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The Second Iteration of the Systems Prioritization Method: A Systems Prioritization and Decision-Aiding Tool for the Waste Isolation Pilot Plant

Volume III: Analysis for Final Programmatic Recommendations

N. H. Prindle, D. M. Boak, R. F. Weiner, W. Beyeler, S. Hora, M. G. Marietta, J. C. Helton, D. Rudeen, H. Jow, M. Tierney

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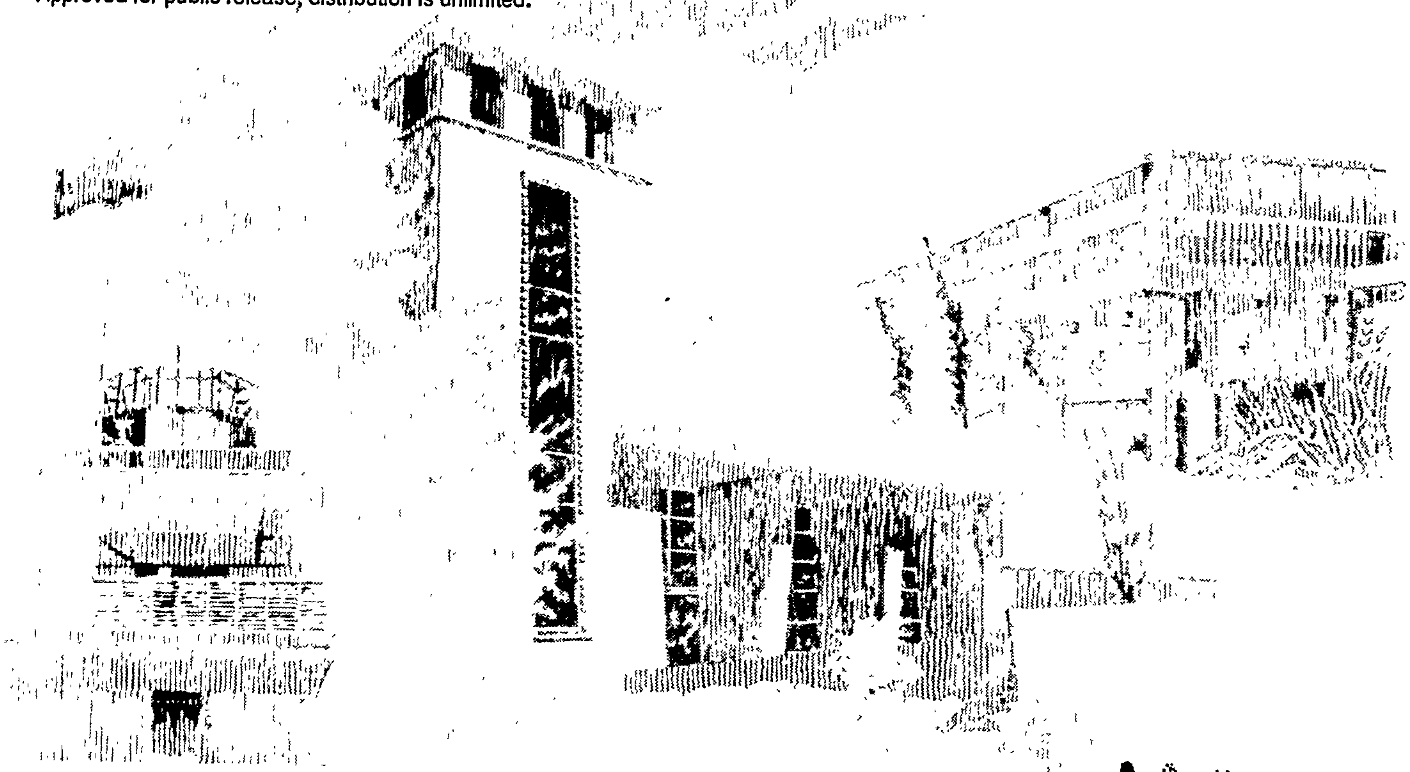

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The Second Iteration of the Systems Prioritization Method: A Systems Prioritization and Decision-Aiding Tool for the Waste Isolation Pilot Plant

Volume III: Analysis for Final Programmatic Recommendations

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ABSTRACT

Systems Prioritization Method (SPM) is a decision-aiding tool developed by Sandia National Laboratories for the U.S. Department of Energy Carlsbad Area Office (DOE/CAO). This tool provides an analytical basis for programmatic decision making for the Waste Isolation Pilot Plant (WIPP). SPM integrates decision-analysis techniques, performance and risk-assessment tools, and advanced information technology. Potential outcomes of proposed activities and combinations of activities (activity sets) are used to calculate a probability of demonstrating compliance (PDC) with selected regulations. The results are presented in a decision matrix showing cost, duration, and maximum PDC for all activities in a given cost and duration category. This is the third and final volume in the series *The Second Iteration of the Systems Prioritization Method: A Systems Prioritization and Decision-Tool for the Waste Isolation Pilot Plant* (SPM-2). Volume I of this report provides a synopsis of the method and preliminary observations on the SPM-2 results. Volume II describes the technical input and model implementation for SPM-2. SPM-2 analyzed combinations of scientific investigations, engineered alternatives (EAs), and waste acceptance criteria (WAC) for supporting the final compliance application for WIPP. The scope of SPM-2 was limited to evaluating the predicted performance of the disposal system with respect to selected portions of the applicable Environmental Protection Agency long-term performance regulations, 40 CFR 191.13(a) (radionuclide containment requirements) and 40 CFR 268.6 (hazardous constituent concentration

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requirements). SPM-2 was completed in March 1995. The results of SPM-2 contributed to the basis for DOE/CAO decisions made in March and May 1995 to focus the WIPP Project on a compliance strategy based on scientific investigations with regulatory assurance provided by EAs. This volume describes the analysis of the SPM-2 results to determine recommended paths for meeting the following DOE/CAO objectives: maximize PDC, minimize duration, and minimize cost. A statistical regression analysis of the SPM-2 decision matrix was performed to determine the most favorable activity set(s) for meeting the DOE/CAO objectives. Two pareto-optimal activity series were found: one for a duration-constrained scenario, and one for a unconstrained duration scenario. Potential sources of uncertainty were reviewed and studies were performed to evaluate quantitatively the effects of these uncertainties on the SPM-2 results and the pareto-optimal series. Qualitative aspects of the SPM-2 input and analysis were also considered. The two pareto-optimal series were recommended for DOE/CAO consideration based on the results of the uncertainty analyses and the sensitivity studies. DOE/CAO made a final decision in May 1995 based on final programmatic recommendations on the scope and content of the scientific investigations. The scientific investigation program developed subsequent to the completion of SPM-2 has begun to yield results that will contribute to an evaluation of compliance of the WIPP disposal system with the selected long-term regulations.

ACKNOWLEDGEMENT

Completion of Volume III of the SPM-2 final report required a dedicated team effort. We would like to thank Fred Mendenhall for building this team spirit during his tenure as SPM-2 team leader.

EXECUTIVE SUMMARY

In March 1994, the U.S. Department of Energy Carlsbad Area Office (DOE/CAO) embarked on an effort to design and implement a performance-based decision-aiding tool to provide an analytical basis for planning, prioritizing, and selecting programmatic options for the Waste Isolation Pilot Plant (WIPP) Project. The effort resulted in a decision-aiding analysis tool called the Systems Prioritization Method (SPM), which analyzed combinations of scientific investigations, engineered alternatives (EAs), and waste acceptance criteria (WAC) for supporting the final WIPP compliance application. The scope of SPM was limited to selected portions of applicable Environmental Protection Agency (EPA) long-term performance regulations. SPM calculates the probabilities of certain sets of activities demonstrating compliance with portions of 40 CFR 191.13(a) (radionuclide containment requirements) and 40 CFR 268.6 (hazardous constituent concentration requirements promulgated under the Resource Conservation and Recovery Act (RCRA)). SPM results are presented in a decision matrix showing cost, duration, and maximum probability of demonstrating compliance (PDC) for all activities in a given cost and duration category to identify cost-effective programmatic paths with a high probability of success.

The results of the second iteration of SPM (SPM-2), with consideration of issues outside the scope of SPM, are intended for programmatic decision making. SPM-2 was completed in March 1995. The results contributed to the basis for a preliminary DOE/CAO decision made in March 1995 to focus the WIPP Project on a strategy that relies on scientific investigations for demonstrating compliance with 40 CFR 191.13(a) and 40 CFR 268.6. Regulatory assurance is to be provided by EAs.* In-depth analysis of the SPM-2 results were performed between March and May 1995 to determine which combination(s) of the scientific investigations should be pursued as the preferred programmatic path. Final programmatic recommendations on the scope and content of the scientific investigations based on this analysis were made to DOE/CAO in May 1995. DOE/CAO made its final decision in May 1995 to fund the following scientific investigations: 1) colloid concentrations and transport; 2) Culebra fracture/matrix/flow – laboratory; 3) multi-well tracer test; 4) chemical retardation in the Culebra; 5) dissolved actinide solubilities; and 6) short- and long-term seal component studies using multimechanism deformation coupled fracture (MDCF) rock mechanics model and blowout releases.

This is the third and final volume in the series *The Second Iteration of the Systems Prioritization Method: A Systems Prioritization and Decision-Tool for the Waste Isolation Pilot Plant.* Volume I of the final report provides a synopsis of the method and preliminary observations on the SPM-2 results. Volume II describes the technical input and model implementation for SPM-2. This volume describes the analysis of the SPM-2 results to determine recommended programmatic paths for meeting the following DOE/CAO objectives: maximize PDC, minimize duration, and minimize cost. Optimization analyses of the subset of decision matrix results consisting of scientific investigations alone were performed to determine optimal

* Regulatory assurance refers to the use of engineered barriers for the WIPP disposal system as required by 40 CFR 191.14(d).

series of activity sets leading to the highest incremental gains in PDC for the least incremental additional cost. Potential sources of uncertainty were also identified, and studies were performed to quantitatively evaluate the effects of these uncertainties on the SPM-2 results and the identified optimal activity series. Qualitative aspects of the SPM-2 input and analysis were also considered.

The regression analysis performed on the SPM-2 results yielded pareto-optimal series of activity sets leading to the highest possible PDC as a function of cost for both unconstrained and constrained duration. The results of the regression analysis revealed programmatic dependencies that had not been explicitly anticipated. For example, some activities are found only in combination with one other because they must be done together for the postclosure performance benefit. Also, some activities that actually decrease the PDC are included in the pareto-optimal series because they are necessary precursors to other activities in the series. Moreover, how the information provided by the activities is interrelated and dependent on predecessor activities for its value to the program is important in case of budget cuts or failure of activities to produce the predicted information. The pareto-optimal activity series allow DOE/CAO to maintain an optimal programmatic path in light of all the interrelationships and dependencies.

The following potential sources of uncertainty in SPM were identified and evaluated for their impact on the SPM-2 results and the pareto-optimal series: uncertainty in the PDC, the use of a binary indicator for compliance (as opposed to a continuous measure), the impact of assumptions made in performance calculations, the accuracy of the cost and duration information supplied for each activity, the appropriateness of the performance objectives, and the influence of other qualitative programmatic considerations. The primary sources of uncertainty about the PDC resulted from: using mean parameter values in the performance calculations instead of latin hypercube sampling (LHS), the elicitation of probabilities of outcomes by expert judgment, the accuracy of the performance benefit estimates of each activity outcome (captured as a conceptual model, a scenario, or a parameter distribution) and the final form of the Performance Assessment (PA) codes used to model this benefit, and the use of a binary measure to indicate compliance as opposed to a continuous indicator.

SPM-2 used the existing WIPP PA computer codes with required modifications to calculate complementary cumulative distribution (CCDFs) for radionuclide releases. For SPM-2, a mean-value approach was used to generate a single vector from parameter distributions for input to WIPP performance modeling. LHS has been the procedure for WIPP PA modeling, but it was not used for SPM-2 because of the large number of activities modeled. The accuracy of the approximations(s) used in SPM-2 was thus evaluated for a specified activity set to determine whether the PDC would change if LHS, rather than mean value parameters, were used in the SPM-2 analysis.

The composite mean CCDF from the LHS compared reasonably well with the CCDF resulting from the mean parameter values. However, the particular activity set evaluated would have failed the test for compliance with 40 CFR 268.6 for a single vector of extreme parameter values. This implies that, for the activity set analyzed, the PDC would have changed if LHS rather than mean value parameters were used in the SPM-2 analysis. In SPM-2, it was conservatively assumed that *any* contaminated brine reaching the accessible environment would result in a RCRA violation. This assumption, however, is likely to change prior to submitting the final WIPP compliance certification application; the assumption was an interim position to be used only until the WIPP Project established the basis for using solubility data for heavy metals in brine. Because of the conservatism of the assumption and the fact that only extreme vectors violated the assumption, this issue was determined not to be of significant concern in the SPM-2 results.

In SPM-2, a structured elicitation process was employed to control potential sources of error and uncertainty. Uncertainties arising from the elicitation of probabilities of outcomes by expert judgment were evaluated in two areas of concern: colloid studies and actinide solubility. It was determined that the activities in the pareto-optimal series would remain the same in spite of the uncertainties in the probability outcomes for these two activities. In the case of colloid studies, a more refined probability distribution would have the effect of linearly scaling down the highest PDC, but would not change the conclusion that a colloid activity belongs in the optimal sets. In the case of actinide solubility, previous sensitivity studies confirm the inclusion of these activities in the optimal set.

The standard utility calculations for SPM-2 used a binary compliance indicator to measure whether the WIPP disposal system is predicted to succeed or fail in meeting the selected performance requirements, and made no additional distinction as to how far the resulting CCDF was from the regulatory limits. An analysis was conducted using a continuous release measure (CRM) that gives an indication of how far a CCDF is below the regulatory limit by calculating the expected value of the integrated normalized releases for each activity set. A multivariate linear regression analysis was used to characterize the importance of the SPM-2 activities with respect to the CRM. A statistical evaluation identified a duration-constrained series and an unconstrained series of SPM-2 activities that tend to minimize the CRM for a given cost. Both series provided very close approximation to the pareto-optimal set based on PDC values at most cost levels. Therefore, the SPM-2 results for the pareto-optimal activity series were considered to be insensitive to this issue.

The technical rationales used to extrapolate the PA input and models from the predicted results of the scientific investigations could be a significant source of uncertainty in SPM-2. The specification of PA implications in the SPM-2 problem definitions may also be a source of uncertainty. It was not possible to quantify the influence of this uncertainty on the calculated PDC values, however. Decisions based on the SPM-2 PDC values must be made under the assumption that these values would not change if this uncertainty was eliminated.

Additional uncertainties within the SPM-2 decision matrix stemming from cost and duration estimates were not explicitly considered because of the lack of actual data on these uncertainties. It is unlikely that they affected the pareto-optimal activity series. These uncertainties, however, can be expected to be lowest for scientific activities (and lower for funded activities than for unfunded activities) and highest for EAs and WACs for which detailed performance evaluations had not been conducted and detailed implementation plans had not been developed. It is recommended that a detailed implementation plan and cost estimate be developed prior to selecting an EA or WAC.

Although not part of the original SPM concept, side investigations became an integral part of SPM-2. They are supplementary and confirmatory evaluations required to 1) fully address certain technical positions taken in the SPM-2 baseline, 2) investigate the impact of potential activities, where the cost and expense of carrying an activity outcome all the way through the formal SPM decision process was not warranted, and 3) investigate the impact of choice of calculational models† used in SPM-2, such as using two-dimensional versus three-dimensional models for both baseline and activity outcomes. The side investigations consist of investigations that could not be completed by the end-date of SPM-2, March 1995. Expected outcomes of the side investigations, however, were included in SPM-2 calculations because the probability of their successful completion was considered very likely. Side investigations have been incorporated into the WIPP Features, Events, and Processes (FEP) study for scenario screening.

Senior management of the Sandia National Laboratories (SNL) WIPP Project evaluated the degree to which the quality of the SPM-2 work may or may not have impacted the validity of technical conclusions. The SPM-2 performance calculations were also evaluated qualitatively for the adequacy of the conceptual models that were used and the potential impact of the results of side investigations on the conclusions. The input in all program areas was determined by SNL management to be of sufficient quality to support the conclusions reached in the analysis of the SPM-2 results. Other bases for analysis were also considered. For example, it was suggested that demonstration of safety be considered as a performance objective, and that the same weight be given to EPA design requirements as was given to the demonstration of compliance with the long-term performance regulations. After analysis of these alternative approaches, it was determined that there were no instances in which a significantly different pareto-optimal activity series would have resulted. The SNL management also determined that the results of the uncertainty analyses, in large part, substantiated earlier sensitivity studies such as the 1992 WIPP PA Sensitivity Analysis (WIPP PA, 1993) and scientific knowledge developed over WIPP's twenty year history. When examined against this background of Project knowledge, the SNL management judged the SPM-2 results to be of sufficient quality for programmatic decision-making.

The evaluation of the SPM-2 results showed that scientific investigations alone (without EAs or modification of existing WACs) appear sufficient to achieve a high PDC within the Disposal Decision Plan (DDP) schedule. The scientific investigation program developed subsequent to the completion of SPM-2 has begun to yield results that will contribute to an evaluation of compliance of the WIPP disposal system with the selected long-term regulations.

† For the purposes of the SPM-2 final report, the term "calculational model" refers to the numerical model used in the SPM-2 calculations. (See Volume I of this report for more details.)

CONTENTS

Figures

Tables

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ACRONYMS

CCDF	Complementary Cumulative Distribution Function
CI	Compliance Indicator
DOE	U.S. Department of Energy
CAO	Carlsbad Area Office
CRM	Cumulative Release Measure
DDP	Disposal Decision Plan
DRZ	Disturbed Rock Zone
EA	Engineered Alternative
EATF	Engineered Alternatives Task Force
EPA	U.S. Environmental Protection Agency
FEP	Features, Events, and Processes
LHS	Latin Hypercube Sampling
MDCF	Multimechanism Deformation Coupled Fracture
NAS	National Academy of Sciences
PA	Performance Assessment
PDC	Probability of Demonstrating Compliance
PI	Principal Investigator
RCRA	Resource Conservation and Recovery Act
SNL	Sandia National Laboratories
SPM	Systems Prioritization Method
SPM-2	Systems Prioritization Method - Second Iteration
TZ	Transition Zone
WAC	Waste Acceptance Criteria
WID	Westinghouse Waste Isolation Division
WIPP	Waste Isolation Pilot Plant

CODES

BRAGFLO	BRine And Gas FLOw

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1. INTRODUCTION

1.1 Background

The Systems Prioritization Method (SPM) is a decision-aiding tool developed for the U.S. Department of Energy Carlsbad Area Office (DOE/CAO). SPM provides an analytical basis for evaluating programmatic options for the Waste Isolation Pilot Plant (WIPP) to meet selected portions of the applicable Environmental Protection Agency (EPA) long-term performance regulations, 40 CFR 191.13(a) (radionuclide containment requirements) and 40 CFR 268.6 (hazardous constituent concentration requirements promulgated under the Resource Conservation and Recovery Act (RCRA)). SPM uses potential outcomes of proposed activities and combinations of activities (activity sets) to calculate a probability of demonstrating compliance (PDC) with the regulations. The results are presented in a decision matrix showing cost, duration, and maximum PDC for all activities in a given cost and duration category.

In March 1994, DOE/CAO initiated SPM to prioritize programmatic combinations of scientific investigations, engineered alternatives (EAs), and waste acceptance criteria (WAC) for supporting the final WIPP compliance certification application. The first iteration of SPM (SPM-1) served as a benchmark and a test bed for developing the tools needed for the second iteration of SPM (SPM-2), completed in March 1995. The results of SPM-2 contributed to the basis for a decision made in March 1995 to focus the WIPP Project on a strategy that relies on scientific investigations for demonstrating compliance with 40 CFR 191.13(a) and 40 CFR 268.6. Regulatory assurance[1] is to be provided by EAs. In-depth analyses of the SPM-2 results were performed between March and May 1995 to determine which combinations of scientific investigations should be pursued as the preferred programmatic path. Final programmatic recommendations on the scope and content of the scientific investigation program based on the analysis of SPM-2 results were made to DOE/CAO in May 1995. In May 1995, DOE/CAO made its decision to fund a program based on these recommendations.

This is the third and final volume in the series *The Second Iteration of the Systems Prioritization Method: A Systems Prioritization and Decision-Tool for the Waste Isolation Pilot Plant*. The formulation of input for SPM-2, the analysis of that input, and the preliminary interpretation of the SPM-2 decision matrix are described in Volumes I and II of this report (Prindle et al., 1996a; Prindle et al., 1996b).[2] This volume describes the analysis of the SPM-2 results that was done to determine recommended paths for meeting the following DOE/CAO objectives:

[1] Regulatory assurance refers to the use of engineered barriers for the WIPP disposal system as required by 40 CFR 191.14(d).
[2] The reader is also referred to Helton et al. (in preparation) for a detailed description of the computational procedures used in SPM-2.

- Maximize PDC
- Minimize duration
- Minimize cost

This volume is organized around four major topic areas: (1) statistical regression analysis of the SPM-2 decision matrix for the pareto-optimal solution sets (Section 2); (2) potential sources of uncertainty inherent in SPM (Section 3); (3) uncertainty and sensitivity analyses of SPM-2 results (Section 4); and (4) summary and final programmatic recommendations (Section 5). A brief description of each activity evaluated by SPM-2, with its cost, start and end dates, and duration, can be found in Appendix A.

1.2 Approach

The SPM-2 decision matrix was completed in March 1995. Final programmatic recommendations were made to DOE/CAO in May 1995. These were based on the analysis of the SPM-2 decision matrix, which consisted for the following four steps:

1. First, the SPM-2 decision matrix was analyzed in order to answer the following strategic question: "Will the DOE/CAO depend on EAs, scientific investigations, WACs, or some combination of these for a demonstration of compliance on an accelerated schedule[3] with a reduced budget?" Based on a preliminary examination of SPM-2 results, DOE made the decision in March 1995 to depend on an experimental program comprised of scientific investigations for demonstrating compliance with 40 CFR 191.13(a) and 40 CFR 268.6 and to reserve EAs strictly for regulatory assurance.

2. Optimization analyses of the subset of decision matrix results were then performed to determine the most favorable activity set(s) within the constraints set by DOE/CAO's decision. Statistical regression analyses of the SPM-2 activity sets were performed to produce optimal series of activity sets leading to the highest incremental gains in PDC for the least incremental additional cost. This step resulted in showing marginal (incremental) value provided by each activity set in the optimal series.

3. Sensitivity studies were then performed to investigate quantitatively the impact of uncertainties in the SPM-2 results on the optimal series. These uncertainties stem, for the most part, from practical limitations that arose during the implementation of SPM-2. This step provided an indication of the robustness of the SPM-2 decision matrix and looked at the impact (if any) that each uncertainty might have on the conclusions drawn from the statistical regression analysis.

[3] The 1994 WIPP Disposal Decision Plan (DDP) called for a schedule accelerated over those in previous plans for a decision to submit a compliance application. This DDP called for the completion of performance assessment calculations for demonstrating compliance by the end of the 1996 calendar year.

4. The quality of the SPM-2 input and analysis were considered in addition to the quantitative sensitivity analysis. Senior management evaluated the degree to which the quality of the SPM-2 work may or may not have impacted the validity of technical conclusions. The relative significance of the weakest areas was explored, and these areas were discussed with DOE/CAO prior to making final recommendations. Additional discussions with DOE/CAO in this final step included the choice of applicable regulations used in the analysis and how technical issues raised by various stakeholders were addressed.

Note that SPM-2 did not address how changes in regulatory requirements might impact the SPM-2 results. As indicated in Volume I of this report, DOE/CAO directed SPM-2 to consider 40 CFR 191.13(a) and 40 CFR 268.6, but not proposed rule 40 CFR 194.

Section 2 of this report describes the evaluation of the SPM-2 decision matrix, and summarizes the preliminary interpretations of the SPM-2 results, DOE/CAO's strategic decision, and the results of the regression analysis. Section 3 reviews potential sources of uncertainty inherent in SPM, and Section 4 presents the results of the evaluation of uncertainties specific to the SPM-2 decision matrix. The final programmatic recommendations and conclusions are appear in Section 5.

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2. EVALUATION OF THE SPM-2 DECISION MATRIX FOR PROGRAMMATIC RECOMMENDATIONS

2.1 Summary of Preliminary Interpretations of the SPM-2 Results

The SPM-2 decision matrix contains results for the three independent performance measures for each activity set: PDC, cost, and duration. The three-dimensional bar chart of the SPM-2 decision matrix (Figure 2-1) displays the activity sets that lead to the highest PDC within given cost and duration categories. The full set of SPM-2 results was examined using two-dimensional scatterplots.

Preliminary interpretations of the SPM-2 results contained in the two-dimensional scatterplots appear in Volume I and are summarized below. Figure 2-2 shows a plot of the PDC versus cost for a random sample of 4,000 SPM-2 activity sets. As indicated in Volume I and shown in Figure 2-2, the PDC generally tends to increase with increasing cost. Figure 2-2 also shows that the results fall into four groups, activity sets with EA 1[4] and/or EA 2[5] (III and IV in Figure 2-2), activity sets with WAC 1[6] (V in Figure 2-2), activity sets with EA 3[7] (VI in Figure 2-2), and activity sets with scientific investigations only (I in Figure 2-2). A more detailed study of these results showed that there are multiple activity sets that lead to the points plotted in Figure 2-2. The choice of programmatic options therefore depended on the priorities of the decision maker with regard to incremental cost, duration, and PDC for the activity sets, in conjunction with other considerations (see Section 5.3).

In Volume I, it is reported that approximately 30% of the SPM-2 activity sets have a calculated PDC value equal to 1.0. The activity sets with PDC values equal to 1.0 are associated with particular EAs in combination with one of two scientific investigations (III and IV in Figure 2-2). However, these EAs were assigned a 100% probability of yielding the predicted disposal system performance, as were the outcomes of the requisite scientific programs in that group. The EAs in activity sets with a PDC value equal to 1.0 were those that add a backfill with a pH buffer to control actinide solubility and those that add an engineered backfill (such as clay) in combination with a waste form modification (such as shred and grout). These EAs by themselves have a PDC of 0.0, and it was only in combination with scientific activities that investigate colloid formation and transport that they became effective. Moreover, no single EA and no other single activity taken with the existing baseline led to a nonzero PDC; a nonzero PDC could be achieved only by combining one or more EAs with scientific activities.

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[4] EA 1 consists of backfill modified to control pH. (See Appendix A for a complete list and description of all SPM-2 activities.)
[5] EA 2 consists of both a backfill modified to control pH and waste form modification, such as shred and grout.
[6] WAC 1 requires replacing metal containers with noncorroding material.
[7] EA 3 is passive markers.

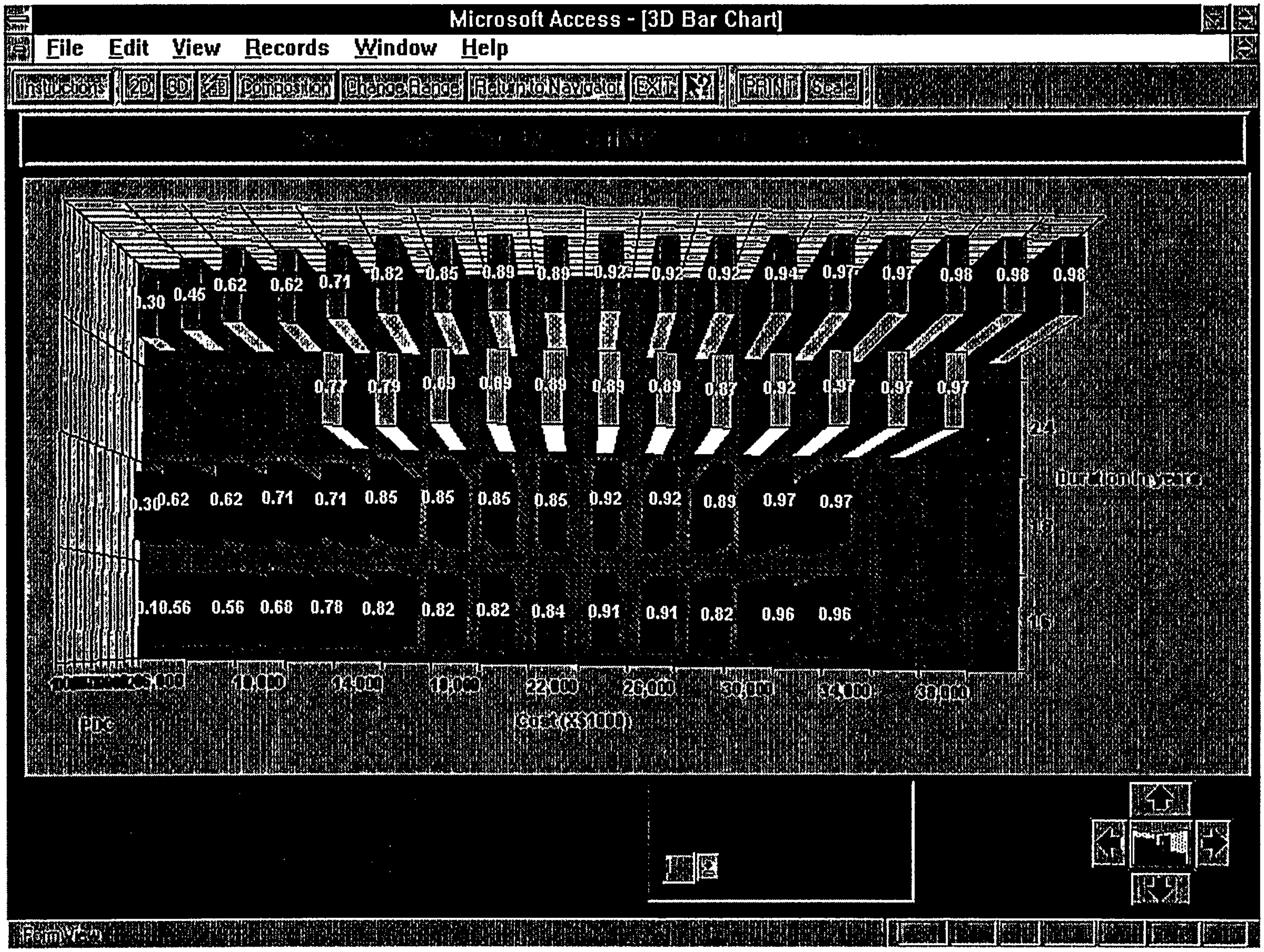

Figure 2-1. SPM-2 decision matrix: 3-D bar chart for scientific investigations (PDC versus cost and duration).

Figure 2-2. SPM-2 decision matrix: 2-D scatterplot of PDC versus cost for a random sample of 4,000 activity sets.

SPM-2 included two WACs in the analysis. For WAC-1, steel drums for waste storage were replaced with noncorrodible materials. The activity sets containing WAC-1 resulted in significant additional expense to the program and a slightly reduced PDC. WAC-2, the elimination of all high-molecular weight organic compounds (such as soils) from the waste, had no discernible impact on the PDC of any activity set.[8]

2.2 Strategic Decision Based on Preliminary Interpretation of the SPM-2 Decision Matrix

Based on the preliminary interpretations of the SPM results, summarized above, DOE/CAO made the decision in March 1995 to depend on the scientific investigation program (I in Figure 2-2) for demonstrating compliance, reserving EAs for assurance, and requiring no additional WACs for demonstrating compliance with 40 CFR 191.13(a) and 40 CFR 268.6. With the focus narrowed to scientific investigations, the next step was to further analyze the SPM-2 results within the scientific program to determine which of the many cost-effective paths with a high PDC were preferable.

Statistical regression analyses of the SPM-2 results for the activity sets containing only scientific investigations were performed to answer the questions: What are the dominant activity sets? Within these activity sets, what is the incremental value of information provided by each activity? What dependencies, if any, exist between the activities in these sets? These statistical analyses yielded important insights into the predicted performance as well as the cost/benefit relationship for the elements of the scientific program. Programmatic dependencies that were not explicitly anticipated became apparent as a result of these regression analyses, and were important factors in making the final decision.

2.3 Regression Analysis Results — The Pareto-Optimal Series

The regression analysis yielded pareto-optimal series of activity sets[9] leading to the highest possible PDC as a function of cost for both unconstrained and constrained duration. The constrained duration scenario placed a time constraint on the duration of the activity series (less than or equal to 19 months) to produce optimal series consistent in duration with the existing WIPP Disposal Decision Plan (DDP). A detailed mathematical description of the regression analysis appears in Appendix B.

Important insights provided by the regression analysis are that performance interdependencies do exist between activities, and that programmatic decisions must account for these dependencies

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[8] As with all of the SPM-2 results, this conclusion was dependent on the predicted outcomes: in this case, the formation and transportation of actinide-bearing colloids due to the presence of soils.

[9] The elements of the pareto-optimal series are activity sets. Each activity set that is pareto-optimal has the property that no other combination of activities is both higher in PDC and lower in costs (after von Winterfeldt and Edwards, 1986).

in order to maximize the PDC. Because of these interdependencies, the activity sets in the pareto-optimal series should not be regarded as mix-and-match sets of activities, but rather a series of activities ordered from those with the greatest impact on the PDC to those with the least impact.

The regression analysis produced two pareto-optimal activity series: one for unconstrained duration and one for constrained duration. The unconstrained pareto-optimal activity series consists of 10 scientific activities and has a final cumulative PDC of 0.97; the end date of the series is September 30, 1997, with a total estimated cost of $32.364 million.[10] The pareto-optimal activity series for the constrained duration consists of eight scientific activities and has a final cumulative PDC equal to 0.96. The series has an end date of November 30, 1996, and a total estimated cost of $29.250 million.

The cumulative PDC value of the activities in each activity series is plotted as a function of cost in Figure 2-3 and a function of duration in Figure 2-4. Figure 2-3 shows how each activity set in the series includes the activity specified at the plot in the figure plus all activities of lower cumulative cost. Similarly, Figure 2-4 shows how the PDC for activities in the activity series accumulates over the time domain required for completion.

The suboptimal series shown in Figure 2-3 is one of many other possible paths that achieve the same final cumulative PDC as the pareto-optimal series for the same total cost. The suboptimal series in Figure 2-3 is shown only to illustrate that there is a risk of choosing a path based solely on the final cumulative PDC of the set and total cost without considering the incremental value of each activity in the series. Looking at the suboptimal series provided insights about how the information provided by the activities would be interrelated and dependent on predecessor activities for its value to the program. These insights can be important in case of budget cuts or failure of activities to produce the predicted information. Selecting the pareto-optimal and understanding the interrelationships and dependencies between activities, DOE/CAO can respond to changes in an optimal fashion.

Tables 2-1 and 2-2 list the pareto-optimal series shown in Figures 2-3 and 2-4 for the unconstrained scenario and the duration-constrained scenario, respectively. Each row in the tables indicates an activity set in the series that includes the specified activity in the given row plus all activities in the preceding rows. Each activity set has a corresponding PDC and cost. The activity set cost is the sum of the costs for all activities in the set and the activity set PDC is the cumulative PDC provided by all activities up to that point. The activity series end date is determined by the latest end date of the activities in the set. Thus, although NS 2 has an end date of September 30, 1996 (see Appendix A), the end date of the activity set is determined by the end date of the predecessor activity with the latest end date in the series, which is November 30, 1996.

Not surprisingly, the programmatic value of the activities is not fully captured by the value of the PDC. For instance, every activity set with a nonzero PDC contains NS 8.1 (colloid

[10] These figures represent the cost estimates as they were reported to the SPM-2 team.

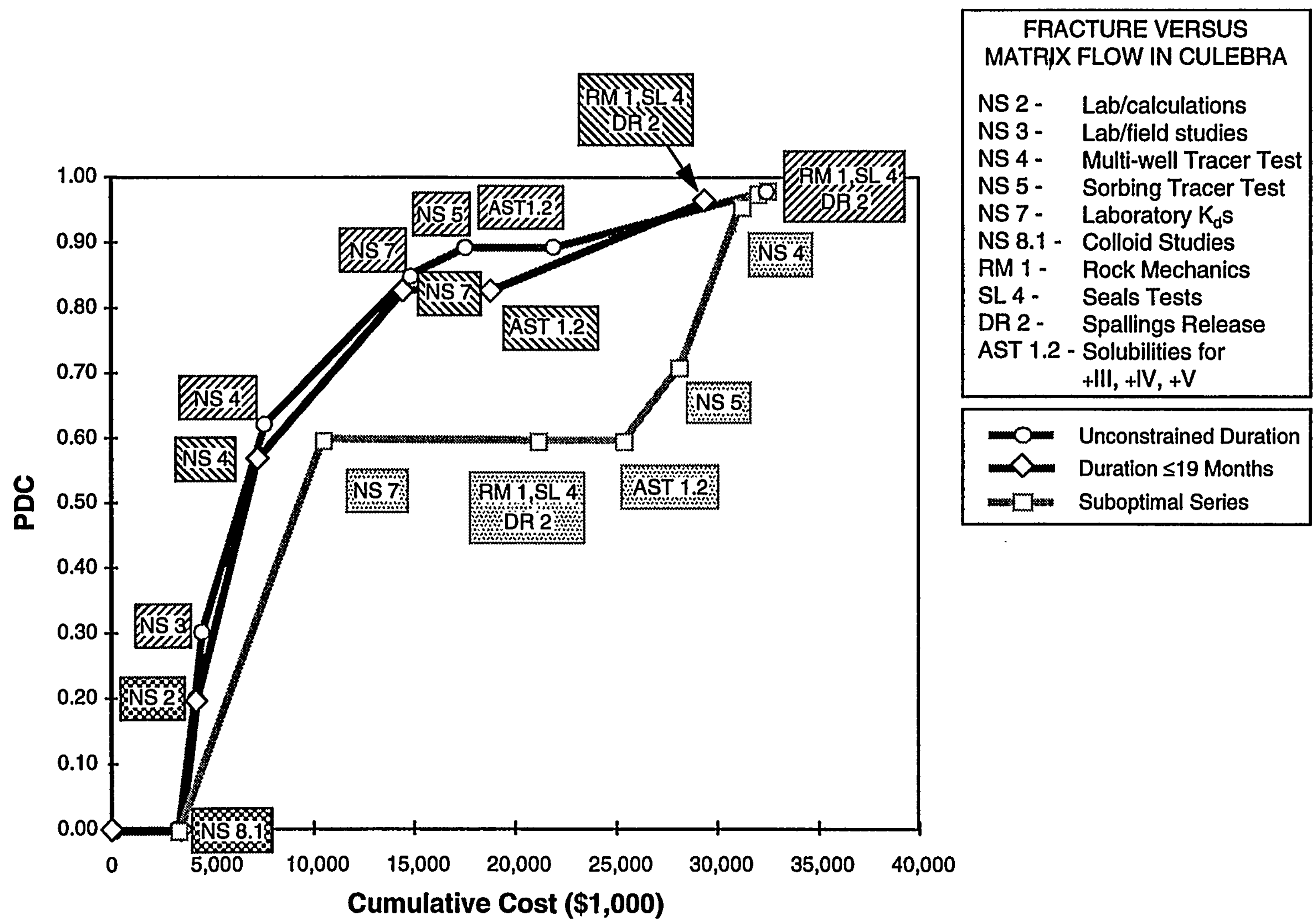

Figure 2-3. Pareto-optimal series of activity sets for scientific investigations (PDC versus accumulated cost).

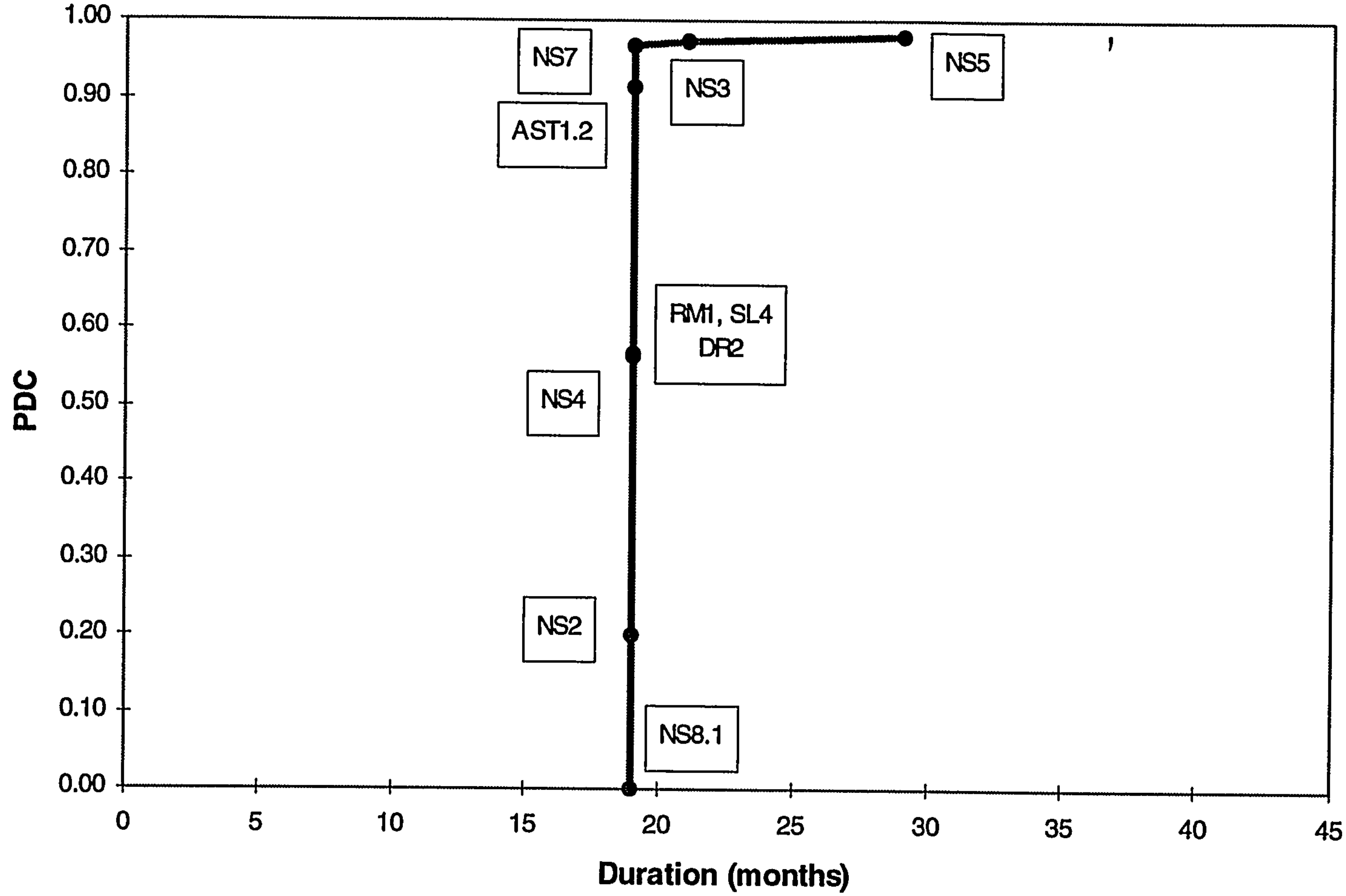

Figure 2-4. Pareto-optimal series of activity sets for scientific investigations (PDC versus duration).

Table 2-1. Pareto-Optimal Activity Series for Unconstrained Duration

Activity	Description	Activity Set Identification Number*	Activity Set Cumulative PDC	Activity Cost ($K)	Activity Set Cumulative Cost ($K)	Activity Set End Date
NS 8.1: Colloid Concentrations and Transport	Colloid concentrations formed for humic and microbial materials, physical and chemical retardation of each	16384	0.0	3,242	3,242	11/30/96
NS 2: Culebra Fracture/Matrix/Flow - Lab	Reexamine core data, review 1992 PA for matrix participation, 3D simulations, improve understanding of transmissivity field, conduct multiphase flow scoping calculations.	16896	0.19	816	4,058	11/30/96
NS 3: Culebra Fracture/Matrix/Flow - Field	Drill additional wells over the repository for information on the T-field. Implement a technically defensible model for compliance calculations.	17920	0.30	404	4,462	2/1/97
NS 4: Multi-Well Tracer Test	Specific surface area for matrix diffusion in Culebra	19968	0.62	3,113	7,575	2/1/97
NS 7: Chemical Retardation in the Culebra	Examine mechanisms of retardation and conceptual model to determine K_d (chemical retardation factor) distributions for modeling	28160	0.85	7,200	14,775	2/1/97
NS 5: Sorbing Tracer Test	Perform field non-sorbing tracer test to confirm laboratory-derived K_d distribution	32256	0.89	2,710	17,485	9/30/97
AST 1.2: Dissolved Actinide Solubilities	Actinide solubility in oxidation states +III, +IV, +V	32258	0.89	4,304	21,789	9/30/97
SL 4 + RM 1 + DR 2: Short- and Long-Term Seal Component Studies using MDCF Rock Mechanics Model; Blowout Releases	Time-dependent permeability of upper (short-term) and lower (long-term) shaft seals; MDCF rock mechanics model; improved model for high pressure releases during human intrusion	32310	0.97	6,665 3,660 250	32,364	9/30/97

* The activity set identification number corresponds to the activity set ID on the Compact Disk-Read Only Memory (CD-ROM) that accompanies the SPM-2 final report.

Table 2-2. Pareto-Optimal Activity Series for Constrained Duration

Activity	Description	Activity Set Identification Number*	Activity Set Cumulative PDC	Activity Cost ($K)	Activity Set Cumulative Cost ($K)	Activity Set End Date
NS 8.1: Colloid Concentrations and Transport	Colloid concentrations formed for humic and microbial materials, physical and chemical retardation of each	16384	0.0	3,242	3,242	11/30/96
NS 2: Culebra Fracture/Matrix/Flow – Lab	Reexamine core data, review 1992 WIPP PA for matrix participation, 3D simulations, improve understanding of transmissivity field, conduct multiphase flow scoping calculations.	16896	0.19	816	4,058	11/30/96
NS 4: Multi-Well Tracer Test	Specific surface area for matrix diffusion in Culebra	18944	0.56	3,113	7,171	11/30/96
NS 7: Chemical Retardation in the Culebra	Examine mechanisms of retardation and conceptual model to determine K_d distributions for modeling	27136	0.82	7,200	14,371	11/30/96
AST 1.2: Dissolved Actinide Solubilities	Actinide solubility in oxidation states +III, +IV, +V	27138	0.82	4,304	18,675	11/30/96
SL 4 + RM 1 + DR 2: Short- and Long-Term Seal Component Studies using MDCF Rock Mechanics Model; Blowout Releases	Time-dependent permeability of upper (short-term) and lower (long-term) shaft seals; MDCF rock mechanics model; improved model for high pressure releases during human intrusion	27190	0.96	6,665 3,660 250	29,250	11/30/96

* The activity set identification number corresponds to the activity set ID on the CD-ROM that accompanies the SPM-2 final report.

concentration and transport), suggesting that NS 8.1 must be funded in any logical activity set. (Note that the pareto-optimal set contains NS 8.1 in preference to NS 8.2, because the impact on the PDC is the same for both activities, and NS 8.1 has a lower cost.) In addition, some activities (such as RM 4 and SL 4) are only found in combination with one another because they logically must be done together for the postclosure performance benefit. Also, one activity (AST 1.2) actually slightly decreases the PDC of an activity set. This is due to the fact that some of the outcomes for AST 1.2, which are given in terms of solubility, are actually less favorable than the baseline (see Volume 2 of this report for detailed activity outcome and baseline descriptions). If a higher PDC is desired, however, AST 1.2 must be included, because it is a necessary precursor to activities further along the series that do increase the PDC. Programmatic interdependencies are thus a key factor in programmatic decisions.

The results of the regression analysis indicate that, based on the decision maker's priorities in terms of cost, duration, and programmatic value (which includes both the PDC and programmatic interdependencies), a number of logical programmatic choices exist. If the decision maker is willing to accept a PDC of 0.62, for instance, then a logical programmatic option is to fund activities NS 8.1, NS 2, NS 3, and NS 4 at a cost of $7.575 million and an end date of November 30, 1996. If the decision maker prefers a PDC value of 0.85, then activity NS 7 must be performed in addition to NS 8.1, NS 2, NS 3, and NS 4, for a total activity cost of $14.775 million. If a 0.97 PDC is desired, the NS 5, AST 1.2, and SL 4, RM 1, and DR 2 must also be performed.

The final activity set in the constrained pareto-optimal activity series has a PDC value of approximately 0.97. The differences between the final activity set in the unconstrained pareto-optimal activity series and the final activity set in the pareto-optimal activity series constrained by the DDP is an increment of the PDC of 0.01, an additional cost of approximately $3 million, and approximately one additional year of duration. As shown in Figure 2-2, there is essentially no difference in the shape of the PDC/accumulated-cost curve between the two sets. A PDC greater than 0.96 requires funding NS 5 (the sorbing tracer test) and NS 3 (field tests for transmissivity in the Culebra), which moves back the activity set end date beyond the DDP to September 30, 1997. It is up to the decision maker to determine the threshold PDC that is acceptable, what it is worth to achieve that threshold, and what cost is warranted for an increase in the PDC. However, it seems clear that spending $3 million for a calculated increase of PDC of 0.01 would not be warranted.

In summary, the results of the regression analysis indicate the preferred decisions to make, depending on the DOE/CAO priorities with respect to PDC, cost, and scheduling concerns. The SPM-2 results were further examined for robustness to ensure a quality decision. This entailed evaluating the potential effects of uncertainties in the SPM-2 results themselves and the sensitivity of the pareto-optimal series to those uncertainties, as well as the quality of the input to SPM-2.

3. POTENTIAL SOURCES OF UNCERTAINTY IN SPM

The purpose of SPM is to assist DOE/CAO to make informed strategic decisions that have a high likelihood of achieving the programmatic objectives—in this case, demonstrating compliance with the long-term performance requirements within the shortest time and for the least cost. The very nature of SPM, therefore, is to provide a consistent technical basis for making decisions despite uncertainty about what the future state of knowledge about the WIPP repository will be after implementing certain courses of action. However, when invoking any process for decision making, including SPM, one must ask: How robust is the decision-analysis process? The decision maker must then determine how to weigh the uncertainty in the process itself when using the information provided by the process. This section reviews the potential sources of uncertainty inherent in SPM. The results of the analysis of uncertainties specific to SPM-2 are presented in Section 4.

The theoretical basis underlying SPM can be found in decision analysis literature, in which the value of decision options are calculated on the basis of elicited judgments of the probability of obtaining different outcomes for each of the options (Von Winterfeldt and Edwards, 1986). SPM integrates existing WIPP Performance Assessment (PA) tools (see WIPP PA, 1992) into such a decision analysis method to calculate the PDC, as shown in Figure 3-1. Uncertainties in the input and in the way the input is modeled may create uncertainties in the calculated PDC, cost, and duration results. Other potential sources of uncertainty in SPM arise when setting the performance objectives and when establishing the measure (i.e., compliance indicator in Figure 3-1) for analyzing whether those objectives may be met by the options under consideration.

Figure 3-2 illustrates the potential sources of uncertainty and where they may occur in SPM. In Figure 3-2, oval shapes represent primary sources of uncertainty that may affect portions of the SPM calculations and could therefore affect SPM results, conclusions, and recommendations. The following sources of uncertainty are discussed below: uncertainty in the PDC, the use of a binary indicator for compliance (as opposed to a continuous measure), the accuracy of the cost and duration information for each activity, uncertainty in the performance objectives, and uncertainties introduced by other programmatic considerations.

3.1 Uncertainty in the Probability of Demonstrating Compliance

Calculating the PDC is an attempt to anticipate the results of compliance calculations in a compliance certification application. However, the PDC in SPM is actually a surrogate, obtained by estimating the potential results of proposed activities that are designed to yield information about disposal system performance relative to 40 CFR 191.13(a) and 40 CFR 268.6. The calculated PDC values are a sound basis for compliance-based decision-making to the extent that

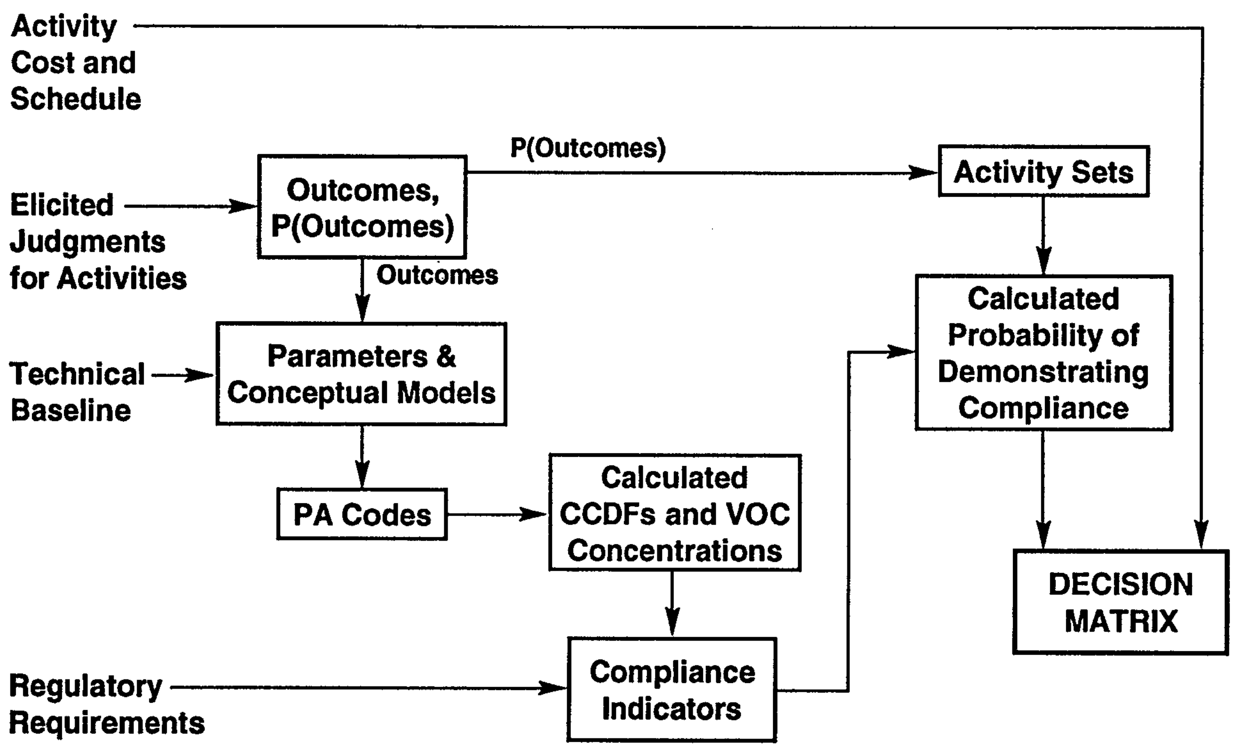

Figure 3-1. Information flow in SPM.

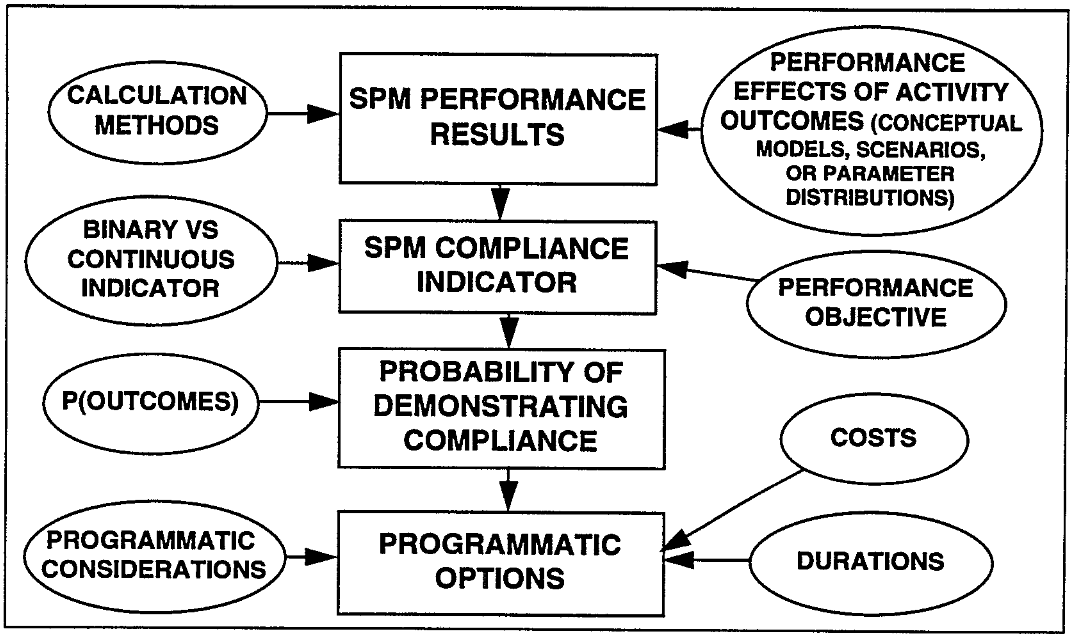

Figure 3-2. Potential sources of uncertainty in SPM. (Note that performance effects of activity outcomes are expressed as conceptual models, scenarios, or parameter distributions.)

in the process, the technical input approximates not only the potential outcomes, but also addresses all relevant issues defined in 40 CFR 191.13(a) and 40 CFR 268.6.

SPM is valuable even apart from anticipating compliance calculations. It provides a technical rationale for evaluating the value of activities through explicitly defining the value of the information they provide. It is important to identify and understand potential uncertainties inherent in the PDC results. These uncertainties, however, will not undermine the programmatic relevance of these results to the DOE/CAO as long as the results are robust with respect to showing the value of the information for assessing the disposal system performance.

There are three distinct steps for characterizing the uncertainty in the PDC results and understanding how those results may be interpreted in a determination of compliance :

1. For each activity considered, a range of possible outcomes is described by a set of specific, empirical statements that could be verified or refuted at the conclusion of the activity (e.g., the measured quantity will be in a specific range, or the results of the experiment will be consistent with a specific model or processes occurring at the experimental scale). Activity outcomes are possible data or parameter values upon which calculations might be based. Uncertainty in the activity outcomes is expressed by assigning probabilities to these outcomes. These probabilities are based on expert judgment and will introduce some uncertainty in the results of the decision-analysis process.

2. The functional relation between activity outcomes and performance calculations must be identified. This functional relation includes the technical basis for extrapolating the predicted results of the scientific investigations (e.g., experimental data, parametric modeling studies, literature searches) to the parameters used in performance calculations over large spatial and time scales under the assumed repository conditions. Uncertainty in the PDC is introduced where there is lack of rigor in specifying the technical basis for extrapolating from predicted outcome results of scientific investigations to performance effects in terms of input parameters for performance calculations.

3. The values for the regulatory performance measures (i.e., complementary cumulative distribution functions (CCDFs) and RCRA hazardous constituent concentrations) for each outcome and combinations of outcomes are calculated using the disposal system model and parameter values from steps 1 and 2, and compared with the performance objective. Uncertainty can be introduced both in the calculations and in the validity of the performance objective that is specified.

Uncertainty in the PDC can arise from uncertainty introduced in each of the three steps above. Each step has different potential sources of error and different requirements for controlling uncertainty.

Step 1 involves characterizing the possible outcomes of experiments and assigning probability to those outcomes. These assignments represent a degree of belief in the occurrence of each outcome, and are necessarily subjective. The principle investigators (PIs) for these activities are uniquely qualified to express the range of possible outcomes in empirically testable terms. The PIs have access to a great deal of information relating to the activities they are conducting, so their probability assignments are especially meaningful. A properly developed and implemented elicitation process is a reliable way for managing uncertainty in identifying outcomes and assigning probabilities to these outcomes (Trauth et al., 1994). See Section 4.1.1 for a discussion on the sensitivity of the SPM-2 results to the quality of elicited expert judgment in defining the activities and the probabilities of activity outcomes.

Step 2 begins by regarding each activity outcome as hypothetical data, and then connects this data (in combination with all other information that might be included in performance calculations for a compliance application) to modeling assumptions and sampling parameter values for use in the performance calculations. For example, suppose outcome A of an activity is hypothesized to be x number of fractures per square meter with a probability of 30% in step 1. Step 2 would then generate the technical basis for assigning hydrologic and chemical transport properties to be used in performance calculations, based on the number of fractures. The same processes that help to ensure the quality and robustness of the arguments in the baseline (e.g., evaluation with reference to critical comments) are appropriate for defining the PA implication of activity outcomes. Uncertainty can arise in the PDC calculations when the reasoning that connects activity outcomes to potential performance calculations is not well-defined or critically evaluated.

In some cases, step 3 may involve approximating the conceptual models and parameter values defined in step 2 using existing software. Uncertainty in PDC is a function of the quality of this approximation. This uncertainty is controlled by understanding the differences between the ideal calculation (step 2) and the capabilities of the existing code. For SPM-2, this involved evaluating of the sensitivity of the results to the sampling approach used (see Section 4.1.2), defining side investigations (supplementary and confirmatory evaluations) to investigate the degree of uncertainty introduced by some of the choices made for calculation models (see Section 4.1.3), and evaluating the performance benefits of activities (see Section 4.1.5).

3.2 Compliance Indicator

The binary measure of compliance used for each activity set in SPM simply indicates whether or not the performance results for that activity set are predicted to comply with the selected regulatory containment requirements as interpreted in terms of the performance objective. In SPM, the compliance indicator is equal to 1 only when performance results predicted compliance with the specified performance objectives. Predictions that the performance objectives are violated give an SPM compliance indicator of 0 for an activity set. (For SPM-2, the compliance indicator was 1 only when performance results predicted CCDFs below the release limits set for long-term performance in 40 CFR 191.13(a) and when the limits on soil-based concentrations of hazardous constituents specified in 40 CFR 268.6 were met.)

The National Academy of Science (NAS) WIPP Panel questioned whether a continuous measure of compliance may be more appropriate for decision analysis (NAS WIPP Panel meeting, November 17, 1994). A continuous measure shows not only whether the CCDF meets the regulatory limits, but also how far the CCDF is from the limits. The use of either indicator has merit, depending on the goals and criteria of the decision maker and the context of the decision. The issue of which measure to use should be resolved as a policy decision. However, in addressing potential sources of uncertainty, there was concern about whether the recommended pareto-optimal set was sensitive to the choice of a binary compliance indicator over a continuous measure. This issue was investigated for SPM-2. The results of this analysis are discussed in Section 4.1.4.

3.3 Cost and Duration

There are inherent uncertainties in the cost and duration of SPM activities. This is because cost and duration input in the SPM analysis consisted of single-value estimations made using varying budget estimates and varying durations for scientific investigations. In the original concept of SPM, these uncertainties were not explicitly considered, but, in retrospect, are unlikely to have affected the decision matrix results. In theory, future applications of SPM to other projects could consider cost and duration uncertainties and treat them more explicitly. See Sections 4.2 and 4.3 for discussions on cost and duration uncertainties specific to SPM-2.

3.4 Performance Objectives

The performance objectives chosen for the basis of the decision analysis are the cornerstone of SPM. These must be appropriate for the context and accurately reflect the objectives of the decision maker and the concerns of key stakeholders. Uncertainty is introduced into SPM in as much as these objectives fall short of these goals. The process of setting the performance objectives lies in a framework currently outside SPM, but could be combined with SPM. There are several existing processes in use today that are appropriate for formally setting performance objectives. Examples include the Vital Issues Process (Engi and Glicken, 1995), the Analytical Hierarchy Process (Saaty, 1990), and Multiattribute Utility Analysis (Merkhofer and Keeney, 1987; Jenni et al., 1995; Kadvany and Kann, 1995; Keeney and Raiffa, 1976).

3.5 Qualitative Programmatic Considerations

There will always be qualitative programmatic considerations that are important to consider before making final decisions. SPM does not attempt to deal directly with uncertainties introduced by such considerations. Therefore, a values trade-off study was performed after completing SPM and prior to making final decisions to investigate the impact of any of these considerations. The degree to which these were an influence in SPM-2 is discussed in Section 4.5.

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4. EVALUATION OF UNCERTAINTY IN THE SPM-2 DECISION MATRIX

This section discusses the sensitivity of the pareto-optimal series identified by the regression analyses to both quantitative and qualitative evaluation of the uncertainties specific to the SPM-2 results. A complete assessment of the sensitivity of these uncertainties is beyond the scope of the SPM-2 effort. However, the analyses described in this report were sufficient to convince the authors and the WIPP senior Sandia National Laboratories (SNL) management that no significant sources of-uncertainty (or variability in uncertainty) were found that would provide the basis for further discrimination between activities, or that would lead to different pareto-optimal activity series, so long as the decision analysis is restricted to scientific activities and further evaluation of EAs and WACs is conducted outside the SPM-2 structure.

Section 4.1 describes the quantitative evaluation of the effects of uncertainty in calculating the PDC. Sections 4.2 and 4.3 discuss the uncertainties in activity cost and duration in SPM-2. Section 4.4 discusses consideration of the SPM-2 results along with information in existing sensitivity and uncertainty analyses of the WIPP Project. Section 4.5 discusses qualitative effects of uncertainty resulting from considerations related to the implementation of SPM-2.

4.1 Probability of Demonstrating Compliance

In SPM-2, the primary sources of uncertainty about the calculated PDC values stem from:

1) elicitation of probabilities of outcomes by expert judgment,
2) using mean parameter values instead of latin hypercube sampling (LHS) parameter values in the performance calculations,
3) accuracy of the performance benefit estimates of each activity outcome and the final form of the PA codes used to model this benefit, and
4) a binary measure for indicating compliance, as opposed to a continuous indicator.

Constraints imposed by the existing PA codes in defining the SPM-2 calculations were discussed by the analysts and experimentalists during the elicitation meetings to characterize outcomes in a manner that would both accurately reflect the intent of the experimentalists, and to provide information that could be accommodated meaningfully and efficiently. Side investigations were defined to investigate the degree of uncertainty introduced by some of the choices made for calculation models. (See discussion in Section 4.1.3.)

4.1.1 Sensitivity of SPM-2 Results to Quality of Expert Judgment in Elicited Activities and Probabilities of Activity Outcomes

PDC values were calculated directly from elicited activity outcome probabilities. In SPM-2, a structured elicitation process was employed to control potential sources of error and uncertainty. This process was modeled after the formal elicitation format described in Trauth et al. (1994) for identifying outcomes and probabilities of outcomes. Ideally, there should be consistency of assumptions between all PIs providing this information. As mentioned above, however, exact consistency can never be fully realized. Eliciting information from a large number of PIs introduced degrees of interpretation that could not be completely controlled, although all PIs were provided with the same training.

Moreover, multiple elicitors were required for SPM-2, introducing variations in techniques of elicitations. The elicitation process was designed to reduce the impact of using multiple elicitors; however, there were cases where differences in elicitation style resulted in inconsistent representations of the probabilities of the activity outcomes. It became important, therefore, to investigate how these factors might affect the SPM-2 results for the recommended programmatic path.

In some cases, such as with those activities defining existing experimental programs, a firm technical rationale between the activity outcome and PA calculation models was already in place. In other cases, there was a need for developing the technical rationale for either the outcome or a PA model to emulate the outcome. These latter cases required iteration between principal investigators (PIs) and PA analysts in follow-on meetings through a controlled, documented process. Follow-on meetings were also required to resolve differences in the way the elicitation results were reported and interpreted by the multiple elicitors. A script was developed to guide the discussions in these follow-on meetings in a consistent manner. The expert judgment used as input to SPM-2 was also of inconsistent quality. Each of these issues was examined through limited sensitivity studies for its impact on the calculated PDC values.

One of the key assumptions going into the elicitations was that there would be some nonzero probability of failure of the activity, as well as some distinction between possible outcomes for a successful experiment. However, there were four types of activities where activity outcomes and probabilities of outcomes were presented in terms of only the two outcomes: complete success (100% probability) and failure (zero probability). These were: EAs, WACs, colloid studies, and actinide source term. One interpretation of these numbers is that the outcome of the activity investigations can be predicted with 100% certainty. This raises the question: Why should the activity be performed at all?

The answer lies in the way in which this information was collected and how the probabilities were expected to be used in the performance analysis. With respect to EAs and WACs, there was no basis for establishing a value for the probability of success and failure other than 100% and 0%. With respect to scientific investigations for colloids and actinide solubility, the uncertainty in the outcome of an activity was captured in the outcome parameter distributions (i.e., retardation factors and solubilities) rather than the elicited probability of the activity outcome. If this is true for all affected scientific investigations, then uncertainty is embedded in the performance analysis (or at least the input), as opposed to being an independent calculation done after the performance analysis when determining the PDCs for the decision matrix.

In the case of colloid studies, it is clear that irrespective of the probability of success of the activity by itself, colloid studies are essential for a successful activity set. A more refined probability distribution for success or failure to use in the decision analysis would therefore have the effect of linearly scaling down the highest PDC, but would not change the conclusion that a colloid activity (either NS 8.1 or NS 8.2) belongs in the optimal sets. This is described in more detail below.

An unambiguous conclusion is more difficult with respect to the actinide solubility. Previous sensitivity studies, such as the WIPP 1992 PA, confirm that performance results are highly sensitive to actinide solubility. Whether the results of the experimental program for actinide solubility can increase the PDC, however, is a separate issue. The actinide solubility outcomes for SPM-2 did predict some positions less favorable than the baseline; the probabilities of those outcomes, however, were a concern. A complete sensitivity study of the SPM-2 results to these probabilities was not performed because of the inordinate amount of effort required.

4.1.1.1 INFLUENCE OF NS 8.1 AND EA 1 ON SPM-2 PDC VALUES

An analysis of the SPM-2 PDC values shows that the PDC is strongly controlled by the presence or absence of activities NS 8.1, NS 8.2, EA 1, and EA 2. The effect of NS 8.1 on the PDC is indistinguishable from the effect of NS 8.2, and the effect of EA 1 is indistinguishable from EA 2. NS 8.2 and EA 2 are more expensive than their counterparts, and were therefore excluded from further analysis. Any observations or conclusions regarding the effects on PDC of different outcome probability assignments for NS 8.1 or EA 1 are also valid for analogous sets including NS 8.2 or EA 2.

The effect of NS 8.1 and EA 1 on PDC can be concisely summarized:

1. Activity sets that do not include NS 8.1 have a PDC of 0.

2. All activity sets that include EA 1 (and include NS 8.1) have a PDC of 1.

Both NS 8.1 and EA 1 have the following characteristics:

- Two outcomes (success and failure) were defined;

- The probability of the outcome of success was assigned a value of 1, and the probability of failure (which implies use of baseline assumptions) was assigned the complementary probability value of 0;

- Activity set PDC values are strongly influenced by the presence of the activity.

A probability value of 1 for the outcome of success is effectively an assertion that the result of the activity can be absolutely predicted using existing information. However, for experimental activities, an outcome probability of 1 implies that no new information will be provided by the experiment and that existing information is sufficient to predict the outcome with certainty. A probability of 0 for outcomes leading to the baseline assumptions is an assertion that existing information precludes the possibility of the baseline assumptions being appropriate. This assertion is inconsistent with a baseline based on existing information. Therefore, the sensitivity of the SPM-2 results to the probability assignments of EA 1 and NS 8.1, listed above, was investigated as described below.

4.1.1.2 EFFECT OF NS 8.1 OUTCOME PROBABILITY ASSIGNMENTS

4.1.1.2.1 Effect of NS 8.1 Outcome Probability Assignments on PDC Values

The effect of alternative assignments of NS 8.1 outcome probability on PDC values can be easily described. The PDC value of an activity set S_i that contains NS 8.1 can be written as a sum of conditional probabilities based on the possible outcomes of NS 8.1:

$$
\begin{aligned}
PDC(S_i) = {} & PDC(S_i|Outcome(\text{NS 8.1}) = Success) * P(Outcome(\text{NS 8.1}) = Success) + \\
& PDC(S_i|Outcome(\text{NS 8.1}) = Failure) * P(Outcome(\text{NS 8.1}) = Failure).
\end{aligned} \tag{1}
$$

The outcome of failure for NS 8.1 would imply baseline assumptions with respect to colloid mobilization and transport. According to conclusion (1) in Section 4.1.1.1, no activity set has a PDC value greater than 0 when constrained by the baseline colloid assumptions, so that

$$PDC(S_i|Outcome(\text{NS 8.1}) = Failure) = 0.$$

For the outcome of success, the PDC values are given by the existing calculated values. Denoting PDC_o to mean those PDC values calculated where the probability of success of NS 8.1 is equal to 1, and PDC_n to be those PDC values calculated using some modified value for the probability of NS 8.1 success, equation (1) reduces to:

$$
\begin{aligned}
PDC_n & = PDC(S_i|Outcome(\text{NS 8.1}) = Success) * P(Outcome(\text{NS 8.1}) = Success) \\
& = PDC_o * P(Outcome(\text{NS 8.1}) = Success.
\end{aligned}
$$

In words, reducing the assigned probability for a successful outcome of NS 8.1 amounts to multiplying all existing PDC values by the assigned outcome probability. Because the success of NS 8.1 is a necessary precondition for producing a CCDF that complies with the containment requirements in 40 CFR 191.13(a), assigning a probability of P_n to the success of NS 8.1 effectively establishes P_n as the maximum value of PDC. All existing PDC values would be "compressed" from the range [0,1] to the range $[0,P_n]$.

4.1.1.2.2 Possible Effects of NS 8.1 Outcome Probability Assignments on PDC-Based Decisions

Modifying the assigned outcome probability for NS 8.1 from 1 to P_n would reduce the PDC value for all activity sets by a factor of $P_n/1$. To the extent that PDC-based decisions would be predicated on *relative* PDC values, or predicated exclusively on cost or duration, the decision would be insensitive to P_n. For decisions based on *absolute* PDC values, additional activities would be necessary to achieve the same value of PDC. The specific activities that might be required would, of course, depend on the specific PDC criterion, as well as cost and duration limits. Note that because NS 8.1 appears as a necessary element of all activity sets, it is not possible to achieve a PDC value greater than P_n.

4.1.1.3 EFFECT OF EA 1 OUTCOME PROBABILITY ASSIGNMENTS ON PDC VALUES

As with sets containing NS 8.1, PDC values for sets S_i containing EA 1 can be written in terms of conditional probabilities and EA 1 outcome probabilities:

$$PDC(S_i) = PDC(S_i|Outcome(\text{EA 1}) = Success) * P(Outcome(\text{EA 1}) = Success) + PDC(S_i|Outcome(\text{EA 1}) = Failure) * P(Outcome(\text{EA 1}) = Failure). \qquad (2)$$

If S_i is further restricted to sets that contain NS 8.1 as well as EA 1, the second observation described in subsection 4.1.1.2.1 leads to:

$$PDC(S_i|Outcome(\text{EA 1}) = \text{Success}) = 1 \qquad (3)$$

for all sets S_i.

The PDC values conditional on failure of EA 1 can be estimated from existing calculations. In the context of SPM, "failure" of an EA means an inability, due to inadequate technical support, to take credit for the putative effects of the EA as part of a compliance argument. "Failure" does *not* refer to non-performance following repository closure: failure in the sense of nonperformance would be addressed in the compliance application. If EA 1 "fails" in the sense of an SPM activity, the design modification would not be implemented. The compliance calculation that corresponds to failure is therefore approximated by the analogous "no EA" calculation.

Symbolically, if S_i is an activity set that includes EA 1, and S_i' is the analogous activity set that does not include EA 1 (i.e. $S_i = S_i' \cup \{\text{EA 1}\}$), then

$$PDC(S_i | Outcome(\text{EA 1}) = Failure) = PDC(S_i'). \tag{4}$$

Combining equations (2), (3), and (4) gives the following expression for PDC in terms of EA 1 outcome probabilities:

$$PDC(S_i) = P(Outcome(\text{EA 1}) = Success) + PDC(S_i') * P(Outcome(\text{EA 1}) = Failure). \tag{5}$$

Suppose that the outcome of success for EA 1 is assigned a value of P_e. The probability of failure has the complementary value of $1-P_e$. P_e establishes the *minimum* PDC value for activity sets including EA 1 (and NS 8.1). The distribution of PDC values above P_e is identical to the distribution of PDC values for sets that do not include EA 1, but is compressed from the original interval of [0,1] to the interval $[P_e,1]$.

4.1.1.3.1 Possible Effects of EA 1 Outcome Probability Assignments on PDC-Based Decisions

The possible effects of alternate probability assignments for EA 1 success can be illustrated by assuming that the selected activity set is pareto-optimal with respect to PDC and cost. The pareto-optimal series can be developed from two separate activity sets, one consisting of *only* experimental activities, and a second consisting of the same experimental activities in combination with EA 1. The pareto-optimal series of scientific activities in combination with EA 1 is shown as a function of the assigned probability of success of EA 1 in Figures 4-1 and 4-2.

The pareto-optimal series of activities *excluding* EAs and WACs was shown earlier in Figure 2-2. This series is similar to the series discussed previously, but only consists of activities with a duration of 19 months or less. An analogous series can be developed for sets *including* EA 1 based on equation (5). Note that equation (5) is a linear transformation of PDC values, so that the pareto-optimal series for the sets $\{S_i\}$ (in the interval $[P_e,1]$) is identical to the series for $\{S_i'\}$, but is " compressed" along the PDC axis and shifted along the cost axis. Figure 4-3 shows how the PDC for the pareto-optimal series that included EA increases as a function of the probability of success for EA 1.

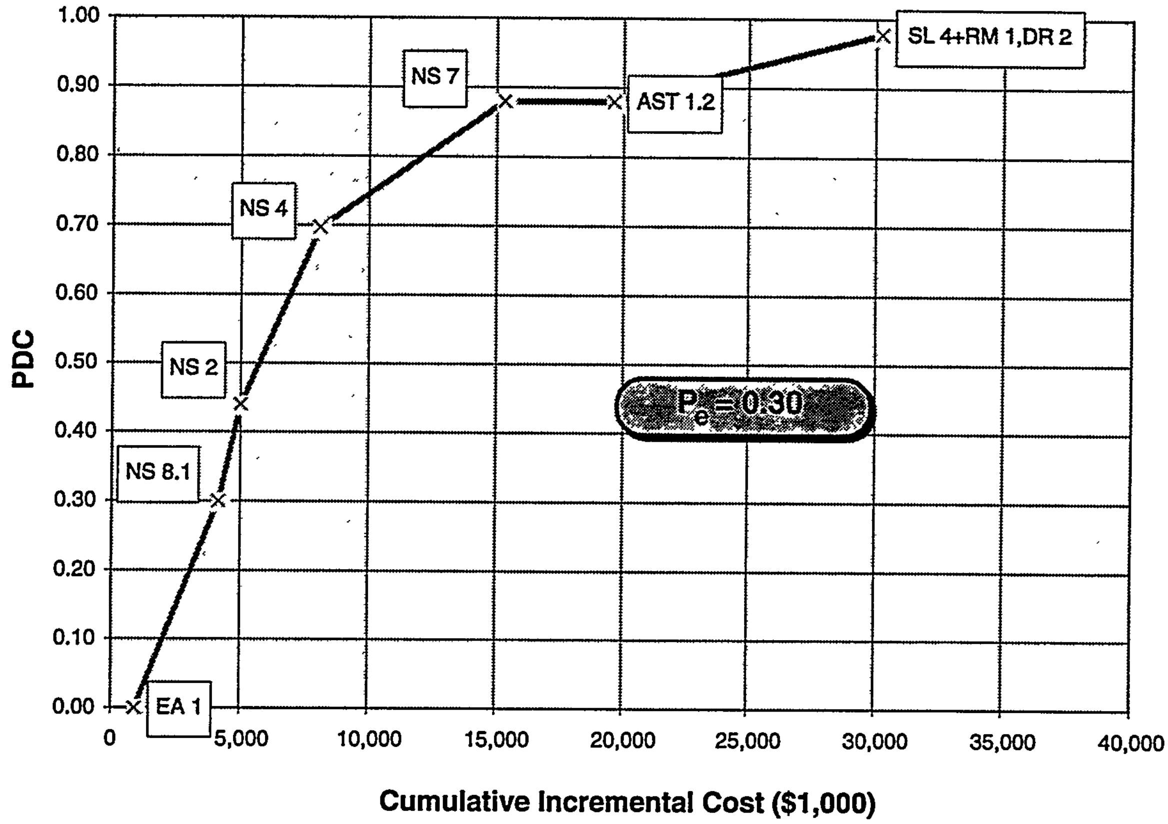

Figure 4-1. Pareto-optimal series of activity sets for scientific investigations in combination with EA 1 when $P_e = 0.30$: Duration $\leq$ 19 months.

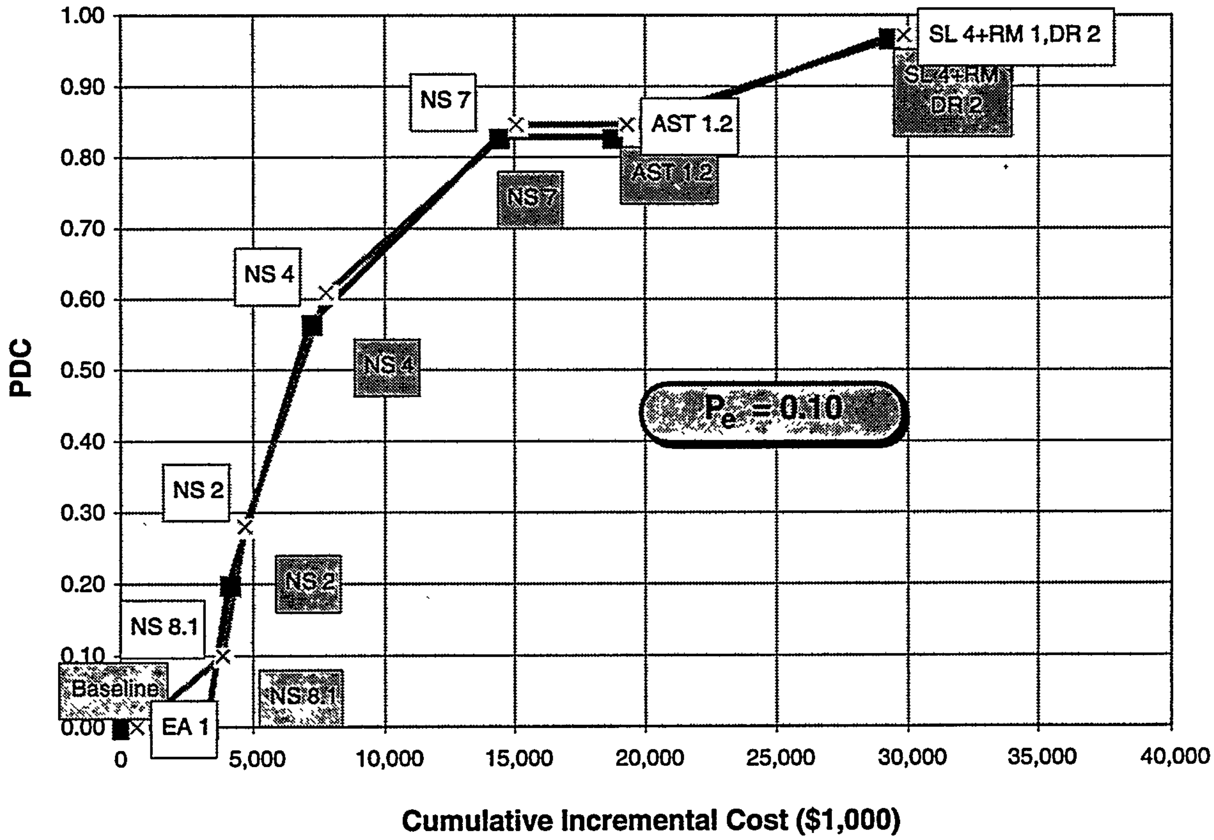

Figure 4-2. Two pareto-optimal series of activity sets, one for scientific investigations in combination with EA 1, and one for scientific investigations alone, when $P_e = 0.10$: Duration ≤ 19 months.

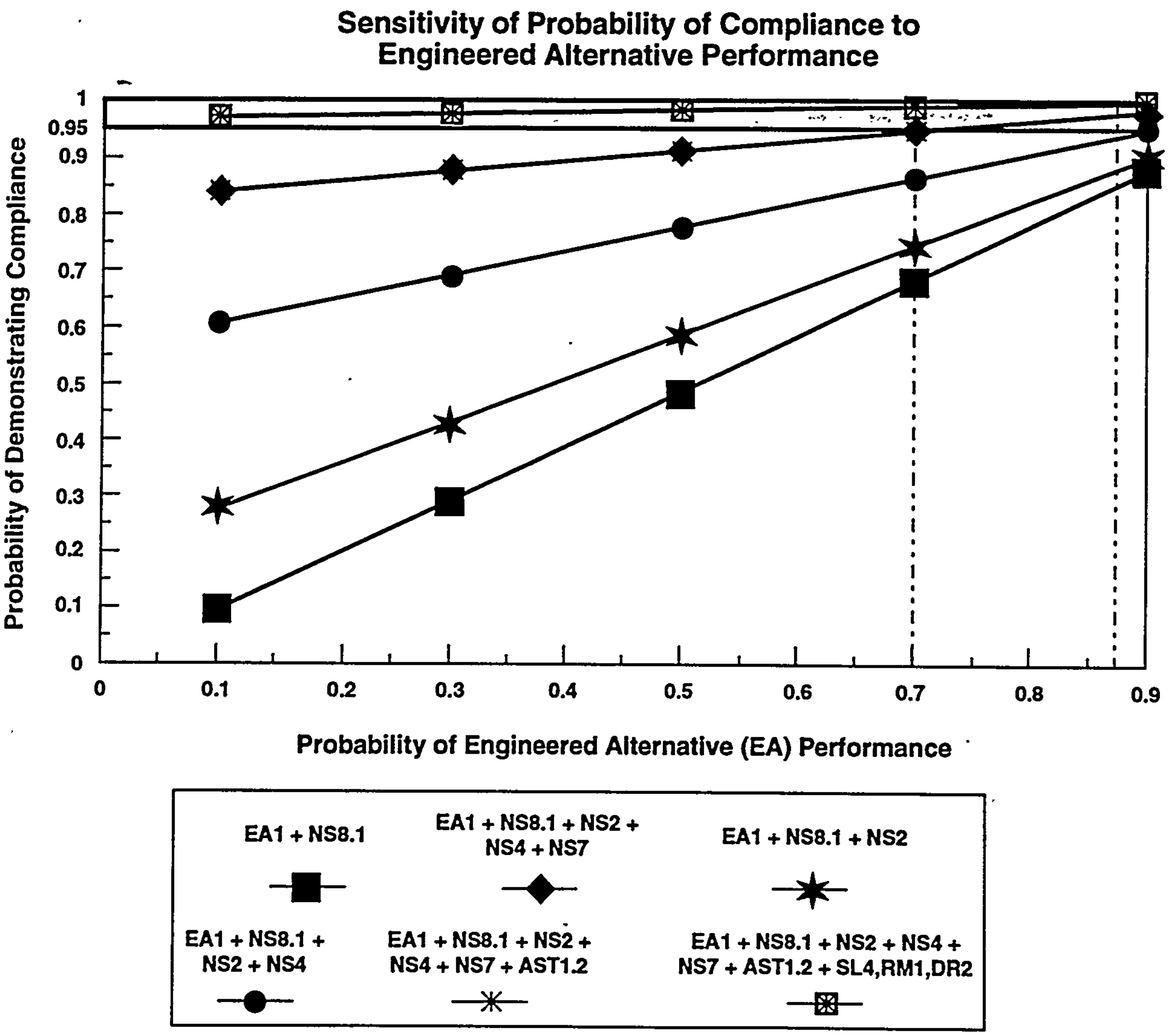

Figure 4-3. Mapping of PDC to EA performance.

There are two types of cost associated with activity EA 1: " demonstration" costs associated with experimental demonstration of the efficacy of EA 1 (approximately $500,000), and implementation costs associated with amending the backfill (approximately $1.5 million). As discussed in Section 4.1, the outcome of " failure" corresponds to inability to demonstrate the efficacy of the amendment: implementation costs will not be incurred in this case. The cost displacement associated with EA 1, therefore, includes a fixed component and a conditional component that depends on the assigned success probability:

$$Cost(\text{EA 1}) \geq \$500{,}000 + \$1.5 \text{ million} * P(Outcome(\text{EA 1}) = Success)$$

Figure 4-1 shows the activity series corresponding to an EA 1 success probability of 0.3.

For a given value of EA 1 success probability, the overall pareto-optimal surface can be identified as the " leftmost" of the separate paths (the path excluding EA 1 and the path including EA 1) at all probability levels. For an EA 1 success probability (P_e) of 0, the " pure experimental" path is obviously dominant: demonstration costs are incurred with no incremental improvement of PDC. For all but very small success probabilities ($P_e \leq 0.05$), the EA 1 path appears to dominate the "pure experimental" path. Figure 4-2 shows the two paths when P_e = 0.10.

The possible effects of assigning different EA 1 outcome probabilities on programmatic decisions was characterized by the following procedure:

- The decision-maker is assumed to choose an activity set along the approximate pareto-optimal path discussed above.

- The decision-maker will select the cheapest pareto-optimal set that meets or exceeds some specific PDC decision level. PDC decision levels of 0.5, 0.7, 0.8, 0.9, and 0.95 were considered.

- Each decision level leads to a single activity set along the " pure experimental" series. For $P_e = 0$, the analogous activity set would be selected from the " EA 1" series, but at an increased cost. As P_e increases above 0, certain scientific activities may no longer be required to achieve the decision level PDC. The overall cost, therefore, tends to decrease due to the dominance of the EA 1 series.

- For each decision level, and for a series of P_e values, the following information was recorded: the scientific that were screened by the decision rule, the PDC value for the selected set, and the cost of the selected set.

The results of the above characterization procedure are presented in Tables 4-1 through 4-6 (and graphically represented for a few select cases of PDC in Figure 4-1.)

Table 4-1. Sensitivity of the PDC for the Pareto-Optimal Activity Series (Unconstrained Duration) to EA Performance at Decision Threshold 0.50

	"Pure Experimental" Series				
Components	NS 8.1, NS 2, NS 4				
PDC	0.57				
Cost ($1,000)	7,200				
	Sensitivity to EA 1 Success Probability P_e				
P_e	0.10	0.30	0.50	0.70	0.90
Screened Activities			NS 4	NS 2	
PDC	0.61	0.69	0.60	0.70	0.90
Cost ($1,000)	7,800	8,100	5,000	4,800	5,100

Table 4-2. Sensitivity of the PDC for the Pareto-Optimal Activity Series (Unconstrained Duration) to EA Performance at Decision Threshold 0.70

	"Pure Experimental" Series				
Components	NS 8.1, NS 2, NS 4, NS 7				
PDC	0.83				
Cost ($1,000)	14,400				
	Sensitivity to EA 1 Success Probability P_e				
P_e	0.10	0.30	0.50	0.70	0.90
Screened Activities			NS 7	NS 4, NS 2	
PDC	0.84	0.87	0.78	0.70	0.90
Cost ($1,000)	15,000	15,300	8,400	4,800	5,100

Table 4-3. Sensitivity of the PDC for the Pareto-Optimal Activity Series (Unconstrained Duration) to EA Performance at Decision Threshold 0.80

	"Pure Experimental" Series				
Components	NS 8.1, NS 2, NS 4, NS 7				
PDC	0.83				
Cost ($1,000)	14,400				
	Sensitivity to EA 1 Success Probability P_e				
P_e	0.10	0.30	0.50	0.70	0.90
Screened Activities				NS 7	NS 4, NS 2
PDC	0.84	0.87	0.91	0.87	0.90
Cost ($1,000)	15,000	15,300	15,600	8,700	5,100

Table 4-4. Sensitivity of the PDC for the Pareto-Optimal Activity Series (Unconstrained Duration) to EA Performance at Decision Threshold 0.90

	"Pure Experimental" Series				
Components	NS 8.1, NS 2, NS 4, NS 7, AST 1.2, SL 4+				
PDC	0.97				
Cost ($1,000)	29,300				
	Sensitivity to EA 1 Success Probability P_e				
P_e	0.10	0.30	0.50	0.70	0.90
Screened Activities			SL 4+ AST 1.2		NS 7, NS 4, NS 2
PDC	0.97	0.98	0.91	0.95	0.90
Cost ($1,000)	29,900	30,200	15,600	15,900	5,100

Table 4-5. Sensitivity of the PDC for the Pareto-Optimal Activity Series (Unconstrained Duration) to EA Performance at Decision Threshold 0.95

	"Pure Experimental" Series				
Components	NS 8.1, NS 2, NS 4, NS 7, AST 1.2, SL 4+				
PDC	0.97				
Cost ($1,000)	29,300				
	Sensitivity to EA 1 Success Probability P_e				
P_e	0.10	0.30	0.50	0.70	0.90
Screened Activities					NS 7, NS 4, NS 2
PDC	0.97	0.98	0.98	0.99	0.96
Cost ($1,000)	29,900	30,200	30,500	30,800	9,000

Table 4-6. Pareto-Optimal Activity Series for Duration ≤ 19 Months

Activity	Cumulative PDC	Activity Set Cumulative Cost ($1,000)
NS 8.1	0.00	3,242
NS 2	0.19	4,058
NS 4	0.56	7,171
NS 7	0.82	14,371
AST 1.2	0.82	18,675
SL 4 + RM 1 + DR 2	0.96	29,250

- By using the PDC decision threshold criterion as a model of decision-making behavior, the influence of different P_e assignments on activity-set composition can be summarized from the information in the above tables:

- For P_e between 0 and 0.3, EA 1 would not be considered. Although EA 1 increases PDC in relation to the " pure experimental" set, this increment is never sufficient (for the decision thresholds considered here) to eliminate a scientific activity.

- For P_e between 0.5 and 0.7, and for PDC decision thresholds below 0.95, EA 1 generally allows significant cost reductions by allowing one or more scientific activities to be eliminated.

For $P_e = 0.9$, EA 1 permits cost reductions at all decision thresholds.

Table 4-7 shows the marginal expected cost associated with including EA 1 in the selected activity set for the P_e values and decision thresholds considered above.

4.1.1.4 EFFECT OF SIMULTANEOUS NS 8.1 AND EA 1 OUTCOME PROBABILITY REASSIGNMENTS

The analysis in the previous section was done under the assumption that the probability of success for NS 8.1 is 1. For alternative probability assignments for both NS 8.1 and EA 1, the PDC values given by equation (5) in Section 4.1.1.4 should be multiplied by the NS 8.1 success probability, as described in Section 4.1.1.2.2.

4.1.2 Evaluation of Mean Value Sampling Approach Versus Latin Hypercube Sampling

For SPM-2, a mean-value approach was used to generate a single vector from parameter distributions for input to WIPP performance modeling. The mean-value approach produced a first-order approximation to the mean of a family of CCDFs that would result from LHS of the parameter distributions. LHS has been the procedure for WIPP PA modeling, but it was not used for SPM-2 because of the large number of activities modeled. Because SPM-2 used the mean-value approach, the results did not capture the uncertainty in model parameters values allowed by the use of LHS.[11] The accuracy of the approximation(s) in the mean-value approach was thus

[11] The LHS approach samples distributions of input parameters to create sets of parameter values, called parameter sample vectors. Each sample vector is modeled by the PA modeling codes that simulate repository geometry and behavior to calculate integrated releases for each of the three intrusion scenarios, E1, E2, and E1E2. The location and timing of approximately 1,000 drilling events are modeled with the repository geometry to yield releases for each scenario. The integrated release, the weighted sum of the three scenario releases, is then calculated for the three scenarios. The weighting depends on the spatial and temporal pattern of intrusions and on the frequency of penetration of the pressurized brine underlying the repository. This probability distribution reflects uncertainty in the release caused by uncertainty about future

Table 4-7. Marginal Expected Costs of EA 1 ($K)

	Decision Threshold				
P_e	0.50	0.70	0.80	0.90	0.95
0.10	600	600	600	600	600
0.30	900	900	900	900	900
0.50	-2,200	-6,000	1,200	-13,700	1,200
0.70	-2,400	-9,600	-5,700	-13,400	1,500
0.90	-2,100	-9,300	-9,300	-24,200	-20,300

[Light box] No cost reduction due to EA 1

[Dark box] Cost reduction due to elimination of one or more activities

evaluated to determine whether the PDC would change if LHS rather than mean value parameters were used in the SPM-2 analysis.

The accuracy of the mean value approximation is dependent on the linearity of the system of equations being solved and the activity outcome being modeled relative to the baseline. For the nonlinear models used to evaluate the performance of the WIPP, the accuracy of the approximation is unknown. For some of the outcome combinations in which the implied parameters resulted in an almost linear component of the system model controlling the performance, the approximation will be quite accurate. For other outcome combinations, the approximation to the mean CCDF that would have resulted from LHS could be considerably different. In addition, the mean value approximation should also be quite adequate to model potential activity outcomes that are represented by a shift in the baseline mean value of a

drilling. Because each simulated drilling history produces a different integrated release, the resulting distribution of integrated release values represents the uncertainty about future drilling, but not the uncertainty in parameter values. The complement to this distribution (the distribution subtracted from 1) is the conditional probability of exceeding the release value. Uncertainty in the parameter values in the sample vector is incorporated into the CCDF by estimating the independent (or unconditional) distribution of integrated releases. LHS allows all parameter sample vectors to be considered equally likely. Therefore, for a given integrated release value, the estimated *unconditional* probability of exceeding that value is the average of the conditional exceedence probabilities.

parameter distribution or a completely different conceptual model. On the other hand, the mean value approximation is not likely to be as accurate in modeling outcomes represented by a reduction in uncertainty about the baseline mean value. For SPM-2, all activity outcomes except for SAL 1 did involve either a shift in the mean or a different conceptual model (see Volume II of this report).

A comparison between results using mean values and those using LHS is discussed below for the activity set consisting of the activities in Table 4-8. This activity set is the one that most closely matched performance assessment calculations for the Draft Compliance Certification Application submitted to the EPA (U.S. DOE/CAO, 1995a). Only one combination of outcomes for this activity set was evaluated with both the mean-value approach and LHS using a sample size of 40. Baseline models and parameters were used in the analysis for all components not specifically described in Table 4-8. This discussion is not intended to generalize the effect of using mean parameter values to approximate the average CCDF resulting from LHS, but rather to serve only as one example. Most parameter distributions used in the performance calculations are log normal. Therefore, the mean value comparison used, in most cases, the mean of the logs.

The results of the performance modeling of the activity set are summarized in Figures 4-4, 4-5, and 4-6 as CCDFs of integrated normalized release. The mean CCDF generated from the LHS for groundwater release (Culebra and Anhydrite) appears in Figure 4-4. The mean CCDF generated from LHS is overlaid with the CCDF generated using the mean of the logs for the parameter distribution in the performance modeling for cuttings and spallings release (Figure 4-5) and total release (Figure 4-6). Figure 4-4 also includes a curve for the groundwater releases calculated using true mean values.

Figure 4-4 shows the CCDF for groundwater release to the accessible environment through the Culebra formation and Salado anhydrite interbeds (Magenta and Dewey Lake releases were zero). The mean CCDF for the LHS approach is shown in the figure, along with the curve for the vector using mean parameter values. The CCDF that resulted using the mean of the logs indicated integrated normalized release less than 10^{-5} of the EPA allowed release, several orders of magnitude less than the mean CCDF calculated from LHS sampling, and is therefore not shown in Figure 4-4. The dual porosity assumption, with a fracture spacing of 0.5 m and mean K_d (chemical retardation factor), resulted in decreased radionuclide transport in the mean parameter case. Using LHS to sample on two-phase flow parameters, room chemistry parameters, and K_ds resulted in a relatively large spread of CCDFs for groundwater releases, and radionuclides reach the Culebra formation in four to 22 of the 40 sample vectors, depending on the intrusion scenario.

The abrupt leveling of the mean CCDF for the LHS case at a probability of 0.025 in Figures 4-4 and 4-6 results from a single vector exceeding the anhydrite storage capacity used for the activity set outcome. Figures 4-7 and 4-8 show the CCDFs generated from the single violating vector and all other vectors, for groundwater release and groundwater + cuttings + spallings,

Table 4-8. Activities and Outcome Descriptions Used in the LHS Analysis

Activity	Activity Description	Number of Outcomes	Outcome Description
AST 1.2	Dissolved Actinide Solubility for Oxidation States +III, +IV, and +V	1	Success, use parameter distributions in Volume II, Section 3.2.2
RM 1 + SL 4	Rock Mechanics and Studies of Short- and Long-Term Seal Components	1	Success, use seal permeability in Volume II, Section 3.5.2
SAL 1	Laboratory/Field Properties of Anhydrite	1	Success, use parameters in Volume II, Section 3.6.1
NS 4	Multi-Well Tracer Test	3 or 4	Fracture spacing fixed at 0.5 m
NS 7	Chemical Retardation for Th, Np, Pu, U, and Am	1	Success for both K_d determination and dual porosity demonstration, use K_ds from Volume II, Section 3.7.8
NS 8.1	Concentration and Transport of Colloid Carriers	1	Success, use colloid concentrations and transport properties from Volume II, Section 3.7.9
DR 2*	Blowout Releases	10	Use reduction factor of 0.05 from Volume II, Section 3.4.2
DR 3*	Non-Blowout Releases	5	Use reduction factor of 0.008 from Volume II, Section 3.4.3

*These activities were not a part of the Draft Compliance Certification Application activity set.

respectively. For this vector, the marker bed anhydrite bed fractured and then healed (resealed) prior to the 1,000-year time of intrusion. The model shows anhydrite release in the undisturbed case and in all intrusion scenarios for that particular vector. An unusual combination of extreme parameter values resulted in significant brine flow out the marker bed: high halite permeability and porosity, high anhydrite permeability, medium to large gas generation rates, a relatively tight seal permeability, the smallest fracture initiation pressure, and one of the smallest brine storage coefficients.

The significance of Figure 4-4 is twofold. First, even with the extreme values, the calculated groundwater releases comply with the standards set by 40 CFR 191.13(a) for radionuclide releases. However, this particular activity set would have failed the test in SPM-2 for compliance with 40 CFR 268.6. This is because in SPM-2, it was conservatively assumed that *any* contaminated brine reaching the accessible environment would result in a RCRA violation.

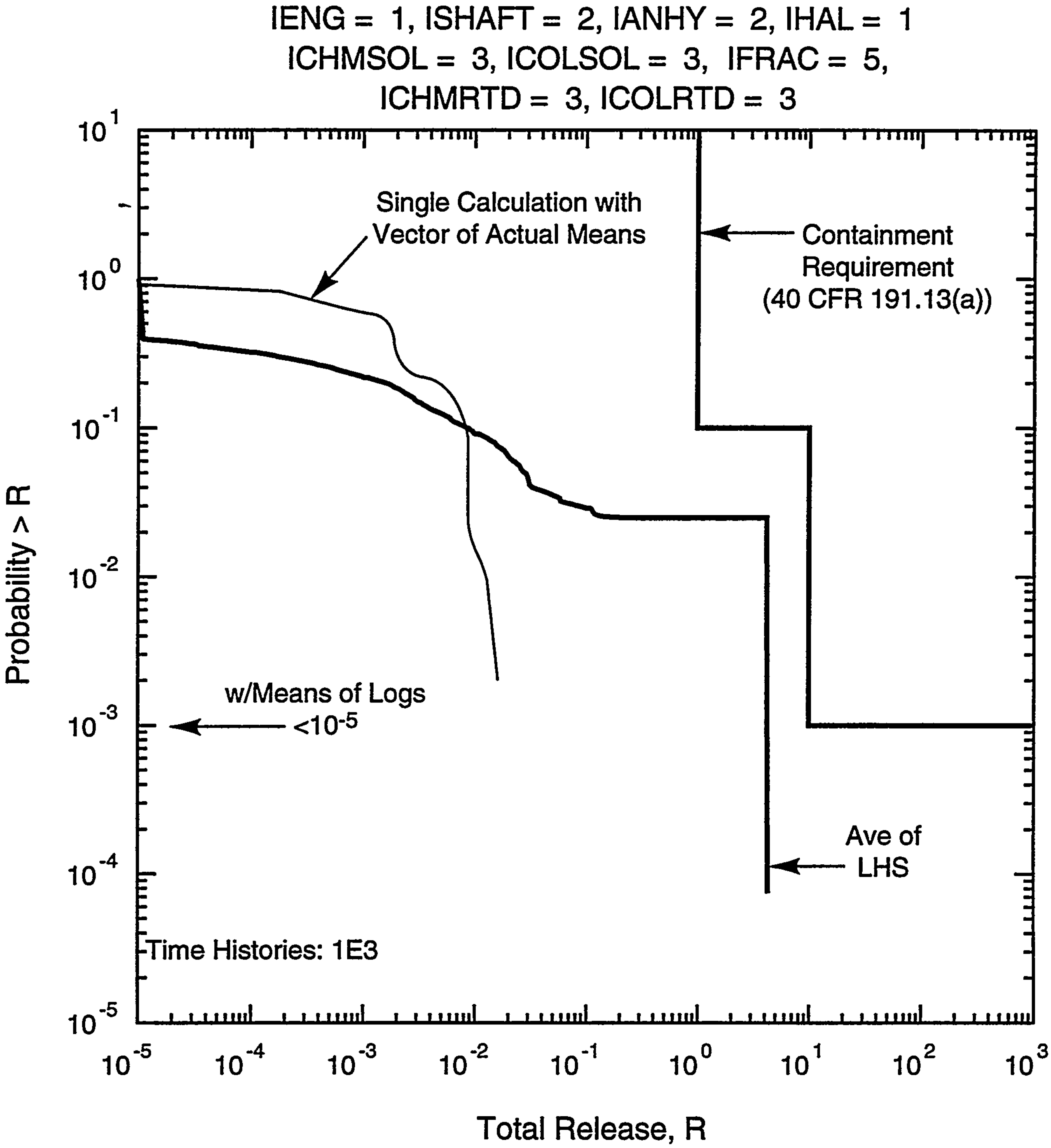

Figure 4-4. CCDFs for groundwater release (Culebra and Anhydrite) generated using LHS and using a single calculation with vector of actual means.

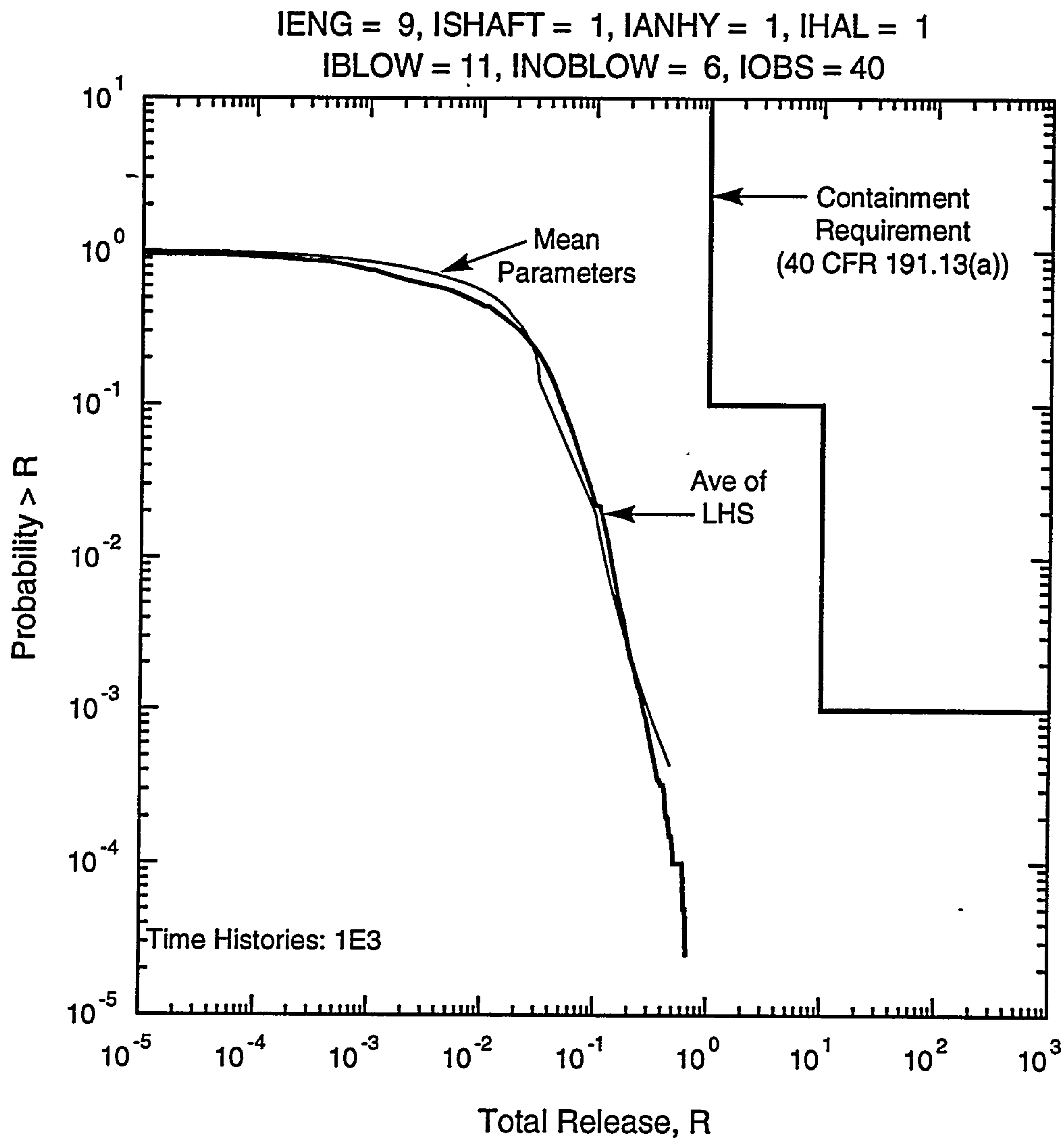

Figure 4-5. CCDFs for cuttings and spallings generated using LHS and mean parameters.

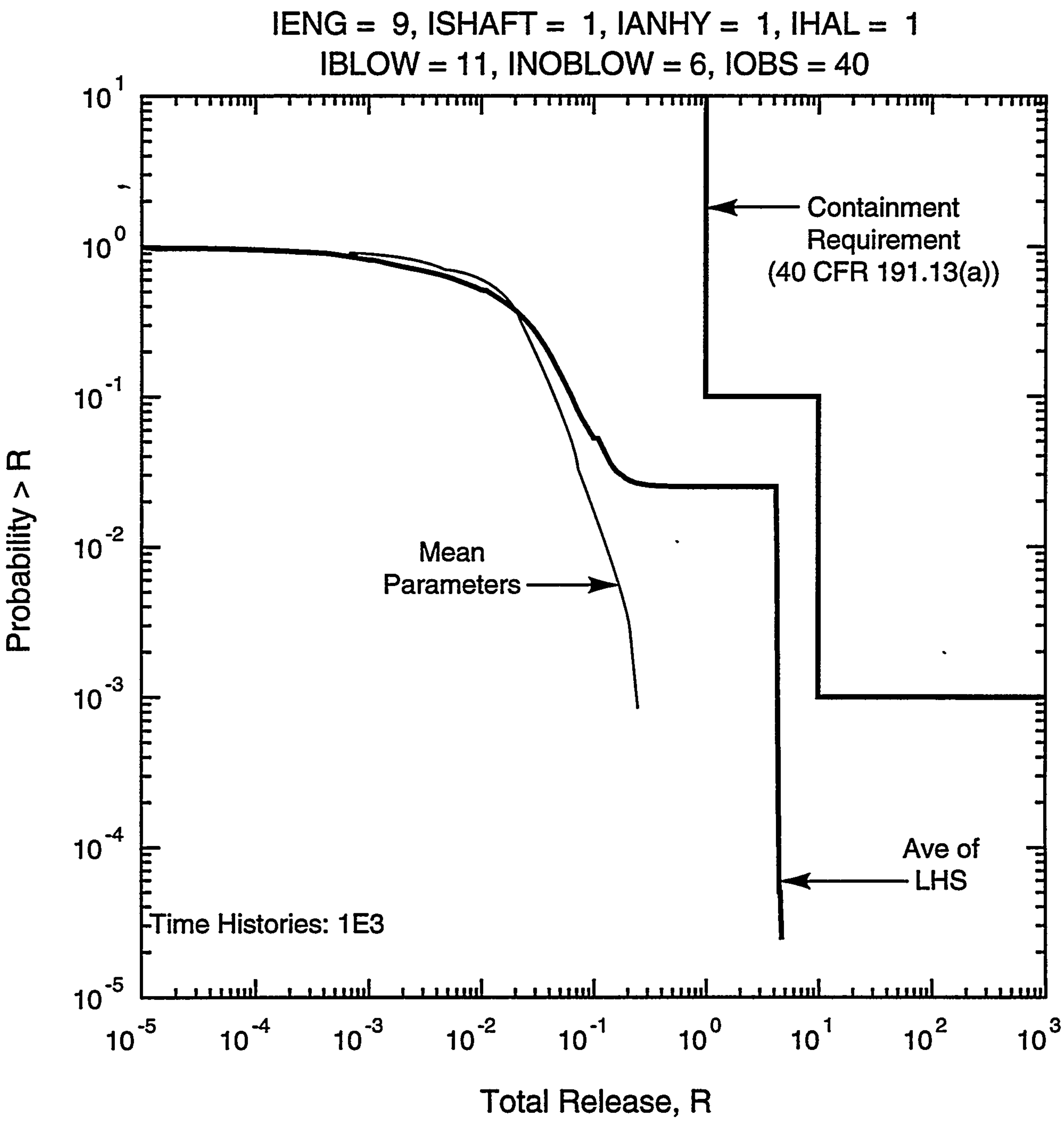

Figure 4-6. Groundwater + cuttings + spallings CCDFs generated using LHS and mean parameters.

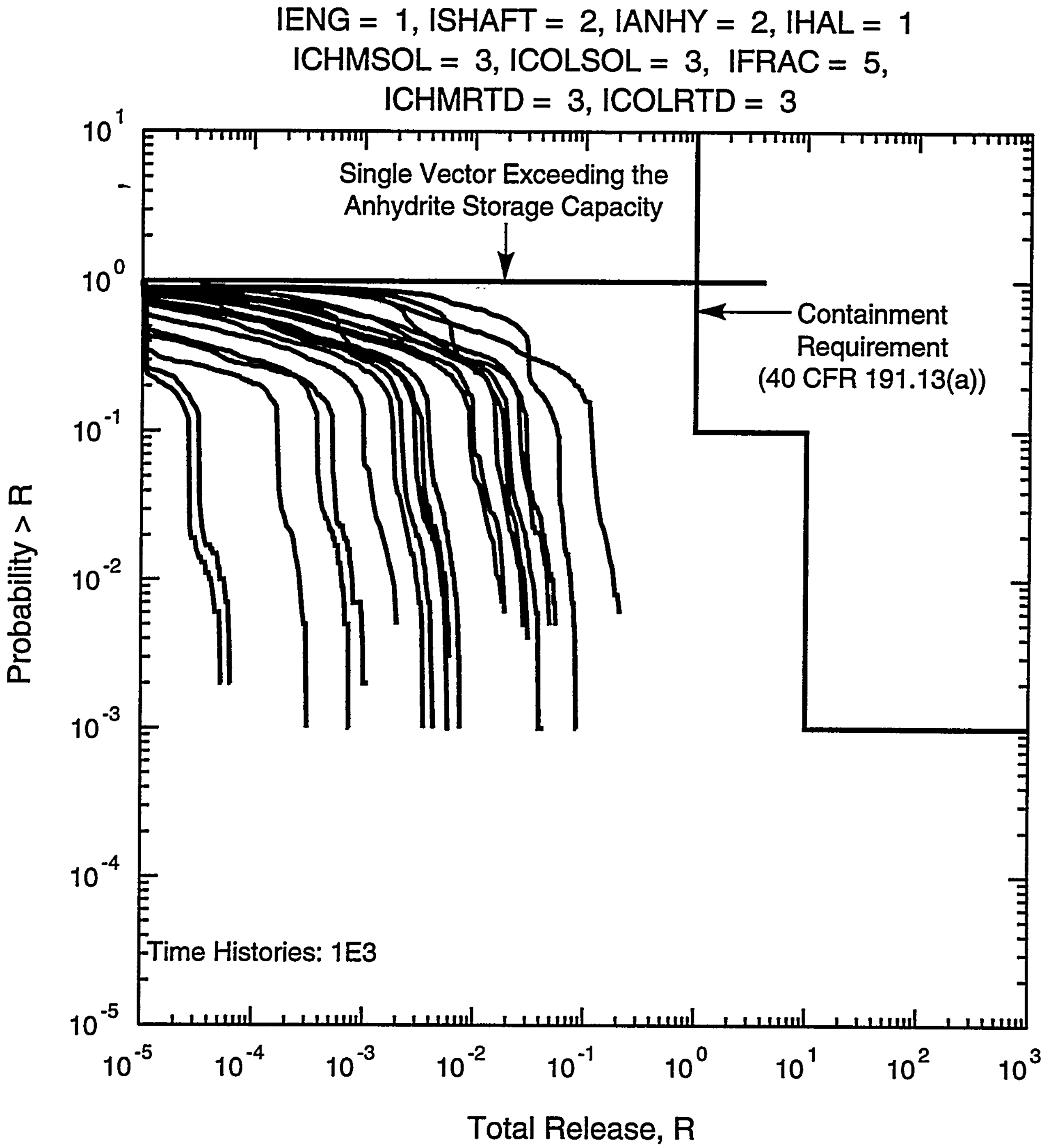

Figure 4-7. CCDFs for groundwater release for the single vector exceeding the anhydrite storage capacity and all other vectors for the LHS case.

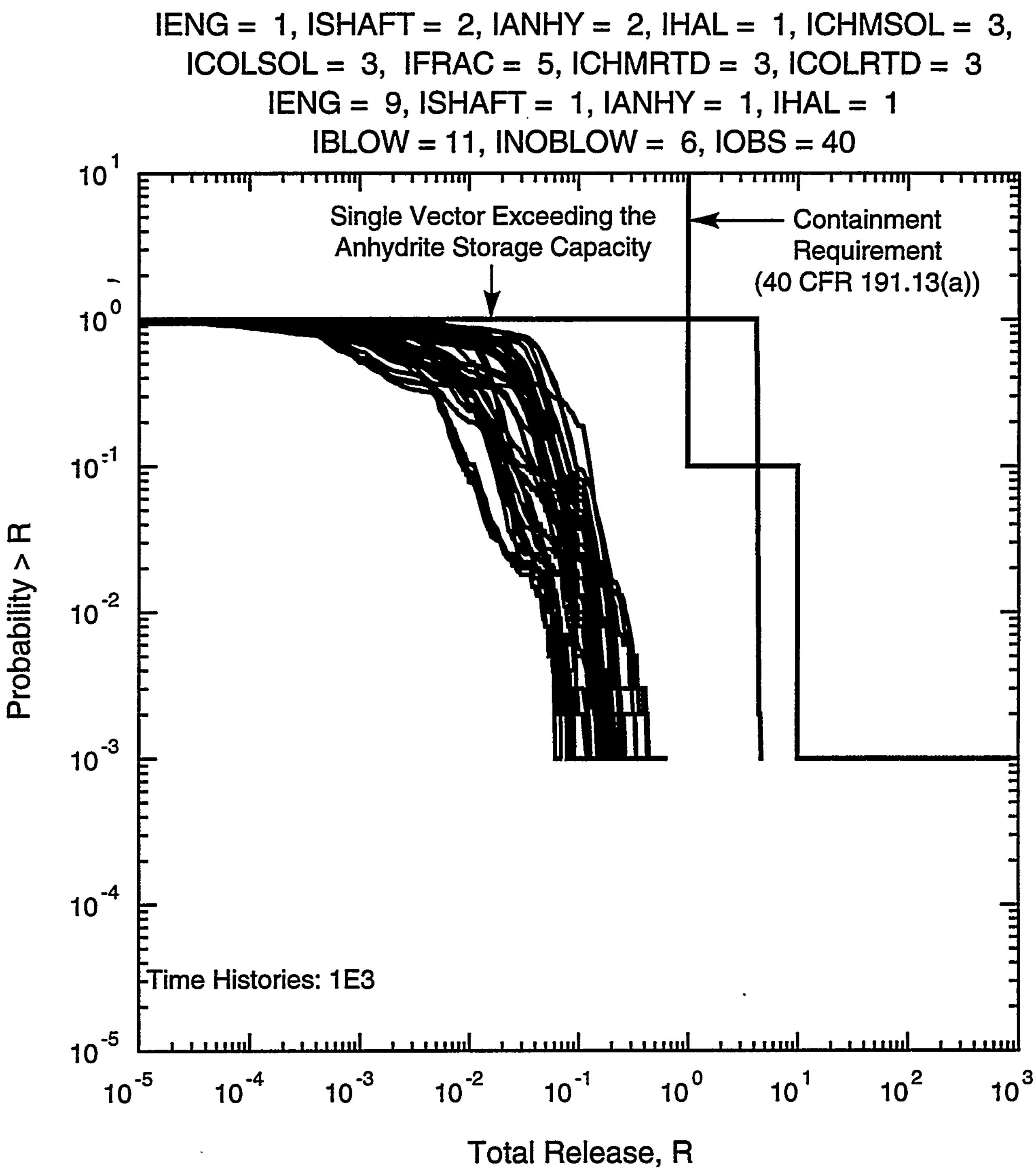

Figure 4-8. CCDFs for the single vector exceeding the anhydrite storage capacity and all other vectors for groundwater + cuttings + spallings generated using LHS.

Therefore, with LHS, a single vector of extreme parameter values fails the RCRA regulatory release requirements for this activity set.

Figure 4-5 shows the CCDFs for cuttings and spalling release of radioactive material. The CCDF generated using the mean parameter values compares well with the mean CCDF generated using LHS, because no cuttings or spalling parameters were sampled. The only parameters that varied in the model are the pressure and porosity that come from the corresponding BRine And Gas FLOw code (BRAGFLO) repository calculations and a relatively tight grouping of the family of CCDFs for spalling releases.

The combined total or composite CCDFs of normalized releases are shown in Figure 4-6. These CCDFs are the results that determine the compliance indicator for this particular outcome combination with respect to 40 CFR 191. The mean CCDF from the LHS and the CCDF resulting from mean parameter values compare reasonably well, except for the step in the mean CCDF caused by the anhydrite " bucket model" releases. These CCDFs are dominated by the spalling release, which is considerably larger than groundwater releases, except for the single anhydrite release. Both CCDFs demonstrate compliance with 40 CFR 191.13. However, the SPM-2 compliance indicator[12] for the LHS case is 0, because of the RCRA violation. These differences imply that the PDC for the activity set could change if LHS, rather than mean value parameters, were used in the SPM-2 analysis However, the very conservative assumption regarding the RCRA violation is likely to change prior to submitting the final compliance certification application. Because of the conservatism of the assumption, and the fact that only extreme vectors violated the assumption, the WIPP management concluded that the mean-value approach used in SPM-2 to approximate LHS results was sufficient for guiding the decisions made.

Note that the conclusions drawn from this comparison should not be generalized as to their effect on the PDC or the calculation of the compliance indicator for other outcome combinations or activity sets. These particular results are driven by two phenomena that could vary significantly from outcome to outcome: the large spread in groundwater releases, and the significant single anhydrite releases for one input vector.

4.1.3 Side Investigations

Although not part of the original SPM concept, side investigations became an integral part of SPM-2. They are supplementary and confirmatory evaluations required to 1) fully address certain technical positions[13] taken in the SPM-2 baseline, 2) investigate the impact of potential activities

[12] As stated in Section 3.2, the SPM-2 compliance indicator is, by definition, equal to 1 only when the WIPP disposal system is predicted to meet *both* 40 CFR 191.13(a) and 40 CFR 268.6. Failure of either regulation results in a SPM-2 compliance indicator of 0.

[13] Technical positions refer to the conceptual models, scenarios, data, and parameter distributions defined by the scientific investigators for WIPP to use in assessing the performance of the repository. These are described in detail in Volume II of this report.

where the cost and expense of carrying an activity outcome all the way through the formal SPM decision process was not warranted, and 3) investigate the impact of calculational models chosen for SPM-2, such as two-dimensional versus three-dimensional models for both baseline and activity outcomes. The expected outcomes of the side investigations were included in SPM-2 calculations because the probability of their successful completion was considered very likely. Some side investigations consisted of work that is required to support a compliance application under the long-term performance requirements. The calculations cannot be considered programmatic options, and it would therefore have been inappropriate to represent them as activities in the SPM-2 analysis. In some cases, including side investigations in the calculations would have significantly expanded the number of PA cases to be run without clear benefit and would have increased the risk of diluting resources needed to produce high-quality results. Finally, some technical positions identified during the elicitation process could not be incorporated into PA calculations because of time constraints. In particular, it was considered more cost-effective to resolve certain technical issues in side investigations, rather than carry through the activity through the entire decision-analysis process. The complete list of SPM-2 side investigations appears in Table 4-9. (See Volume I, Section 4.1.3 for more information.)

As described in Volumes I and II, and indicated in Table 4-9, the three areas of side investigations were:

1) investigations to substantiate positions taken in the technical baseline,

2) investigations into the importance of some conceptual models that were called for either in the baseline or in activities that could not be incorporated into the existing PA suite of calculation tools in a timely fashion, and

3) investigations to support the scenario screening effort.

These side investigations could be completed over a short time frame with moderate effort and existing funds. They were incorporated into the WIPP Features, Events, and Processes (FEP) study for scenario screening. The results of the study will be reviewed as they become available to determine if they validate the assumptions that were made in SPM-2.

4.1.4 Sensitivity of Results to the Use of Binary Compliance Indicator

The standard utility calculations for SPM-2 used a binary compliance indicator (CI) to measure whether the WIPP disposal system is predicted to succeed or fail in meeting the selected performance requirements. The CI was derived from the CCDF associated with each activity set outcome as follows:

$$\text{CI} = \begin{cases} 1, & \text{if the CCDF is less than the regulatory limits defined in 40 CFR 191.13(a),} \\ 0, & \text{otherwise.} \end{cases}$$

Table 4-9. SPM-2 Side Investigations

Side Investigation	Rationale*
Brine storage in the anhydrite and surrounding halite	1
Mechanical effects of gas generation on the Salado Formation	2
Applicability of using 2-D/pseudo 3-D calculations including dynamic alteration of disturbed rock (transition) zone	1, 2
Effect of disturbed rock zone (DRZ) and transition zone (TZ)	1
Gas exsolution effects on brine inflow	2
The effects of one-degree dip in the repository	1, 2
Dynamic dependence of threshold displacement pressure with permeability in anhydrite interbeds	1, 2
Detailed 3-D room flow model (including dip) with detail at the drum scale to support	1, 2
Circulation of fluid in repository during drilling and after abandonment	1
Reevaluation of gas entrainment	1
Wicking, mobile brine saturation, and two-phase flow properties of the waste	2
Dynamic closure of unfilled excavations (north end)	1
Dynamic dependence of permeability on porosity during creep consolidation	1
Red Bed retardation and the role of the Dewey Lake in regional hydrologic behavior	1, 2
Radiolysis	3
Reaction Path Model	3
Calculations related to thermal effects on fluid flow	3
Salado near misses, flow to surface during drilling, and flow through abandoned boreholes	3
Nuclear criticality	3
Evaluation of borehole connections to units below repository	3
Non-Salado/Regional 3-D modeling	3
Screening of minor FEPs	3

* 1 = Investigation is required to substantiate a technical position taken in the SPM-2 technical baseline.
2 = Conceptual models in the SPM-2 technical baseline that were not incorporated into the SPM-2 codes.
3 = Investigation is required to support scenario screening.

The binary CI was sensitive only to whether or not the CCDF complied with the containment requirements in 40 CFR 191.13(a), that is, whether the position of the CCDF fell to the left or right of the regulatory limits appearing in Figures 4-4, 4-5, and 4-6. It made no additional distinction between a CCDF that is " near" the regulatory limits and one that is " far" from the limits. The NAS asked if a different optimal path would result if the goal was to move farther to the left of the regulatory limit, not just to comply with it. A separate analysis was thus conducted using a continuous release measure (CRM) that *is* sensitive to the absolute position of the CCDF. The CRM is the expected value of the integrated normalized releases for each activity set. This CRM was obtained by calculating the area under the curve of each activity set CCDF.

Activity sets with relatively small CRMs were assumed to be of greater utility in demonstrating compliance than those with higher CRMs in examining whether different activities would be included in a pareto-optimal series if the goal was to not just comply with the containment requirements, but to obtain CCDFs further to the left of the regulatory limits in Figures 4-4, 4-5, and 4-6. Note that an even more rigorous two-point examination of this issue is possible by looking at the distance between the two CCDFs at the " benchstep" points of the regulatory limit. However, the extra computational effort this approach would require was not deemed necessary for this sensitivity study.

A multivariate linear regression analysis was used to characterize the importance of the SPM-2 activities with respect to the CRM. The CRM was calculated for each activity set and plotted against cost. The results are shown in Figure 4-9, in which disutility, the measure of the expected value of the integrated normalized releases, is a variable to be minimized. A statistical evaluation similar to the regression analysis of PDC values then identified a series of SPM-2 activities that tend to minimize this measure, for a given cost.

Similar to the regression analysis of PDC values, the CI sensitivity analysis identified a series of activity sets for unconstrained duration that provides the near-maximal *decrease* in CRM for a given increase in cost. This series, shown in Figure 4-9, can be used to identify the approximate pareto-optimal activity set at a given cost level. The series presented in Figure 4-10 contains the same activities in the pareto-optimal activity series based on PDC, with the addition of the Salado activities at the upper end.

A second path was identified consisting of only activities consistent with the schedule for the WIPP Disposal Decision Plan (i.e., duration values ≤ 19 months assuming a start date of May 1995). This path, and the associated population of activity sets, is shown in Figure 4-11. As with the unconstrained series in Figure 4-10, the identified series provides very close approximation to the pareto-optimal set based on PDC values at most cost levels.

Results of the CRM analysis were compared with the results using the binary CI, leading to the following observations:

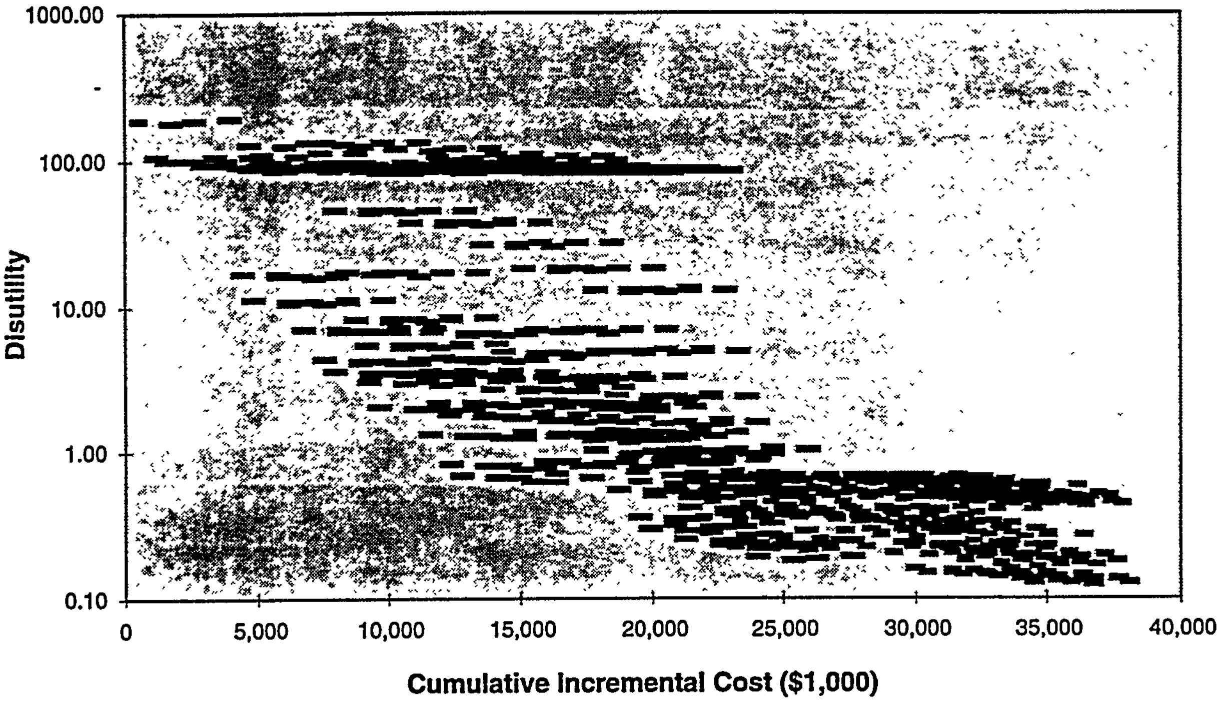

Figure 4-9. Cumulative normalized mean releases of activity sets excluding EAs and WACs as a function of cost.

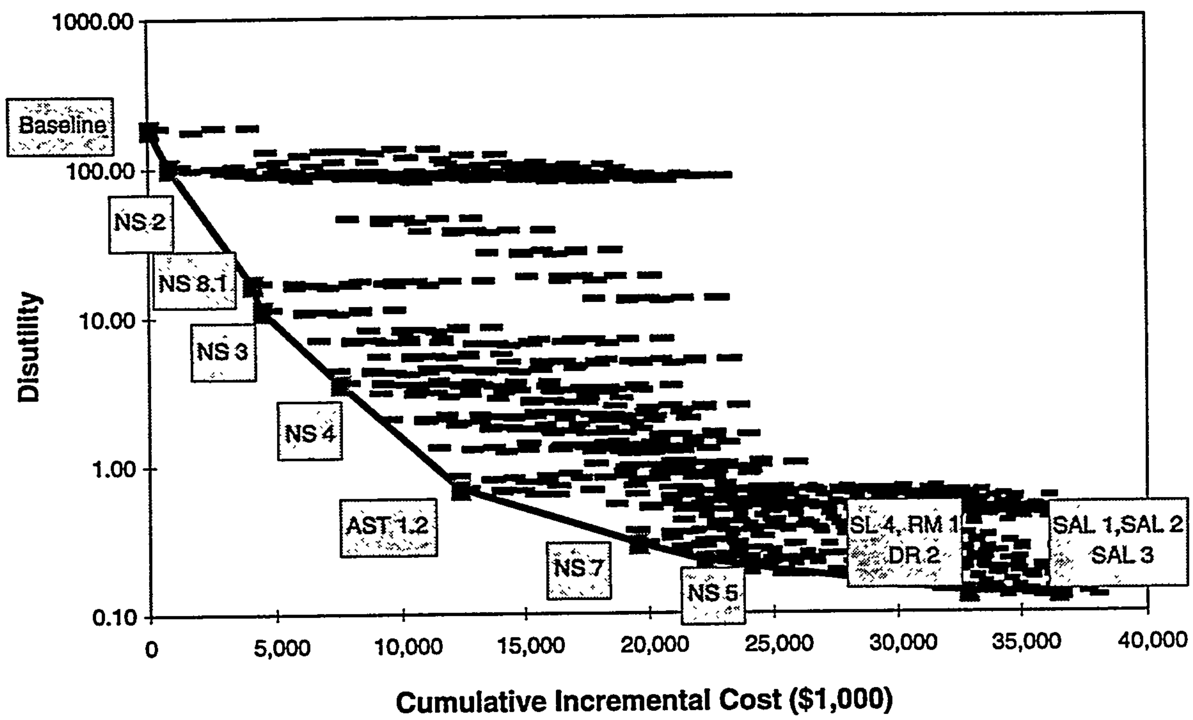

Figure 4-10. Pareto-optimal series of scientific investigations generated using the CRM: No duration restrictions.

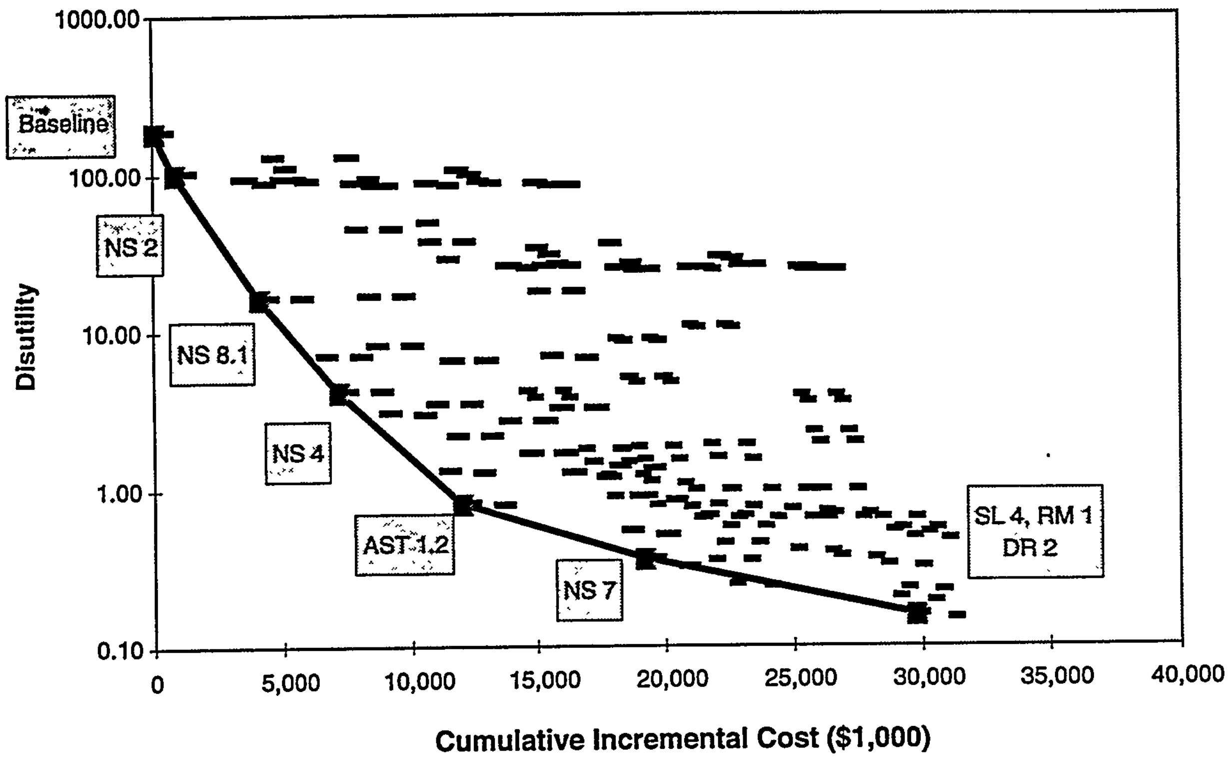

Figure 4-11. Pareto-optimal series of scientific activities excluding EAs and WACs generated using the CRM: Duration ≤ 19 Months.

1. The PDC was insensitive to differences between activities AST 1.1 and AST 1.2, NS 8.1 and NS 8.2, and EA 1 and EA 2. Coefficient values were different for each of the activities in these pairs, and were smaller (as expected) for the larger level of effort in each case.

2. In the PDC analysis, EA 1 and EA 2 (in conjunction with NS 8.1 or NS 8.2) resulted in PDC values of 1; EA 3 tended to elevate the PDC value, but did not produce PDC values of 1. In contrast, EA 3 had a higher rank than either EA 1 and EA 2 in the CRM analysis.

3. The order of inclusion of activities in the pareto-optimal series based on the CRM analysis is slightly different from the order of inclusion based on PDC. However, the set corresponding to maximum PDC also produces a near minimum CRM, and is on the pareto-optimal path. Some additional reduction in CRM is possible beyond the PDC-maximizing set due to the marginal effects of NS 8.2 versus NS 8.1. and AST 1.1 versus AST 1.2. This reduction, however, appears relatively small.

In summary, the use of a CRM provides essentially the same pareto-optimal activity series for SPM-2 as that resulting from the use of the binary CI for both the duration-constrained and unconstrained scenarios.

4.1.5 Performance Benefits of Activities

The technical rationale used to extrapolate the PA input and models from the predicted results of the scientific investigations could be a significant source of uncertainty in SPM-2. The technical arguments for these PA implications have undergone considerable review through the technical position paper process.[14] Over time, the justification for these implications will either be borne out in the compliance application or refuted. In the meantime, the DOE/CAO and its technical advisors must make decisions based on the results of SPM-2 with consideration of this uncertainty. Because it is not possible to quantify the influence of this uncertainty on the calculated PDC values, decisions based on these values must be made under the assumption that PDC would not change if this uncertainty was eliminated.

4.2 Cost

Additional uncertainty within the SPM-2 decision matrix stems from cost estimates. Given the lack of actual data on uncertainty in cost, meaningful quantitative evaluation of this uncertainty was not possible. Explicit consideration of uncertainty in activity cost may have led to further discrimination between the scientific investigations, EAs, and WACs.

[14] The SPM-2 technical position papers are: *Actinide Source Term*; *Disposal Room and Cuttings Models*, Volumes I and II; *Gas Generation in the Waste Isolation Pilot Plant*; *Non-Salado Flow and Transport*; *Performance Assessment Methodology*; *Repository Seals Program*; *Rock Mechanics: Creep, Fracture, and Disturbed Rock Zone*; *Salado Formation Fluid Flow and Transport Containment Group*; and *Scenario Development for Long-Term Performance Assessments of the WIPP*.

4.2.1 Uncertainty in Cost of Scientific Investigations

Costs for scientific investigations were based on the scope of these activities as they were defined during the SPM-2 elicitation process. Costs for currently funded activities were based on the January 19, 1995, version of the SNL 5-year plan. Some scientific investigations and costs were subsequently redefined for budget exercises outside the SPM-2 effort. Some ensuing discrepancies required resolution in detailed planning following DOE/CAO's final funding decision. The costs for scientific investigations ranged from $150,000 to almost $11 million. It was recommended to DOE/CAO that a detailed implementation plan and cost estimate be developed for the selected activity set.

4.2.2 Uncertainty in Cost of EAs & WACs

Costs for EAs and WACs were based on information from the Engineered Alternatives Task Force (EATF), as described in Volume II of this report. These costs were order-of-magnitude estimates. In addition, SPM-2 calculations required a single value for the cost of an activity, and a range of costs represented by an average. This introduced uncertainty into the cost for EA 3 in particular, because the estimated costs ranged from $30 to $100 million. Average costs for EAs and WACs range from zero to $65 million.

With regard to WACs, it is not clear that the costs used in SPM-2 calculations fully account for system-wide costs, i.e., generator site costs in addition to WIPP costs. WAC 2, the elimination of humic-containing waste drums, for instance, has an estimated activity cost of zero. It is apparent that this estimate does not account for costs that may be incurred in the elimination of humic materials prior to shipment to WIPP or the disposal of these at another repository.

4.3 Duration

Similar to the uncertainty in activity costs, given the lack of actual data on uncertainty in duration, meaningful quantitative evaluation of this uncertainty was not possible. The uncertainty in activity duration, however, is expected to be lowest for scientific activities (many of which are already in process), and highest for EAs and WACs, for which, at the time of SPM-2, detailed performance evaluations had not yet been conducted and detailed implementation plans had not yet been developed.

4.3.1 Uncertainty in the Duration of Scientific Investigations

Similar to activity costs, durations for scientific investigations were based on the scope of the activities defined during the SPM-2 activity elicitation process. The duration of currently funded activities was based on the January 19, 1995, version of the SNL 5-year plan. Scientific investigations already in process were accounted for and the time remaining was prorated to a start date of May 1, 1995. Durations were not considered to have any variability that would be useful in discriminating between scientific activities.

4.3.2 Uncertainty in EA & WAC Durations

Durations for EAs and WACs analyzed in SPM-2 were based on information from the EATF as described in more detail in Volume II of this report. All EAs and WACs were modeled with a duration of zero. The degree of uncertainty in these durations was not established at the time of SPM-2 calculations. The Engineered Alternatives Cost/Benefit Study (EACBS) performed by the Westinghouse Waste Isolation Division (WID) (U.S. DOE/CAO, 1995b) provided a preliminary basis for evaluating EAs and WACs.

4.4 Consideration of Other Sensitivity and Uncertainty Analyses

Systems prioritization for a project as complex as the WIPP contains inherent assumptions and uncertainties. The final programmatic recommendations considered the SPM-2 results along with existing information, such as the 1992 WIPP PA Sensitivity Analysis (WIPP PA, 1993). Consideration of these sensitivity and uncertainty analyses did not alter the recommended pareto-optimal activity series.

4.5 Qualitative Evaluation

The SPM-2 input, the SPM-2 analysis, and the appropriateness of the performance objectives were additional considerations qualitatively evaluated and reviewed by Sandia's senior WIPP management with DOE/CAO.

The SPM-2 input was qualitatively evaluated for the adequacy of the elicitation training, the degree of rigor achieved in the use of subjective probability assignments to outcomes, the degree of specificity in the descriptions of the activity outcomes and the technical arguments for how the activity outcomes would be modeled in performance calculations, and the extent that stakeholder concerns about the baseline and activity outcomes were addressed. Some of the weakest areas noted were in the descriptions for the colloid program and the actinide solubility program. After considering the results of the quantitative sensitivity studies described above, the input in all program areas was determined by SNL management to be of sufficient quality to support the conclusions reached in the analysis of the SPM-2 results. The SNL management also determined that the results of the sensitivity studies, in large part, substantiate earlier sensitivity studies, such the 1992 WIPP PA Sensitivity Analysis (WIPP PA, 1993) and scientific judgment developed over

WIPP's long history. When examined against this background of Project knowledge, the SNL management judged the SPM-2 results to of sufficient quality for programmatic decision making.

The quality of the SPM-2 analysis was also evaluated by examining how the performance calculations were implemented. The two major areas qualitatively evaluated were the degree to which the conceptual models were incorporated into the calculation, and the potential impact of the side investigations on the conclusions. For example, one-degree dip was specified in the conceptual model of the SPM-2 baseline but was not, in fact, implemented in the baseline calculations. DOE/CAO was accordingly advised that this omission could have potential impact on both the calculated value of the Salado program and the value of removing the gas generation potential by WAC 1. The list of side investigations was also reviewed with DOE/CAO, and assumptions made regarding the outcomes of each side investigation and where they were used in the SPM-2 analysis were noted. (See Section 4.1.3.)

Finally, SPM-2 focused on calculating the value of programmatic activities with respect to demonstrating compliance with the long-term containment requirements in 40 CFR 191.13(a) and 40 CFR 268.6. This focus was necessary and the primary motivation for SPM-2. In the course of implementing SPM-2 and interacting with stakeholders, other perspectives about the appropriate frame of reference upon which to base decisions were proposed. For example, the NAS suggested that demonstration of safety should also be considered as a performance objective. Some stakeholders believed that DOE/CAO should give the same weight to EPA design requirements in SPM-2 as was given to the demonstration of compliance with the long-term performance regulations. In the final analysis of the SPM-2 results, qualitative estimates were made where these alternate approaches may have led to a different valuation of information or different decisions. There were no instances in which significantly different pareto-optimal activity series would have resulted.

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5. FINAL PROGRAMMATIC RECOMMENDATIONS AND CONCLUSIONS

5.1 Recommended Pareto-Optimal Activity Series

The evaluation of the SPM-2 results showed that scientific investigations alone (without EAs or modification of existing WACs) appear sufficient to achieve a high PDC within the DDP schedule. Statistical regression analyses of the SPM-2 results yielded the pareto-optimal series of scientific investigations that maximize incremental PDC while minimizing incremental estimated costs. The two pareto-optimal series for constrained duration and unconstrained duration, listed below in Figures 5-1 and 5-2, were recommended for DOE/CAO consideration.

Pareto-Activity Series of Scientific Investigations for Constrained Duration Based on SPM-2 Results

- NS 8.1: Colloid Concentrations and Transport
- NS 7: Chemical Retardation in the Culebra
- NS 4: Multi-Well Tracer Test
- NS 2: Culebra Fracture/Matrix/Flow – Laboratory
- AST 1.2: Dissolved Actinide Solubilities
- SL 4 + RM 1 + DR 2: Short- and Long-Term Seal Component Studies using the Multimechanism Deformation Coupled Fracture (MDCF) Rock Mechanics Model; Blowout Releases

Figure 5-1. Pareto-activity series of scientific investigations for constrained duration based on SPM-2 results.

Pareto-Activity Series of Scientific Investigations for Unconstrained Duration Based on SPM-2 Results

- NS 8.1: Colloid Concentrations and Transport
- NS 2: Culebra Fracture/Matrix/Flow – Laboratory
- NS 3: Culebra Fracture/Matrix/Flow – Field
- NS 4: Multi-Well Tracer Test
- NS 7: Chemical Retardation in the Culebra
- NS 5: Sorbing Tracer Test
- AST 1.2: Dissolved Actinide Solubilities
- SL 4 + RM 1 + DR 2: Short- and Long-Term Seal Component Studies using MDCF Rock Mechanics Model; Blowout Releases

Figure 5-2. Pareto-activity series of scientific investigations for unconstrained duration based on SPM-2 results.

The constrained duration series consists of eight scientific investigations for a total cost of $29.250 million and an end date of November 30, 1996, and yields a PDC of 0.96. The unconstrained duration series includes two additional investigations for a total cost of $32.364 million, and an end date of September 30, 1997, and yields a PDC of 0.97. The pareto-optimal activity sets represent robust programmatic options that maximize the PDC based solely on scientific investigations at minimal cost for both constrained and unconstrained duration.

5.2 EAs as Assurance

The SPM-2 performance calculations for EAs discriminated between backfills, backfills with waste form modification, and passive markers. The performance effect of each of the 18 EAs originally considered in SPM-2 (derived from the Engineered Alternative Task Force Report, U.S. DOE/CAO, 1991) were obtained during the elicitations by asking the PIs how the presence of each EA would alter the potential outcomes of their scientific activities. Based on these expert judgments, the EAs were divided into three activities for purposes of modeling their potential performance effects. These calculations were sufficient for the purposes of SPM-2 to show the potential value and contribution of these EAs relative to scientific investigations towards demonstrating compliance. However, the calculations do not provide sufficient detail to warrant selection of a specific EA for assurance.

During the same period that SPM-2 was implemented, WID was tasked by DOE/CAO to produce a Cost/Benefit Study of EAs (U.S. DOE/CAO, 1995b). The long-term performance measures in this study were calculated with the Design Analysis Model (DAM) to give a high-level discrimination of performance, but did not discriminate at a detailed level on the basis of important phenomena for long-term performance, such as chemical retardation and solubility control.

The results of SPM-2 and the WID Cost/Benefit Study should be examined collectively to set the stage for more detailed performance calculations of a subset of EAs for DOE/CAO's final selection of EAs for assurance.

5.3 Additional Programmatic Considerations

Additional points to consider in using the SPM-2 results for decision making are that:

1. Key components of the unconstrained pareto-optimal set, such as Activity NS 5, do not meet the DDP schedule constraint, but have been requested by NAS regardless of the results of SPM-2.

2. The technical baseline is decision-aiding only. The final Project Technical Baseline (PTB) that will be used for preparing the WIPP compliance application will incorporate information from the activities completed subsequent to the SPM-2 effort.

3. The results were based on calculations using mean values, and were therefore valid for discriminating between activities intended to shift a mean value for a parameter, but not for discriminating between activities intended to reduce uncertainty about a mean.

4. Not all conceptual models initially suggested in development of the technical baseline and activities for SPM-2 technical baseline could be implemented in the SPM-2 analysis.

Some other potential programmatic issues are:

1. The Consultation and Cooperation (C&C) agreement requires the use of an engineered barrier. Because the particular performance aspects of such a barrier are not specified, this analysis cannot regard the specific EAs defined for SPM-2 as a constraint (such as a required portion of the recommended activity set) in the decision analysis. EAs showed sufficient performance promise to merit further detailed assessment outside the SPM-2 framework. This was provided by the Engineered Alternatives Cost/Benefit Study performed by the WID (U.S. DOE/CAO, 1995b.)

2. EA 3 is required by 40 CFR Part 191.

These issues are not attributes of the decision, but were reviewed by Senior WIPP management with DOE/CAO to examine their context and framework within the SPM-2 analysis.

5.4 Lessons Learned

A number of lessons were learned in implementing SPM-2 that should be considered in future prioritization projects.

1. Proper framing of probabilistic calculations is essential. Because of the computational burden, the calculations should be limited to activities that are likely to require explicit quantitative evaluation using the disposal system performance and PDC codes. Single or multiattribute utility analyses may be beneficial in providing a structured and documented process for prioritizing which activities require such explicit treatment and which can be treated as side investigations.

2. Probabilistic tools might be useful in treating uncertainties in cost or duration of activities, particularly long-duration or high-cost activities.

3. Some preliminary results from scientific investigations are not fully consistent with outcomes predicted in the SPM-2 elicitations. Although the goal of a comprehensive decision analysis,

such as SPM, is to fully predict all potential outcomes of activities, some differences in actual outcomes of experiments must be expected. This does not invalidate the calculations or the quality of the decisions made on the basis of the calculations. In fact, a structured process like SPM can be used in an iterative fashion to address such results and to incorporate new knowledge gained over time, continually improving the value of decision-aiding tools like SPM.

4. SPM-2 was a resource-intensive process, partly as a result of the time-consuming process of elicitation, documentation, development of a general consensus on which activities to analyze, and the need to educate the many participants on the implementation of this unfamiliar and technically complex process. Efforts should be made to improve the efficiency of future prioritization efforts. Sufficient time must be allowed for training and education.

5. Bias is an issue in prioritization projects that requires careful attention. There are many types of potential bias that should be addressed when gathering information for a decision-analysis process. Motivational issues were of particular concern in SPM-2 because of the possibility that funding could be cut or reallocated as a result of the prioritization effort. Volume I of this report discusses the approach used in SPM-2 to reduce and understand bias. Arguments could be made that the potential for bias could have been reduced by using outside experts instead of PIs to define the decision-analysis input. On the other hand, the PIs had more complete knowledge of the scientific investigations, so it was preferable to elicit them for certain technical input. For SPM-2, we chose to use the PIs as the primary source of input for most of the activity outcomes and to use professional elicitors trained in addressing potential motivational and cognitive bias to elicit this input (input for EAs and WACs also came from other Project sources, as described in Volumes I and II). In addition, management reviews of the SPM-2 baseline and the activity outcomes were conducted to assure proper integration between technical areas, to provide a consistent perspective on conservatism, and to review the technical justification for the activity outcomes.

5.5 Conclusions

Numerous sources of uncertainty were examined in terms of their potential effects on the SPM-2 decision matrix and associated decision options. Uncertainties in the long-term behavior of such a highly coupled, nonlinear system (and associated decision calculations) will always remain. However, the authors believe the results of these analyses provide valuable insights into programmatic options for maximizing the PDC while minimizing associated costs and durations.

The results of the uncertainty studies were also considered by SNL management to be internally consistent with earlier WIPP PA sensitivity studies (WIPP PA 1993) as well as the large body of scientific knowledge developed over WIPP's twenty year history. SNL management judged the SPM-2 results to be of sufficient quality for programmatic decision making. The scientific investigation program developed subsequent to the completion of SPM-2 has also begun to yield results that will contribute to an evaluation of compliance of the WIPP disposal system with the selected long-term regulations.

Given an understanding of the assumptions and uncertainties inherent in this work, SPM-2 results can be used to assist DOE/CAO in making informed decisions about prioritization of the WIPP in terms of compliance with the long-term performance regulations, 40 CFR 191.13(a) (radionuclide containment requirements) and 40 CFR 268.6 (hazardous constituent concentration requirements).

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APPENDIX A: SPM-2 ACTIVITIES

Table A-1. SPM-2 Activities

Activity	Activity Description	Cost (in $K)	Start Date	End Date	Duration (years)	Comments
AST 1.1	Dissolved Actinide Solubilities for Oxidation States +III - +VI	4,789	5/1/95	10/31/95	1.5	
AST 1.2	Dissolved Actinide Solubilities for Oxidation States +III - +V	4,304	5/1/95	10/31/95	1.5	
GG 1	RPM and Supporting Data	10,998	5/1/95	1/5/00	4.7	Not analyzed. Side investigation.
DR 1	Decomposed Waste Properties	150	5/1/95	10/31/96	0.6	
DR 2	Blowout Releases	250	5/1/95	10/31/96	0.6	
DR 3	Non-Blowout Releases	250	9/1/95	9/30/96	1.1	
RM 1	Rock Mechanics	3,660	5/1/95	9/30/95	1.4	
SL 4	Studies of Short- and Long-Term Components	6,665	5/1/95	9/30/95	1.4	
SAL 1	Lab/Field Properties of Anhydrite	2,228	5/1/95	9/30/98	3.4	
SAL 2	Halite Far-Field Pore Pressure	258	5/1/95	9/30/96	1.4	
SAL 3	Halite Lab/Field Properties	1,107	5/1/95	9.30/98	3.4	
SAL 4.1	Fingering/Channeling Studies - Existing Data	313	5/1/95	10/31/96	1.5	No performance effect.
SAL 4.2	Fingering/Channeling Studies - New Data	1,320	5/1/95	1/31/98	2.8	No performance effect.
SAL 4.3	Anhydrite Fracture Studies	3,405	5/1/95	12/31/98	3.7	No performance effect.
NS 2	Culebra Fracture/ Matrix/Flow - Lab	816	5/1/95	9/30/96	1.4	
NS 3	Culebra Fracture/ Matrix/Flow - Field	404	10/1/95	2/1/97	1.8	
NS 4	Multi-Well Tracer Test	3,113	5/1/95	9/30/96	1.4	
NS 5	Sorbing Tracer Test	2,710	5/1/95	9/30/97	2.4	
NS 7	Chemical Retardation for Th, Np, Pu, U, and Am	7,200	5/1/95	11/30/96	1.6	

Table A-1. SPM-2 Activities (Continued)

Activity	Activity Description	Cost (in $K)	Start Date	End Date	Duration (years)	Comments
NS 8.1	Concentrations and Transport of Colloid Carriers: HMWOC and Microbes	3,242	5/1/95	11/30/96	1.6	
NS 8.2	Enhanced Colloid Experimental Program	4,602	5/1/95	11/30/96	1.6	
EA 1	Backfill with pH Buffer	2,000	NA	NA	0	
EA 2	Backfill with pH Buffer and Waste Form Modification	25,000	NA	NA	0	
EA 3	Passive Markers	65,000	NA	NA	0	Cost range: $30 to $100 million.
WAC 1	Non-Corroding Waste Containers	23,000	NA	NA	0	
WAC 2	Elimination of Humic-Containing Waste Drums (Not Funded)	0	NA	NA	0	

APPENDIX B: STATISTICAL MODELING AND ANALYSIS OF THE SPM-2 DECISION MATRIX

The Systems Prioritization Method – Second Iteration (SPM-2) effort generated over 50,000 unique activity sets for nonzero performance effect. In order to understand the structure of the probabilities of demonstrating compliance (PDC) for these activity sets, a statistical exploratory analysis was conducted. This analysis employed a logit regression approach. A logit regression assumes that a probability, p, (or other number bounded by zero and one) is related to several independent variables through the relation

$$\log\left(\frac{p}{1-p}\right) = \sum_{i=0}^{m} \beta_i x_i$$

where the x_i are indicator variables (0,1), and the β_i are regression coefficients to be estimated. Here, p is the PDC. Because the left side of the equation is unbounded at p = 0 and p = 1, the PDC values were shrunk slightly towards 0.5 by the relation $p^* = (p-.5)(1-\varepsilon) + 0.5$ where ε is a small number such as 0.01.

An initial inspection of the data reveals two very strong boundary condition relations. First, if neither NS 8.1 nor NS 8.2 is included in the activity set, the PDC will be zero. Second, if either NS 8.1 or NS 8.1 is in the activity set, the PDC will be one if EA 1 or EA 2 is also in that activity set and will be less than one otherwise. The first relation provides a sufficient condition of PDC = 0, and the second relation provides a condition that is both necessary and sufficient for PDC = 1. These two relations logically limit the activity sets where activities other than NS 8.1, NS 8.2, EA 1, and EA 2 can moderate the PDC.

Activity sets that do not contain NS 8.1 or NS 8.2 will always have a PDC = 0, regardless of the presence of absence of other activities, and thus these activity sets contain no information about the efficacy of other activities. Moreover, activity sets meeting the second relation will have PDC = 1, regardless of any other activities. Thus, these activity sets will also not yield any information about the efficacy of other activities. The analysis must, therefore, be limited to those activity sets where both 1) NS 8.1 or NS 8.2 is present, and 2) neither EA 1 or EA 2 is present.

Several activities are also found only in combination with one another. This is true of RM 1 and SL 4, and SAL 2 and SAL 3. These activities can be represented by a single indicator variable.

Analysis of the Scientific Program

It is clear that NS 8.1 or NS 8.2 must be undertaken to achieve any PDC greater than zero. In the absence of EA 1 and EA 2, what scientific programs should be undertaken to achieve a high

PDC? This question is important because 1) EA 1 and EA 2 have not (to date) been accomplished, and 2) EA 1 and EA 2 may eventually have a significantly higher cost than initially estimated. To better understand the contribution of the scientific programs, the following statistical analysis was performed.

Using the logit model described earlier, and excluding from the data set those activity sets without either NS 8.1 or NS 8.2 and those having some combination of an NS 8 activity with EA 1 or EA 2, the regression coefficients and p-values shown in Table B-1 were obtained. The regression also included an interaction term for DR 2, RM 1, and SL 4. Examination of preliminary plots revealed that such an interaction was present.

The p-values are those reported by the SAS statistical analysis program. Small p-values, those nearest zero, are indicative of a significant statistical relationship between the indicator variable and the dependent variable of logit, while large p-values (often those above 0.05) are indicative of the absence of such a relationship. However, such an interpretation depends upon a random component, such as an error term, which does not exist in this case. Nevertheless, the p-values provide guides to those variables that have a significant impact on the PDC.

The parameter estimates directly influence the PDC estimated from the regression. Since all indicator variables are either zero or one, the magnitudes of the regression coefficients can be directly compared. Furthermore, an order relation was established from these coefficients based on maximum PDC for minimum incremental costs. This order relation was used to guide the analysis of the decision matrix containing PDC values to obtain the pareto-optimal ordering of activities.

The ordering of activities from those that have the greatest impact to those that have the least impact allows one to create a series of activities. As activities are added to the series, the PDC should increase at a decreasing rate. If the costs of the activities are similar, it is, in principle, possible to build a concave monotonically-increasing function that shows the relation between the PDC and costs as more activities are undertaken. Such a curve is shown in Figure B-1, but it is not uniformly concave, as one might expect. This occurs because there are both thresholds and interactions (synergies) among some activities.

Figure B-1 shows PDC as a function of cost for a pareto-optimal series for unconstrained duration. The optimal ordering of the activities is dependent on both the regression coefficients, which indicate the significance of an activity in increasing PDC, and the incremental cost of the activity. The optimal ordering of activities for each set in the SPM-2 decision matrix was obtained by looking at the ratio between the β coefficients and costs.

Having established the optimal ordering of activities for each activity set (with respect to PDC and cost), one can determine the pareto-optimal series, which consists of those activity sets for which, at every point, there can be no higher PDC at the same cost level. This was determined for an activity series of unconstrained-duration and for an activity series with a duration constraint of

Table B-1. Regression Coefficients and p-values for SPM-2 Activities

Activity	Estimate of β	p-value
Constant	-6.904	0.0000
AST 1.1	0.188	0.0001
AST 1.2	0.188	0.0001
DR 2	0.001	0.9786
DR 3	0.001	0.9849
RM 1 & SL 4	-1.935	0.0000
Interaction DR 2, RM 1 & SL 4	2.519	0.0001
SAL 1	-0.010	0.7627
SAL 2 & SAL 3	0.015	0.6365
NS 2	0.612	0.0001
NS 3	0.151	0.0002
NS 4	0.911	0.0001
NS 5	0.212	0.0001
NS 7	1.252	0.0001
NS 8.1	5.276	0.0000
NS 8.2	5.276	0.0000

19 months. The curve shown in Figure B-1 is for a pareto-optimal activity series unconstrained by duration.

At the lower left of the unconstrained-duration pareto-optimal curve in Figure B-1, it is shown that no improvement in the PDC is obtained by performing NS 8.1 by itself. (Here we have chosen NS 8.1 over NS 8.2 because of equal impact on the PDC and lower cost for NS 8.1.) Since NS 8.1 cannot, by itself, provide a PDC greater than zero, it follows that no single activity by itself can provide a PDC greater than zero. However, with the addition of NS 2, the PDC rises to approximately 0.19. Further improvement is provided by NS 3, NS 4, and NS 2, with a diminishing of returns relative to cost for the addition of NS 5. At this point, it does not seem possible to increase the PDC by adding any single remaining scientific activity. As the figure shows, the addition of AST 1.2 brings a slight decrease in the PDC[B-1]; AST 1.2 is a necessary precursor to RM 1, SL 4, and DR 2. Without first performing AST 1.2, the addition of RM 1, SL 4, and DR 2 would also produce a decrease in the PDC. The same unexpected behavior

[B-1] The increase in PDC is due to the fact that one of the outcomes of AST 1.2 is less favorable than the baseline position.

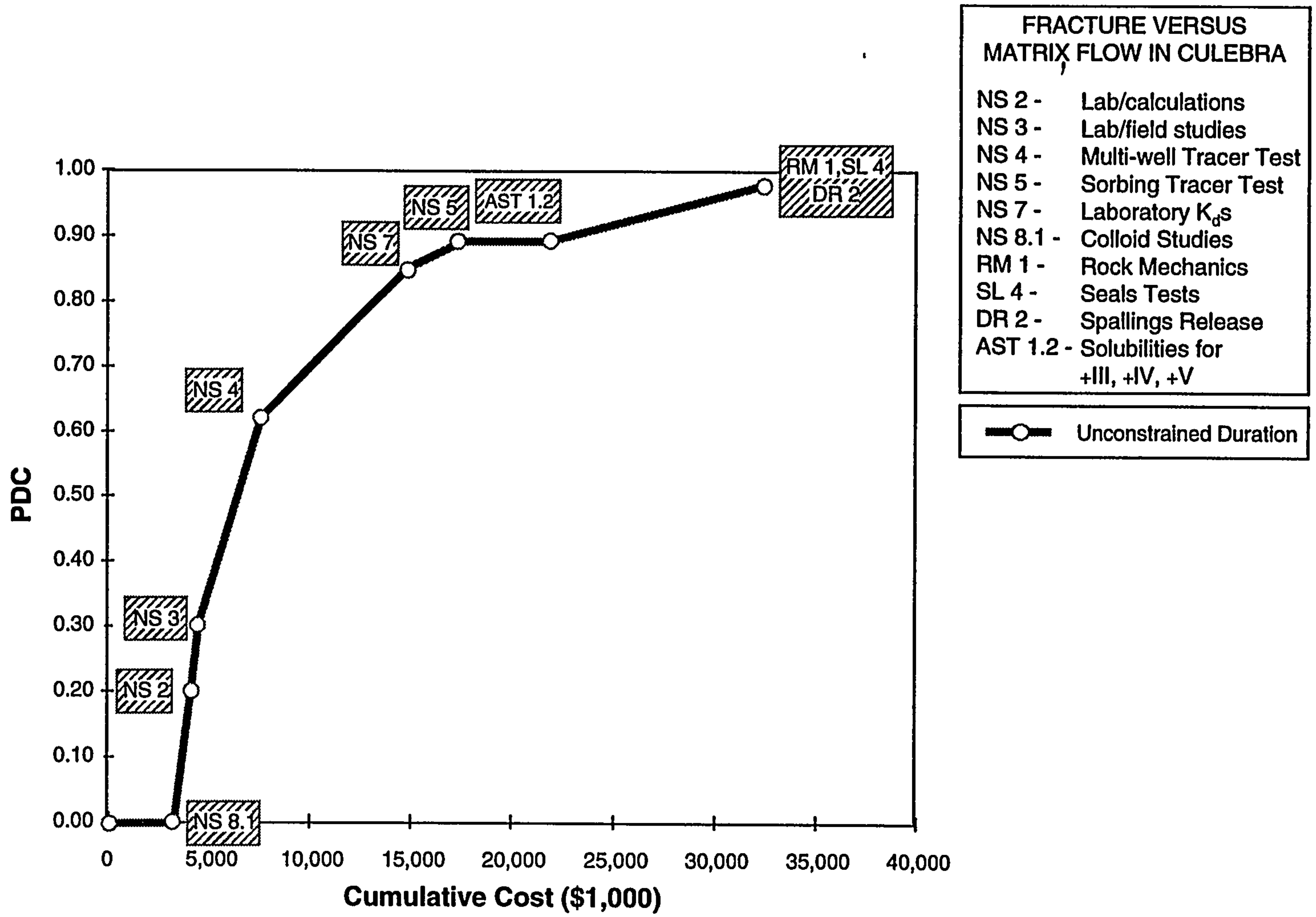

Figure B-1.Pareto-optimal activity series for scientific investigations (PDC versus cumulative cost).

occurs was observed when the order of the three final activities was switched. Therefore, some interaction is taking place between AST 1.2 and RM 1, SL 4, and DR 2 as a group. The addition of any other activities can bring only minuscule improvements. A PDC of 0.97 is achieved from this set of activities.

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