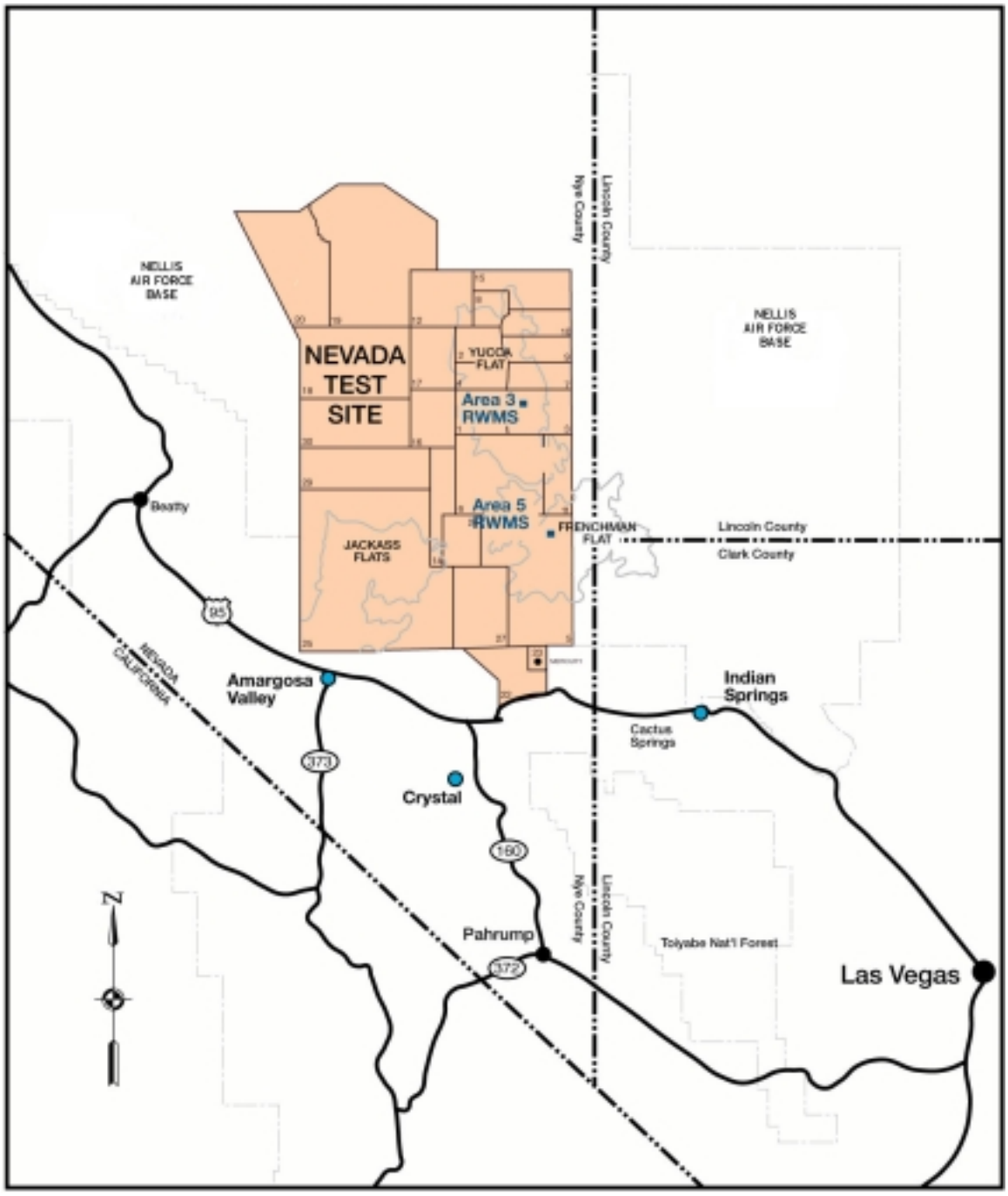

Figure 1. Location of the Area 3 and Area 5 Radioactive Waste Management Sites (RWMSs) within
the Nevada Test Site and southern Nevada.

Figure 2. Aerial photographs of the Area 3 Radioactive Waste Management Site (above), and the Area 5 Radioactive Waste Management Site (below) at the Nevada Test Site taken on July 7, 1998.

A requirement for operation of low-level radioactive waste disposal sites under DOE Order 5820.2A (1) is the preparation and maintenance of a site-specific performance assessment (PA). A PA is a series of analyses conducted to 1) determine potential risks posed by waste management systems to the public and the environment, and 2) compare these risks to established performance objectives (dose thresholds). Results of the PA are used to effect regulatory decisions regarding disposal site design, operation, safety, waste acceptance criteria (WAC), and site characterization. A PA has been conducted, and approved, for the post-1988 disposal units within the Area 5 RWMS (2). A second PA for the Area 3 RWMS (3) and an addendum to the Area 5 PA, describing the derivation of waste concentration limits (WCLs), have been prepared and submitted for regulatory review (4).

Each PA must evaluate facility operations based on four performance objectives, briefly summarized as follows:

1. Protect public health and safety in accordance with applicable environmental standards and DOE Orders.
2. Assure that an effective dose equivalent to any member of the public does not exceed 0.25 milliSievert per year (mSv/yr) through all-pathways and 0.10 mSv/yr through the atmospheric pathway. Limit radon emissions to an average flux density of 0.74 Becquerels per square meter per second (Bq/[m^2 s]).
3. Assure that an effective dose equivalent received by an individual who inadvertently intrudes into the waste after loss of institutional control (assumed to be 100 years) will not exceed 1mSv/yr for continuous exposure and 5 mSv for an acute dose.
4. Protect groundwater resources consistent with federal, state, and local regulations and requirements.

The third performance objective evaluates the likelihood that disposed radioactive waste may adversely impact an inadvertent human intruder (IHI) at some time during the next 1,000 years (the evaluation period). An IHI is a person who, without knowledge or intent, disturbs or uncovers disposed radioactive waste and receives a radiological dose.

DERIVATION OF WASTE CONCENTRATION LIMITS

Waste acceptance criteria, including radionuclide WCLs, are one design specification that can be derived from PA. Waste concentration limits are used to ensure that waste disposed in the future will not cause the performance objectives to be exceeded.

Performance assessment is an iterative process where the results, uncertainties, and sensitivities from previous iterations guide subsequent cycles and decisions. Data flow into the PA process can be derived from five sources: the regulator, the waste generators, the site operator, site characterization, and subject matter experts (SMEs). Two byproducts of the PA process are: 1) results for comparison against the performance objectives, and 2) design specifications, including WCLs. The regulator, in this case the DOE, provides the regulatory standard and its guidance, which define the PA process and

its objectives. The waste generators and site operator describe the waste inventory, disposal site design, and uncertainty in these areas. Environmental features, events, and processes expected at the site and their uncertainties can be obtained from site characterization and SMEs. Features, events, and processes that can be observed and measured, or described from historical evidence, are validated through site characterization. However, features, events, or process that are rare or unprecedented are best defined through elicitation of expert judgment. Formal elicitation of expert judgment from a panel relies on the combined training and experience of the SMEs to evaluate probabilistic estimates of poorly understood phenomena, or for forecasting future events (5, 6, 7, 8, 9). These topics have significant uncertainty that commonly cannot be reduced by conventional means of data gathering.

The PA process begins with the development of conceptual models of site performance based on the design of the facility and the important features, events, and processes identified by site characterization and the SMEs. The conceptual model guides the identification and selection of scenarios for the release and

transport of radionuclides from the disposal site to the accessible environment. Mathematical models are selected to simulate the conceptual model. Once probability density functions (reflecting uncertainty) are assigned to input parameters, consequence modeling is performed to simulate each of the scenarios.

Once the results are obtained, additional steps are required to derive WCLs. The results of the consequence modeling are manipulated to obtain the relationship between radionuclide concentration (or radionuclide inventory) and consequence. A release factor is defined as the ratio between the concentration of the radionuclide in the accessible

$$RF_{m,k,l} = \max \left| \frac{C_{m,k,l}(t)}{C_{w,k}(0)} \right|_{t = End\ of\ Institutional\ Control}^{t = End\ of\ Compliance\ Period}$$

environment and the initial waste concentration:

where:

$RF_{m,k,l}$ = release factor to environmental medium m of radionuclide l produced by decay of radionuclide k, dimensionless;

$C_{m,k,l}(t)$ = activity concentration in environmental medium m of radionuclide l produced by decay of radionuclide k, Bq/m^3; and

$C_{w,k}(o)$ = activity concentration in waste of radionuclide k at time of disposal, Bq/m^3.

The relationship between radionuclide waste concentration and consequence is obtained by multiplying the release factor by a scenario dose conversion factor. The scenario dose conversion factor is derived from radiological assessment models and is the total effect dose equivalent per unit concentration in an environmental media in the accessible

environment under assumed exposure conditions. These data are used to calculate the radionuclide concentration that would cause an outcome equal to the performance objective. The derived WCLs must consider the effects of progeny radionuclides that are produced by radioactive decay after disposal. The waste concentration limit is calculated as:

$$C_{L,k} = \frac{H_L}{P(s) \sum_{m=1}^{p} \sum_{l=k}^{n} \left(RF_{m,k,l} \, SDCF_{m,l} \right)}$$

where:

$C_{L,k}$ = waste concentration limit for radionuclide k, Bq/m^3;
H_L = performance objective limit, Sv/yr;
P(s) = probability of scenario, dimensionless; and
$SDCF_{m,l}$ = scenario dose conversion factor for environmental medium m and radionuclide l,
Sv/yr per Bq/m^3.

The WCL must be calculated for all radionuclides and performance objectives (i.e., all pathways and atmospheric pathway exposure of members of the public, radon flux density, groundwater protection, and intruder protection). The WCL for a given radionuclide is selected as the lowest waste concentration calculated for the various performance objectives.

The WCLs derived by this approach are maximum average concentrations, which are defined as the maximum concentration averaged over a disposal cell that is acceptable for shallow land disposal. When WCLs are evaluated at the disposal cell level, the acceptability of an individual package for disposal is dependent on the concentrations of all other packages in the disposal cell. Because waste is naturally processed and characterized at the package level, it is necessary to convert maximum average concentrations into operational WCLs that can be used to evaluate packages. Waste concentration can vary significantly among waste packages. High-concentration waste packages tend to occur less frequently than low-concentration packages. Therefore, operational WCLs for packages can be adjusted upward to account for less frequent high-concentration packages that may exceed the maximum average concentration limit for the disposal cell. For commercial low-level radioactive waste disposal operations, similar considerations led the U.S. Nuclear Regulatory Commission to increase the concentration limits for shallow land disposal in Title 10, Code of Federal Regulations, Part 61.55, by a factor of 10. Once operational limits are established, compliance with the WAC for an individual package is assured if:

$$\sum_{l=1}^{q} \frac{C_{w,l}}{C_{OL,l}} < 1$$

where:

$C_{OL,l}$ = operational waste concentration limit, Bq/m^3.

If the sum of the fractions is less than one, then the waste package is acceptable for shallow land burial.

PROBABILISTIC APPROACH TO PERFORMANCE ASSESSMENT

The PA process relies heavily on mathematical models to support decision making. These models are used to assess future conditions so that decisions can be made regarding the likelihood of compliance of the waste management system. Models often include projections into the future based on incomplete data, and spatial and temporal components that describe the current state of knowledge, as well as the predicted state of the future. Disposal systems models can be complex, involving many factors related to the inventory or source term, transport mechanisms, and exposure pathways. In addition, information used to develop the models is often incomplete, leading to uncertainties that need to be managed effectively to make an informed decision. Various probabilistic methods are available to address uncertainty in PA.

Mathematical models are specified with parameters that reflect the state of knowledge of the input factors and the relationships between the parameters. Parameters can be specified with a single deterministic value, or by using a distribution that reflects the uncertainties in the state of knowledge and system variability. Single deterministic values become conditions of the model and can represent uncertainty only in the sense of providing a conservative bound. In contrast, probability distributions reflect uncertainty directly. The need for deterministic or probabilistic inputs should be evaluated by considering qualitatively expectations of the outcome against performance objectives. If a large difference is expected (e.g., it is not expected that the performance objectives will be exceeded), then deterministic specifications, based on conservative bounds, might be appropriate. Otherwise some level of probabilistic analysis is warranted to ensure that uncertainties are understood and managed effectively. In particular, a probabilistic analysis should be performed when a decision error leads to costly or unacceptable consequences. Some combination of probabilistic assessment and conditioning using conservative deterministic values usually proves most effective.

The main advantage of a probabilistic approach comes from managing uncertainty more directly. The probabilistic approach allows uncertainty analyses to be performed that provide an assessment of the overall uncertainty in the results and of the relative contributions to the overall uncertainty from the model components. Other advantages include greater defensibility for decision making, a more realistic assessment of performance, a better understanding of the limitations of the modeled system, and a mechanism for prioritizing additional data collection. Sensitivity analyses can be performed on the deterministic specifications in the model. The purpose of the sensitivity

analysis is to determine if changes to deterministic values has a significant effect on the outcome distribution. If unacceptable uncertainties or sensitivities are identified, then the model can be improved (by data collection to reduce uncertainties or by removing conditions) until a model is developed that permits an informed decision to be made.

Performance objectives given in DOE Order 5820.2A specify two potentially exposed population members: the member of public (MOP) and the IHI. Performance assessments have traditionally been conducted assuming that radiological doses are received by the MOP and the IHI at their respective points of

compliance with set scenarios. Bounding scenarios such as residential or agricultural scenarios are usually selected. In probabilistic terms, these assumptions condition on set, conservative scenarios, sometimes with a low probability of occurrence.

The PAs for the Area 3 and Area 5 RWMSs at NTS were conditioned on the occurrence of the MOP scenarios, and assessed the probability that inadvertent human intrusion might occur. These PAs used a probabilistic approach for evaluating the potential for inadvertent human intrusion. The resulting probability of inadvertent human intrusion is used as a modifying factor when applied to the dose calculations for this scenario. In probabilistic terms, the modified dose is the “expected” dose to an IHI.

In summary, the Area 3 and Area 5 RWMS PAs utilize a “conditional” dose for the MOP scenarios, and an “expected” dose for the IHI scenario. The following section describes how the probability of the intruder-drilling scenario was assessed for the Area 3 and 5 RWMSs for use in the PAs, and to derive WCLs.

PROBABILISTIC APPROACH TO ASSESS INADVERTENT HUMAN INTRUSION

Expert elicitation was used to assess the probability of inadvertent human intrusion into buried waste at the Area 3 and Area 5 RWMSs. Specifically, probabilities of drilling inadvertently into the waste were assessed by formally eliciting expert judgments from a panel of SMEs (10, 11). This project was conducted primarily because the Area 3 and Area 5 RWMSs are located in remote, inhospitable areas within the Mojave Desert where, historically, populations have not chosen to reside (see Fig. 1). The RWMSs are located in alluvial basins where the average annual rainfall is less than 16 centimeters; near-surface hydrologic processes are dominated by evapotranspiration; permanent, natural, surface water features are rare; and depths to groundwater exceed 230 meters. This study takes into account site-specific factors to develop a more realistic, probabilistic evaluation of the potential for inadvertent human intrusion to occur.

The probabilistic approach used is consistent with DOE Order 5820.2A and guidance provided by the DOE Performance Assessment Task Team (12) and Case and Otis (13), in which it is recommended to develop site-specific, credible scenarios for dose exposure

calculations based on an understanding of current conditions. Three types of intruder scenarios were considered:

1. The intruder-construction scenario assumes a homesteader builds a house over a waste disposal site and excavates a foundation into the buried waste.
2. The intruder-discovery scenario is identical to the intruder-construction scenario, but assumes the intruder recognizes the hazardous nature of the excavated waste.
3. The postdrilling scenario assumes a homesteader drills for groundwater through a waste disposal site, and is exposed to contaminated drill cuttings while residing on the site.

The elicitation focused on the postdrilling scenario because the results were initially applied to a PA evaluating intermediate-depth disposal options for a high-specific activity, low-level radioactive waste stream (14). For intermediate-depth disposal, a drilling event is most likely to initiate an intrusion scenario. The probabilities derived in this study are limited to use in dose calculations for the postdrilling scenario. However, the scenarios developed by the SMEs and input obtained about the longevity of institutional controls are directly applicable to PAs that evaluate shallow-land waste disposal, with necessary modifications.

The postdrilling scenario considers an individual, the “homesteader,” who unknowingly breaches containment of the waste by drilling to groundwater. The drilling process transports waste to the surface where the drill cuttings are mixed with soil at the homesteader’s home site. Case and Otis (13) indicate that the selection of postinstitutional control scenarios can be a fairly subjective process, therefore justifying the use of the elicitation process for scenario development. Furthermore, Case and Otis indicate that “scenario construction should consider current patterns of activity in the area,” in which case it is appropriate to consider scenarios that go beyond the default scenarios presented in Wood *et al*. (12). While the default “homestead” scenario served as the starting point for the elicitation study, other scenarios were suggested and developed that account for potential “community” scenarios.

Although the expert elicitation approach is justifiable technically, it is important that the process includes development of models and assumptions, and sharing of information among all participants to ensure that the results are credible. This process involves a number of components that are used to build a solid foundation prior to the SME elicitation sessions. Initial steps taken in the process focused on obtaining sufficient information to identify the areas of expertise needed to perform the assessment. Preliminary models were developed in the form of “influence diagrams.” Influence diagrams show important factors or variables, and the relationships between those variables, at a simplified level that facilitates natural interpretation (Fig. 3). The diagram presented in Figure 3 has been simplified to reflect the elicitation inputs that were included in the Area 3 and Area 5 PA calculations. Information about other management control factors such as longevity of site knowledge, placards and markers, and engineered barriers was elicited, but was not credited in these PAs. Consequently, the PA calculations can be regarded as conservative.

The elicitation was conducted using a three-step process:

1. Developing the logic of the pertinent variables affecting inadvertent human intrusion through development of influence diagrams for the scenarios and the management controls.
2. Holding open workshops involving participation of stakeholders, scientists, and the public to examine the logic and acceptability of the approach taken for the probabilistic study.
1. Assessing the probabilities of intrusion into waste units by convening and formally eliciting expert judgments from a panel of SMEs.

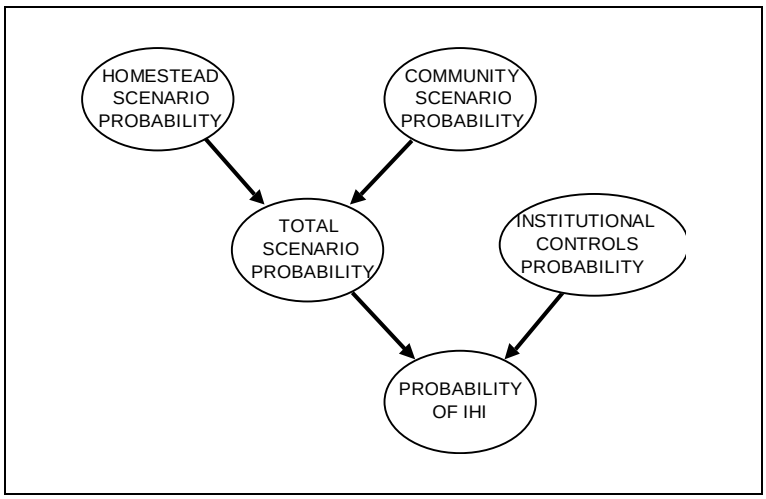

Figure 3. Influence diagram depicting the major components of the probability of inadvertent human intrusion assessment.

Expert judgment has proven to be a particularly useful tool for deriving probabilistic estimates of future scenario occurrences. The issue of inadvertent human intrusion for the RWMSs in Frenchman and Yucca Flats involves multiple factors with largely nonreducible uncertainty. There is uncertainty in the future missions and institutional control of the NTS; uncertainty in the viability, values, and practices of future societies; and uncertainty in future hydrogeologic processes that make arid desert lands either more or less desirable to society.

The foundation of the approach taken in this study is summarized as follows:

- Specify assumptions and models
- Gain acceptance from relevant stakeholders that the assumptions and models are reasonable
- Obtain relevant input to fulfill the needs of the models
- Calculate the probability of inadvertent human intrusion as a consequence of the assumptions and the model input

The initial steps in this probabilistic study involve developing a model of how inadvertent human intrusion occurs. This analysis could become hopelessly complex if every mechanism of possible inadvertent human intrusion were considered, given the uncertainty of future changes in society. Therefore, some basic conditions or assumptions were established for the modeling process.

The homestead and community scenarios were evaluated separately, and then were combined to provide a total scenario probability of inadvertent human intrusion. This represents the probability of inadvertent human intrusion, assuming all management control factors, including active institutional control, are ineffective. If institutional controls are effective, it is assumed that inadvertent human intrusion cannot occur. The next step involves evaluation of the potential effectiveness of the active institutional controls. The results for institutional controls are then combined with the conditional scenario results to provide an overall assessment of the probability of inadvertent human intrusion. The institutional controls module acts as a probability modifier for the scenario probabilities.

A second assumption addresses prediction of future changes in society and technology. Past studies have shown that many aspects of science and technology, particularly social sciences that are more susceptible to human influence, are inherently unpredictable (15). At best, stochastic or probabilistic models of future events can be developed. Accurate prediction of most events is impossible (for example, population growth, technology development, societal patterns, climate change, etc.). Consequently, a working assumption for this probabilistic study of inadvertent human intrusion was that forecasting of future patterns must be based on current technology and current societal practices. This presents a potential credibility problem for future PAs. To counteract this potential problem, a decision was made by the SMEs to periodically revisit the probabilistic estimates, if changes occur in society or technology that could significantly affect the results of the evaluation. Periodic review of intrusion at an interval of 25 years was proposed as an alternative to dealing with the largely unbounded uncertainties of predicting the future.

The final assumption for the basic approach concerns the mechanisms by which an inadvertent intruder who gains access to NTS chooses to settle in a remote alluvial valley. A number of scenarios are possible, including both homestead and community scenarios, and a range of factors may affect the outcome of the probabilistic assessment of inadvertent human intrusion for these scenarios. Examples of such factors include the suitability of the land surface for expected settlement activities and the hydrogeologic setting of the site; that is, future groundwater resource availability. The factors and the models developed by the SMEs for each scenario provided the necessary focus for the expert elicitation.

Preliminary influence diagrams include factors such as the number of homesteads, community lifetime, well density, well lifetime, depth to groundwater, and topographical features. An external review was conducted through a workshop including stakeholders, scientists, and public representatives. The workshop was a key element of the process that ensured that stakeholders understood and shared a basic agreement in the credibility of the probabilistic approach (11). Useful outcomes of the stakeholder and public interactions were to focus on making the probabilistic assessments specific to Nevada, and to validate the logic used in the influence diagrams for the management controls module and the homestead and community scenarios. In particular, the workshop

participants suggested that current population trends indicate that an urban scenario is plausible and should be considered for evaluation. Hence, the rationale for development of site-specific, credible community scenarios. The workshop participants fully endorsed "periodic review of intrusion," with an acknowledgment that such an approach will realize success only with assurances that sufficient funds are made available. A scientific review was also performed by convening a group of leading scientists from government institutions and private companies. The peer review group provided critical input on details of the approach, and confirmed the general findings from the workshop.

The influence diagrams include factors that directly affect the potential for inadvertent human intrusion to occur. The first step in selecting SMEs was to identify relevant disciplines to address these factors. Ten disciplines were chosen: agronomy, anthropology, demography, economic geology, geotechnical engineering, hydrogeology, hydrology, land-use planning, sociology, and drilling technology. Selection criteria for the disciplines included demonstration of classic training in the discipline, familiarity with the discipline application in the arid Southwest, and some familiarity with probability and statistics.

The selected SMEs were provided critical references and background materials prior to convening the first elicitation session to ensure a sufficient knowledge base for an effective session. The first elicitation session began with a field trip that familiarized the SMEs with the Area 3 and Area 5 RWMSs, Waste Management Program functions, topological features, hydrologic and geologic processes, and communities within the vicinity of NTS. The remainder of the first session was dedicated to structuring the influence diagrams. The SMEs were presented preliminary influence diagrams and were encouraged to debate the merits and deficiencies of the diagrams, then to modify them to reflect their consensus opinions. The SMEs' input resulted in the final structuring of the influence diagrams. The first session ended with general training on probabilistic concepts used in expert elicitation. The SMEs became familiar with methods for eliciting probability distributions and with potential sources of bias that can arise in the elicitation process.

The second session focused on formal elicitation of the probabilistic input required to fulfill the specifications of the influence diagrams. The elicitation involved assessment of quantile values from the SMEs using standard methods of expert judgment (7, 8, 9, 16). To ensure that inputs from the SMEs were recorded accurately, and for quality assurance purposes, the elicitation sessions were taped and several sets of written notes were archived. The SMEs were also provided a summary report that described their input. Each SME verified that their input was recorded accurately and was used appropriately. They were also asked to provide an evaluation of the elicitation process. This provided useful feedback on the practical adequacy of the elicitation approach, as well as the validity of and inputs to the model.

The remainder of the process involved the mathematical methods used to propagate the elicited input through the influence diagrams, and the presentation of the assessment of the probability of inadvertent human intrusion. Probability distributions were fit to the

elicited inputs, and Monte Carlo simulation techniques were used to propagate the input distributions through the influence diagrams. The simulations produce an assessment of the probability of inadvertent human intrusion for each scenario when management controls are considered ineffective. These results are then adjusted for the potential effectiveness of management controls to provide a final assessment of the probability of inadvertent human intrusion.

A consensus step at the start of the elicitation was definition of the base assumptions by the SME panel. The SMEs agreed with the workshop findings that using current knowledge of society is the only credible approach to a probabilistic assessment of inadvertent human intrusion. Further, the SMEs agreed that a periodic review of intrusion every 25 years is necessary as the current knowledge base changes; specifically, if societal or technological changes significantly affect the results. The SMEs also indicated that sufficient funds need to be established to ensure that periodic review will occur.

The SMEs were provided complete freedom to discuss and revise the scenarios as necessary. This process resulted in acceptance of the homestead scenario and refinement of the community scenario. Three separate community scenarios were identified:

1. A small community located in the alluvial basins of Frenchman or Yucca Flats (Base Community Scenario).
2. Urban expansion of Las Vegas north up the valley corridor and into the alluvial basins of NTS, including “commuting homesteaders” (Las Vegas Expansion Scenario).
3. A small community located in Jackass Flats, or in another area nearby Frenchman and Yucca Flats, including “commuting homesteaders” (Jackass Flats Scenario).

The SMEs defined “commuting homesteaders” as settlers who commute regularly from their homes located outside of the community or urban resource base. This was distinguished from the homestead scenario for which homesteaders were assumed to be isolated from any central community. The homestead scenario, combined with the three community scenarios, yield the four scenarios that the SMEs considered in this study.

The four scenarios follow a common basic model (Fig. 4). The probability of inadvertent human intrusion was evaluated separately for each scenario. Inputs obtained from the SMEs for each scenario provided information relevant to the top-level factors: the number of wells at a point in time (well density) and the well lifetime. Elicitation of these inputs depended on other factors specific to each scenario. The inputs were used to assess the total number of wells that are anticipated to be drilled in Frenchman and Yucca Flats during the evaluation period.

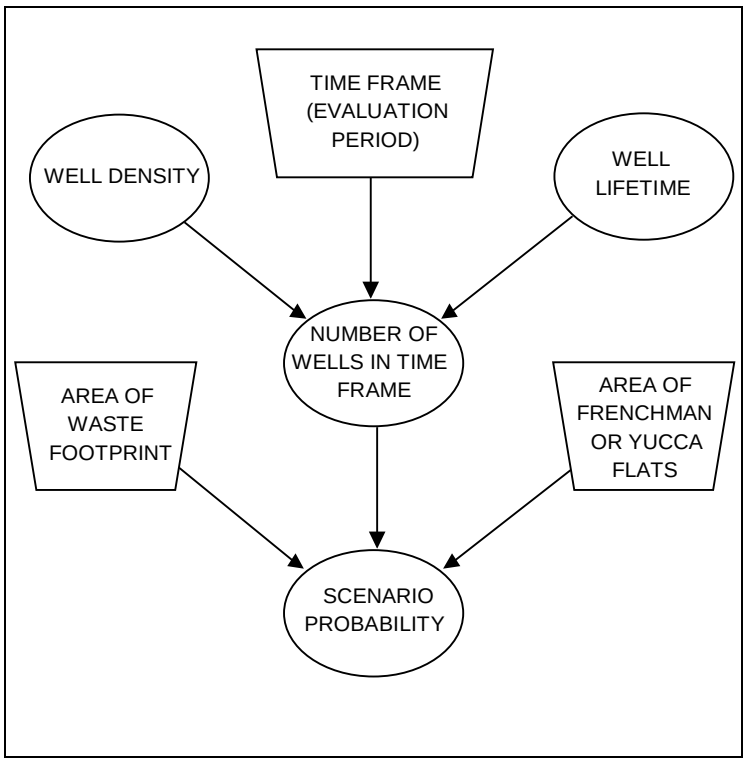

Figure 4. Influence diagram of factors in the basic scenario model.

Area estimates of Frenchman and Yucca Flats were estimated with geographical information system mapping techniques, and the area of the waste footprint is assumed to be 0.8 hectares. The total number of wells and the ratio of area of the waste footprint to the area of the alluvial basins were required to determine the probability that at least one well would intersect the waste footprint, causing an intrusion event.

A number of factors were included in the scenario-specific influence diagrams, all of which effect assessment of the number of wells that will be drilled during the evaluation period. For example, suitability of the land surface and hydrogeologic factors may influence the likelihood of establishing a settlement in the vicinity of the RWMSs. The suitability of the land surface may be influenced by the remoteness of the alluvial basins, playas (dry lakes) that are contained within these basins, and surface-collapse craters that were formed by underground testing (Fig. 2). The SMEs attempted to establish a balance in the selection of factors included in the influence diagrams. This required a conscious effort to ensure that the number of variables were sufficient to document and defend the probabilistic analyses, yet were not so numerous that the elicitation process became onerous, and could not be completed in a reasonable time frame.

Details of the homestead and community scenarios and the results of the elicitation can be found in Black *et al*. (10, 11) . The overall scenario probability of inadvertent human

intrusion was dominated by the Jackass Flats scenario. The overall probability of inadvertent human intrusion at Frenchman Flat was estimated to be about 11 percent; for Yucca Flat, it was estimated to be about 1 percent. The primary reason for the difference was recognition that numerous craters from underground nuclear testing occur in Yucca Flat, particularly around the RWMS. The SMEs considered the craters to be a substantial deterrent to well drilling.

RESULTS

The previous sections described the PA process, application of probabilistic methods, and the elicitation process by which the probability of inadvertent human intrusion was assessed for a nominal 0.8-hectare waste cell and a 10,000-year compliance period. The probabilistic approach has no effect on the estimated release and transport of radionuclides and, therefore, on the estimated concentration of radionuclides in the accessible environment. The extension of the institutional control period, however, reduces the interval over which the release fraction is evaluated. This causes the release fraction to decline for short-lived radionuclides. In the probabilistic approach, the probability of intrusion is also reduced from one to a presumably lesser value based on the elicitation results. These changes cause most WCLs to increase. In some instances, the increase in the WCLs based on the intruder performance objectives is sufficient to allow other performance objectives to become limiting.

To apply the elicitation results to the Area 3 and Area 5 RWMSs, the probability of inadvertent human intrusion must be adjusted for the actual footprint of the waste disposal cells and the 1,000-year compliance period currently assessed in DOE PAs. With the shortening of the compliance period from 10,000 to 1,000 years, the length of the institutional control period becomes an important consideration and the probability of inadvertent human intrusion must be adjusted to account for the delayed onset of the intrusion event. For the Area 5 RWMS, two separate disposal areas were evaluated because their waste streams are very different. The size of the disposal cell footprint for Pit 6 at the Area 5 RWMS is 0.6 hectares, and for the remaining shallow land burial trenches is 7.5 hectares. The Area 3 RWMS disposal cells occupy 7.1 hectares; post-1988 waste is disposed in 3.8 hectare U3-ah/at disposal unit only.

The focus of the probability of inadvertent human intruder calculations is the dominating Jackass Flats scenario. The probability of inadvertent human intrusion for this scenario, based on a 0.8-hectare waste footprint and a 10,000-year compliance period and excluding credit for the assessed active institutional control period, was approximately 11 percent for Frenchman Flat (Area 5 RWMS) and 1 percent for Yucca Flat (Area 3 RWMS). Table I shows the probability of inadvertent human intrusion for the disposal areas at the Area 5 RWMS, based on the waste cell footprint and compliance period adjustments.

Table I Probability of Inadvertent Human Intrusion Based on a 1,000-Year Compliance Period with No
Institutional Control Period

RWMS Location	Waste Footprint Area	Expected Probability of Occurrence of Inadvertent Human Intrusion by Well Drilling
Area 5, Shallow Land Disposal Trenches	7.5-hectares	1×10^{-1}
Area 5, Pit 6	0.6-hectares	9×10^{-3}
Area 3, U3-ah/at	3.8-hectares	6×10^{-3}

The SMEs assessed 250 years as a reasonable longevity of institutional control (10). Given the 1,000-year compliance period, the effect of including credit for this control period is significant because it is assumed that while institutional control exists, inadvertent human intrusion cannot occur. The probabilities presented in Table I were modified to take into account this period of institutional control by multiplying the values in Table I by the proportion of time that institutional control is not active (or, equivalently, the proportion of time that inadvertent human intrusion is possible). That is, the probabilities in Table I were multiplied by 0.75 (1-[250/1,000]). The results are presented in Table II, and are those used in the calculations of WCLs for the postdrilling exposure scenario.

Table II Probability of Inadvertent Human Intrusion Based on a 1,000-Year Compliance Period and
250-Year Institutional Control Period

RWMS Location	Waste Footprint Area	Expected Probability of Occurrence of Inadvertent Human Intrusion by Well Drilling
Area 5, Shallow Land Disposal Trenches	7.5-hectares	8×10^{-2}
Area 5, Pit 6	0.6-hectares	7×10^{-3}
Area 3, U3-ah/at	3.8-hectares	5×10^{-3}

The WCLs from the intruder scenario were derived using the expected dose; that is, the dose multiplied by the probability of intrusion as estimated above. The initial WCLs derived from a deterministic analysis of a postdrilling intruder scenario appear in the second column of Table III. The third column contains WCLs derived from the expected dose to a postdrilling intruder assuming a 0.08 probability of intrusion and a 250-year institutional control period. Using the expected dose and extending the institutional control period increases the intruder derived WCL for all radionuclides. The largest

increases are for short-lived radionuclides because of the effect of the longer institutional control period. The fourth column of Table III contains the lowest WCL derived from all the performance objectives. The last column shows that using the probabilistic approach, the intruder scenario set the WCL for ^{14}C and ^{137}Cs only. Waste concentration limits set by the radon flux density performance objective are unaffected by the use of probabilistic methods.

Table III Comparison of Waste Concentration Limits Set by a Deterministic Versus Probabilistic Intruder Analysis, and the Lowest Waste Concentration Limit Set Considering All Performance Objectives

Nuclide	Deterministic PA WCL Set by Intruder Performance Objective (Bq/m^3)	Probabilistic PA WCL Set by Intruder Performance Objective(Bq/m^3)	Probabilistic PA WCL Set by All Performance Objectives (Bq/m^3)	Performance Objective Setting Probabilistic PA WCL
^{3}H	2.0×10^{13}	8.2×10^{17}	5.2×10^{16}	MOP
^{14}C	2.3×10^{8}	2.8×10^{9}	2.8×10^{9}	IHI, Post-drilling
^{137}Cs	3.4×10^{10}	1.3×10^{13}	1.3×10^{13}	IHI, Post-drilling
^{226}Ra	1.2×10^{19}	1.6×10^{10}	3.3×10^{7}	Radon Flux
^{234}U	9.3×10^{10}	1.1×10^{12}	2.0×10^{10}	Radon Flux
^{238}U	6.4×10^{10}	7.7×10^{11}	5.5×10^{11}	MOP
^{232}Th	8.4×10^{8}	1.0×10^{10}	6.7×10^{9}	MOP
^{239}Pu	2.2×10^{10}	2.7×10^{11}	2.3×10^{11}	MOP

CONCLUSIONS

The DOE has adopted an approach to PA that derives WCLs from site-specific PA results. The WCLs derived from a deterministic PA are usually set by the intruder performance objectives. There are few features in an intruder scenario that will distinguish the site-specific differences among disposal sites when the intrusion scenario is assumed to occur with a probability of one at 100 years after closure. Assigning a probability to intrusion and selecting a site-specific period of institutional control allows a disposal site to acknowledge site-specific features that have an important effect on the derivation of WCLs. Elicitation of a SME panel is a credible and defensible method for assigning probability to future events and for assessing the performance of institutional controls. Application of probabilistic methods to the derivation of WCLs at the NTS had several notable effects.

- Site-specific and credible scenarios for the postdrilling scenario were developed through workshop discussions involving stakeholders, scientists, and the public, as

well as by the SME panel. The probability of inadvertent human intrusion was assessed to be about 10 percent for Frenchman Flat (the Area 5 RWMS location), and about 1 percent for Yucca Flat (the Area 3 RWMS location). The lower probability of inadvertent human intrusion in Yucca Flat is attributed to the presence of surface-subsidence craters, created by underground testing, that effect the expected number of drilled wells.

- Elicited input for the institutional control factor indicates less than 250 years of effectiveness as a reasonable estimate (250 years was the median of the distribution elicited from the SMEs). The SMEs considered it more likely that control would be lost gradually, rather than by catastrophe. The SMEs considered several mechanisms for gradual erosion of institutional control and loss of site knowledge: political change, economic constraints, or less concern by society for the importance of waste management issues.

- The deterministic approach to PA assumes that inadvertent human intruder by drilling *will* occur at a probability of 100 percent. As demonstrated in this study, probabilistic PA results for the NTS are more realistic, and have proven successful in evaluating problematic waste streams (14) that require a more thorough and rigorous method of analysis.

- Considering the probability of intrusion and extending the institutional control period increases the WCLs set by the chronic intruder performance objective. Long-lived radionuclides are most affected by the probability of intrusion. Short-lived radionuclides are affected by the probability of intrusion and the extended period of institutional control.

- Waste concentration limits derived from the probabilistic PA results are set by a variety of performance objectives, while WCLs derived from deterministic results tend to be set by the intruder performance objective only. Short-lived radionuclides, such as ^{90}Sr and ^{137}Cs, still have concentration limits set by the chronic intruder performance objective. The concentration limits of long-lived radionuclides such as ^{238}U, ^{232}Th, and ^{239}Pu are set by the all-pathways or atmospheric pathway performance objective for the MOP. The concentration limits of ^{226}Ra, ^{230}Th, and ^{234}U are set by the radon flux density performance objective and unaffected by the probabilistic approach.

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