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Condensed Summary of the Systems Prioritization Method as a Decision-Aiding Approach for the Waste Isolation Pilot Plant

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ABSTRACT

In March 1994, the U.S. Department of Energy Carlsbad Area Office (DOE/CAO) implemented a performance-based decision-aiding method to assist in programmatic prioritization within the Waste Isolation Pilot Plant (WIPP) project. The prioritization was with respect to 40 CFR Part 191.13(a) and 40 CFR part 268.6, U.S. Environmental Protection Agency (EPA) requirements for long-term isolation of radioactive and hazardous wastes.[1] The Systems Prioritization Method (SPM), was designed by Sandia National Laboratories to: 1) identify programmatic options (activities), their costs and durations; 2) analyze combinations of activities in terms of their predicted contribution to long-term performance of the WIPP disposal system; and 3) analyze cost, duration, and performance tradeoffs. SPM results were the basis for activities recommended to DOE/CAO in May 1995. SPM identified eight activities (less than 15% of the 58 proposed for consideration) predicted to be essential in addressing key regulatory issues. The SPM method proved useful for risk or performance-based prioritization in which options are interdependent and system behavior is nonlinear.

KEY WORDS

Decision analysis, probabilistic performance assessment, geologic disposal, radioactive waste, hazardous waste, risk-based prioritization

INTRODUCTION

The Systems Prioritization Method (SPM) is a performance-based, decision-aiding method developed by Sandia National Laboratories (SNL) for the U.S. Department of Energy Carlsbad Area Office (DOE/CAO) to assist in programmatic prioritization within the WIPP project. SPM was designed to 1) identify programmatic options (activities), their costs and durations; 2) analyze combinations of activities (activity sets) in terms of their predicted contribution to the WIPP disposal system with respect to EPA long-term performance requirements in 40 CFR 191.13(a) (EPA, 1993) and 40 CFR 268.6 (EPA, 1992); and 3) analyze cost, duration, and performance tradeoffs. The second iteration of SPM (SPM-2), completed in March 1995, determined the most viable combinations of scientific investigations, engineered alternatives (EAs), and waste acceptance criteria (WAC) for

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[1] The WIPP Land Withdrawal Act amendments of 1996 effectively removed the need for WIPP to demonstrate compliance with 40 CFR Part 268.6.

supporting the final compliance certification application for WIPP. The results of the second iteration of SPM (SPM-2) were the basis for recommendations to DOE/CAO in May 1995 for programmatic prioritization within the WIPP project. SPM identified eight activities (less than 15% of the 58 proposed for consideration) predicted to be essential for addressing key regulatory issues. This paper is a condensed summary of SPM, its implementation and key results (Boak *et al*, 1996; Helton *et al*, 1996; Prindle *et al*, 1996a, b, and c).

KEY STEPS AND CONCEPTS

The goal of SPM was to provide information about how potential activities—scientific investigations, engineered alternatives, and waste acceptance criteria—when viewed singly or in combination, could contribute to a demonstration of compliance with performance requirements for the WIPP disposal system. For each combination of activities (activity sets), SPM was used to calculate the probability of demonstrating compliance (PDC) if the activity set were implemented. The activity set's PDC, cost, and duration were contained in a decision matrix that was analyzed to find programmatic options that maximized incremental PDC while minimizing activity set cost and duration. SNL performance assessment models were used to estimate how the disposal system might perform if activities were implemented, and this evaluation was the basis for calculating each activity set's PDC. SPM analyzed roughly 46,700 activity sets. Probabilistic performance calculations for these activity sets resulted in over 1.3 million complementary cumulative distribution functions (CCDFs). A relational database on a 600-megabyte CD-ROM was used to store performance assessment results, data analysis and visualization tools, information about the activities, electronic copies of 40 CFR 191 and 40 CFR 268, technical reference papers, and the draft SPM report (Harris *et al*, 1996). Copies of the CD-ROM were distributed to interested members of the public, WIPP participants, and the EPA.

SPM can be described in terms of eleven key steps (Figure 1): 1) Define the performance objective(s); 2) Develop a technical baseline for SPM calculations; 3) Perform computer modeling of the baseline; 4) Determine whether the baseline is predicted to succeed or fail in meeting the objectives; 5) If the baseline fails to meet performance objectives, identify activities that, if implemented, could improve a predicted ability to meet the performance objectives, and elicit potential outcomes for those activities (if the baseline passes, proceed to Step 11); 6) Evaluate the baseline combined with potential outcomes of combinations of activities; 7) Create a decision matrix containing the performance results, cost, and duration for all activities and perform decision analysis to develop final recommendations; 8) Make programmatic decisions about which activities to implement, if any; 9) Implement the activities; 10) Update the technical baseline with actual results from the activities; and iterate the process from step 3 as necessary until the baseline is predicted to meet the performance objectives; and, 11) Perform final performance assessment calculations with approved data and models when the baseline is predicted to comply.

SPM is distinct from performance assessment calculations for compliance in important ways. SPM, in effect, was a strategic planning approach that applied performance assessment codes at a level of abstraction sufficient to discriminate between programmatic options but insufficient for the rigor and detail required in a complete performance assessment. Maintaining this separation is important to keep probabilistic calculations tractable and in maintaining an efficient planning process.

Key to how SPM works is in understanding the relationship between the regulatory performance objectives, the input to and output of the performance calculations, and the tradeoff analysis between activity sets' PDC, cost, and duration. Performance assessment models are used by the WIPP project to produce information about the predicted long-term performance of the disposal system that can be compared to the regulatory requirements (WIPP PA, 1993). For WIPP, this means calculating a CCDF for radionuclide releases, which represents the probability distribution of summed, normalized radionuclide releases from the disposal system to the accessible environment, and estimating potential releases of regulated volatile organic compounds and heavy metals. The WIPP disposal system is predicted to be in compliance with the containment requirements if 1) no point on the CCDF exceeds the summed normalized release limits in 40 CFR 191.13(a) and if 2) of hazardous constituent concentrations in soil do not exceed the limits in 40 CFR 268.6.

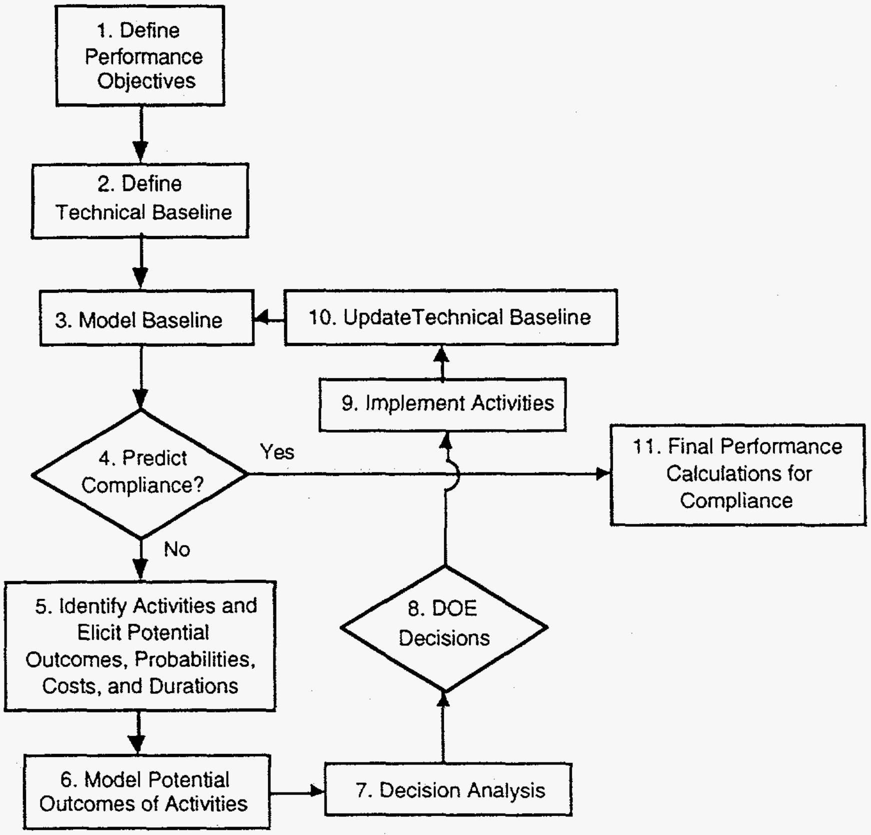

Figure 1: Key steps of SPM as applied to WIPP.

While the regulatory release limits are fixed, estimates of the predicted performance of the WIPP disposal system are not; they are determined by a state of knowledge that changes over time as a result of performing scientific investigations, implementing EAs, or modifying WACs. The changed state of knowledge can alter the position of the CCDF with respect to the release limits and the state of knowledge can be expressed, in part, through probability distributions. For example, although it is not possible to predict the solubility of plutonium in WIPP brines with absolute certainty, a range of solubilities under various chemical conditions and based on many types of existing information can be postulated, thus defining a portion of the SPM-2 calculational baseline.

Consider a scientific experiment (activity A) designed to more accurately determine the solubility of plutonium in brine. The experimental design anticipates a range of possible outcomes based on both published information and expert judgment. For simplicity, suppose that the set of experimental outcomes can be classified into two ranges (actually probability distributions), from lowest to highest solubility. Denote the event that the experimental outcomes for activity A are in the first range by x_{A1} and in the second range by x_{A2}. Denote the two probability distributions corresponding to the two experimental outcomes by f_{A1} and f_{A2}. After the experiment has been completed, the state of knowledge about plutonium solubility changes to reflect the new information produced by the experiment. All uncertainty, however, will not be resolved by the experiment because uncertain repository conditions make it impossible to know with certainty what the chemical environment—and thus actual solubility—will actually be. Nonetheless, after the experiment is completed, residual uncertainty about the solubility can, again, be expressed through a probability distribution that reflects the new information and new expert judgments; this process can continue until the cost of further work is no longer justified by the potential results.

Now, suppose that we use expert judgment to specify the potential experimental outcomes $x_{i,j}$ and associated probability distributions $f_{i,j}$ (where i,j are the activity and activity outcome identifiers, respectively) *before* conducting the experiment, and use these probability distributions in performance assessment models to estimate the consequences. In addition to providing the x_i and f_i, we also use expert judgment to specify the relative likelihood or probabilities of the events x_{A1} and x_{A2}, p_{A1} and p_{A2} respectively. Suppose that performance calculations predict that, if activity A is conducted alone, event x_{A2} will indicate compliance with long-term performance requirements for radionuclide and hazardous material containment, but that the event x_{A1} will indicate noncompliance. The predicted probability of successfully demonstrating compliance for the this activity—viewed prior to conducting the experiment—is then p_{A2}. Note that SPM-2 results showed that, when conducted alone, no single activity had a non-zero PDC, i.e., was sufficient to produce a CCDF indicating compliance with long-term performance requirements.

Finally, consider an *activity set* that is composed of two activities, A and B, each with two possible outcomes, and suppose that performance results show that compliance is indicated *only* if 1) activity A has outcome x_{A1} *and* activity B has outcome x_{B2} *or* if 2) activity A has outcome x_{A2} *and* activity B has outcome x_{B2}. The PDC for the activity set consisting of A and B would then equal $(p_{A1} \times p_{B2}) + (p_{A2} \times p_{B2})$. Because each SPM activity has at least two outcomes and because activity sets consist of between one and 26 activities, activity sets can have anywhere between two and nearly 60,000 possible outcome combinations, each of which corresponds to a CCDF and a RCRA soil concentration. Thus, the PDC for an activity set represents a logically straightforward but very computationally intense set of calculations. SPM-2 results showed that many activity sets were predicted to produce a CCDF indicating compliance with long-term radionuclide containment requirement (Boak *et al*, 1996; Prindle *et al*, 1996c).

SPM-2 RESULTS

The first iteration of SPM (SPM-1), which was completed in September 1994, prototyped the approach implemented in the second iteration (SPM-2). SPM-2, completed in March 1995, was the basis for programmatic decision making. WIPP project technical staff, stakeholders, and oversight groups contributed to establishing the SPM-2 baseline. Technical teams also defined proposed activities and were elicited on the predicted outcomes of those activities. Trained elicitors external to the WIPP project formally elicited the technical baseline and proposed scientific activities from the technical teams DOE/CAO and the Westinghouse Waste Isolation Division provided information regarding EAs, potential changes to WACs, and other programmatic guidance.

Potential outcomes were initially elicited for 58 discrete activities, including 37 scientific investigations, 18 EAs, and three WACs; these were screened to 26 activities (Table 1), including 21 scientific investigations, three EAs, and two WACs (Prindle *et al*, 1996b). SPM-2 used existing WIPP performance assessment computer codes, with modifications required to model the baseline and activity sets, to calculate CCDFs of potential radionuclide releases. SPM-2 evaluated more than 600,000 possible activity sets. Activities with performance impact were removed from the decision matrix, reducing the number to roughly 46,700.

SPM-2 results indicated that PDC generally increased, as expected, with increasing cost and duration. Figure 2 shows the highly nonlinear structure of the results in terms of the PDC versus activity set cost. Programmatic interdependencies were also apparent from general trends in the data and are discussed in the next section, which summarizes the statistical regression analysis of the SPM-2 results. The SPM-2 baseline calculation predicted release of radionuclides in violation of 40 CFR 191.13(a) but compliance with respect to 40 CFR 268.6. About 40% of the SPM-2 activity sets had a PDC of 0 (i.e., with no predicted value in supporting a demonstration of compliance). Of the remaining 60% of the SPM-2 activity sets, one half had a PDC equal to one. When conducted alone, no single activity—scientific investigation, EA, or WAC—had a non-zero PDC.

Activity sets with a PDC of 1.0 included one of two scientific investigations for colloids (either NS 8.1 or NS 8.2) and one of two EAs (either EA 1 or EA 2). Note that EAs and WACs were assumed to be optimally effective and were assigned a 100% probability of yielding the predicted performance. Subsequent sensitivity studies investigated the impact of this assumption on the final decision. Two WACs were analyzed by SPM-2. In the WAC-1 activity, steel drums used to store the waste were replaced with non-corrodible materials. WAC-1 added costs to the program and slightly reduced the 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.

TABLE 1
ACTIVITIES ANALYZED IN SPM-2

Activity	Indicator
Actinide Source Term (AST)	
Dissolved Actinide Solubilities for Oxidation States +III – +VI	AST 1.1
Dissolved Actinide Solubilities for Oxidation States +III – +V	AST 1.2
Disposal Room (DR)	
Decomposed Waste Properties	DR 1
Blowout Releases	DR 2
Non-Blowout Releases	DR 3
Seals and Rock Mechanics (SL and RM)	
Rock Mechanics	RM 1
Studies of Short- and Long-term Components	SL 4
Salado (SAL)	
Lab/Field Properties of Anhydrite	SAL 1
Halite Far-Field Pore Pressure	SAL 2
Halite Lab/Field Properties	SAL 3
Fingering/Channeling Studies – Existing Data	SAL 4.1
Fingering/Channeling Studies – New Data	SAL 4.2
Anhydrite Fracture Studies	SAL 4.3
Non-Salado (NS)	
Dewey Lake - Paper and Low-Effort Field Studies	NS 1
Culebra Fracture/Matrix/Flow – Lab	NS 2
Culebra Fracture/Matrix/Flow – Field	NS 3
Multi-Well Tracer Test	NS 4
Sorbing Tracer Test	NS 5
Chemical Retardation for Th, Np, Pu, U, and Am	NS 7
Concentrations and Transport of Colloid Carriers: High-Molecular Weight Organic Compounds (HWMOC) and Microbes	NS 8.1
Enhanced Colloid Experimental Program	NS 8.2
Engineered Alternatives (EAs)	
Passive Markers	EA 3
Backfill with pH Buffer	EA 1
Backfill with pH Buffer and Waste Form Modification	EA 2
Waste Acceptance Criteria (WAC)	
Non-Corroding Waste Containers	WAC 1
Elimination of Humic-Containing Waste Drums	WAC 2

Based on these results, DOE/CAO had a preliminary decision to make, which was to either: 1) depend on a program consisting of EAs and minimal scientific investigations to provide a basis for the final compliance calculations; or 2) reserve EAs for possible use in providing assurance and depend on the scientific investigations to demonstrate compliance with 40 CFR 191.13(a) and 40 CFR 268.6. In May 1995, DOE/CAO chose the second option. Additional work has been conducted on EAs since the completion of SPM, and the final balance between predicted performance of the geologic system, EAs, and WACs is addressed in the compliance certification application (U.S. DOE, 1996). The final programmatic recommendations to DOE/CAO in May 1995 considered the SPM-2 results, sensitivity and uncertainty analyses, and existing information such as the 1992 WIPP PA Sensitivity Analysis (WIPP PA, 1993).

ANALYSIS OF SPM-2 RESULTS

SPM-2 generated roughly 46,700 unique activity sets. In order to determine the most favorable activity set(s) for meeting the DOE/CAO objectives, a statistical regression analysis was conducted. This analysis employed a logit regression methodology. A logit regression assumes that a probability, p (or other number bounded by 0 and 1), is related to several independent variables through Eqn. 1:

$$\log [p/(1-p)] = \Sigma b_i x_i \tag{1}$$

where x_i is the indicator variable (equal to 0 or 1) and b_i is a regression coefficient 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 decreased slightly towards 0.5 as shown in Eqn. 2:

$$p = (p - 0.5)(1 - \varepsilon) + 0.5, \tag{2}$$

where ε is a small number such as 0.01.

An initial inspection of activity sets in the decision matrix revealed two very strong relationships. First, if neither colloid activity (NS 8.1 nor NS 8.2) was included in an activity set, the PDC was 0. Second, if either NS 8.1 or NS 8.2 was in an activity set, the PDC was equal to 1 *as long as* an EA (EA 1 or EA 2) was also in that activity set, and less than 1 otherwise. Both of these relations were always true, and thus the first relation provided a sufficient condition for creating a PDC equal to 0. The second relation provided a condition that was both necessary and sufficient for PDC to equal 1. These two relations logically limited the PDC of activity sets without EA 1 or EA 2 to $0 \leq PDC < 1$.

In the absence of EA 1 and EA 2, what scientific programs should be undertaken to achieve a high PDC? This question was important because the predicted performance of EA 1 and EA 2 did not account for the possibility that an EA might prove less effective than assumed. Moreover, there were reasons to believe that the system-wide costs of EA 1 and EA 2 might ultimately be larger than initially estimated. For these reasons and to better understand the cost/benefit tradeoffs for the scientific program, a statistical analysis was limited to those activity sets where both of the following occurred: 1) NS 8.1 or NS 8.2 was present, and 2) neither EA 1 nor EA 2 was present.

Using the logit) regression model, excluding from the data set those activity sets without either NS 8.1 or NS 8.2 and excluding those having some combination of colloid activity with EA 1 or EA 2, regression coefficients were obtained. Based on regression results, activities are ordered from those with the greatest impact to those with the least impact, creating a series of activities such that as activities are added to the series, the PDC continues to increase, but 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 maximizes incremental PDC gained while minimizing incremental costs as more activities are added to the series. Two such activity series are shown in Figure 2 (the two curves on the left-most side of the graph), but they are not fully concave. The far-left curve is unconstrained by duration while the middle curve is constrained by a 19-month duration. The reason that these curves are not fully concave is that there are both thresholds and interactions (synergies) among some activities. The right-most curve in Figure 2 is a suboptimal activity series that ultimately reaches nearly the same PDC as the pareto-optimal series but without the same ability to maximize incremental PDC per dollar at every point in the series.

For both the duration-constrained and unconstrained activity series in Figure 2, no improvement in the PDC was obtained by performing NS 8.1 by itself. (Here NS 8.1 was chosen over NS 8.2 because of equal impact on the PDC and lower cost for NS 8.1.) However, for the duration-constrained series, the addition of the two scientific investigations NS 2 and NS 4 increased the PDC to 0.56. The addition of NS 7 further increased the PDC to 0.82. As Figure 2 shows, the addition of AST 1.2 did not increase the PDC. However, AST 1.2 was necessary to gain the PDC improvement provided by the combination of RM 1, SL 4, and DR 2. In fact, without first performing AST 1.2, the addition of RM 1, SL 4, and DR 2 produced a decrement in PDC. The same unexpected behavior occurred when the order of the activities was switched. It can therefore be concluded that some interaction is taking place between AST 1.2 and the collection of three activities. Addition of any other activity to the series only brings minuscule improvements. A PDC of 0.96 is achieved from the duration-constrained pareto-optimal series.

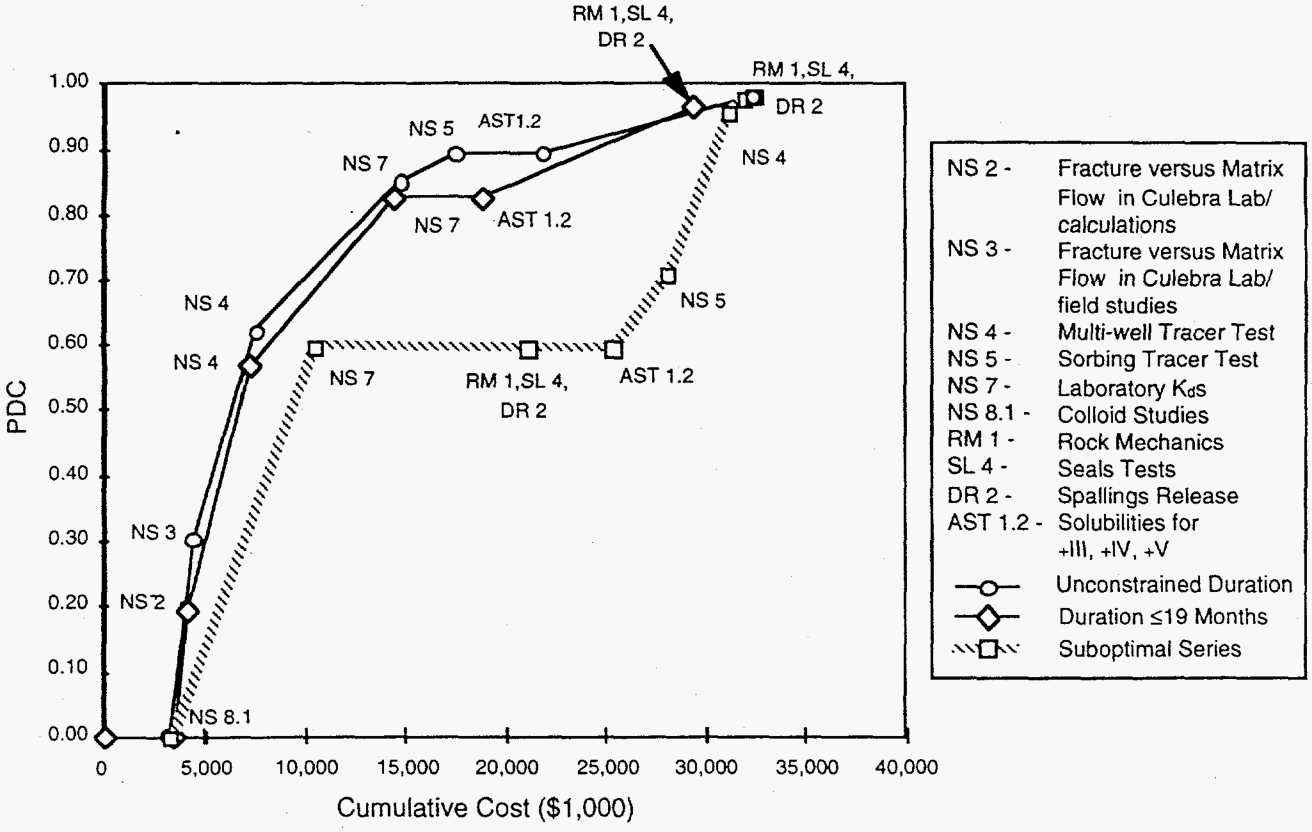

Figure 2. PDC versus activity set cost for pareto-optimal and sub-optimal activity series.

The two series on the left are both considered pareto-optimal, that is, neither series can be bettered simultaneously in both cost and PDC for its respective duration. Faced with programmatic options limited to scientific investigations—without EAs or WAC modifications—both the duration-constrained and unconstrained activity series appear to be logical programmatic choices. However, the duration-constrained series, which eliminated two scientific activities NS 3 and NS 5 resulted in virtually the same PDC as the unconstrained set and with lesser cost. SPM-2 results were the basis for recommendations to DOE/CAO in May 1995 for programmatic prioritization. DOE/CAO chose the duration-constrained series.

CONCLUSIONS

SPM identified eight key activities (less than 15% of the initial 58 activities proposed for consideration) for WIPP that, if implemented, were predicted to lead to a positive demonstration of compliance with EPA long-term performance requirements with a high level of confidence. Moreover, analysis of the results also indicated that optimal programmatic options existed and that activities could be systematically *cut or added* if budgets changed. The analysis indicated that a demonstration of compliance could be anticipated within the DOE/CAO WIPP Disposal Decision Plan schedule. These eight key activities have now been completed, WIPP performance assessment calculations now indicate compliance with applicable EPA long-term performance requirements, and a Compliance Certification Application was submitted to the EPA on October 29, 1996 (U.S. DOE, 1996).

SPM focused on work to achieve compliance with long-term disposal system performance requirements and helped eliminate concerns that activities were not clearly and demonstrably focused on addressing regulatory issues. The use of quantitative analyses balanced with expert judgment proved essential in developing insights about decision options in a highly nonlinear system. SPM built upon the power of both performance assessment and decision analysis techniques, providing insights for decision making.

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