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Decision Analysis of Hanford Underground Storage Tank Waste Retrieval Systems

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DECISION ANALYSIS OF HANFORD UNDERGROUND STORAGE TANK WASTE RETRIEVAL SYSTEMS*

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ABSTRACT

A decision analysis approach has been proposed for planning the retrieval of hazardous, radioactive, and mixed wastes from underground storage tanks. This paper describes the proposed approach and illustrates its application to the single-shell storage tanks (SSTs) at Hanford, Washington.

I. PROJECT BACKGROUND

Hanford's SSTs are among the most challenging of the Department of Energy's (DOE) mixed-waste problems. The 149 SSTs contain wastes in varying amounts and proportions in the form of sludge, salt cake, mixtures, and concrete-like substances. About 45 percent of the tanks are suspected of leaking. Other major concerns include wastes with flammable gases, unstable compounds, and excessive heat generation. Various options have been proposed for removing the waste from the tanks, but most would be relatively costly or not feasible, and many of the proposed technologies are unproven and/or largely undeveloped for this application.

To help assess the options, an Independent Review Group (IRG) was established, composed of an independent consultant and senior representatives from Sandia National Laboratories and Lawrence Livermore National Laboratory (co-authors of this paper). In 1992, the IRG conducted a broad, top-level review of retrieval systems and technologies for application in the Hanford Tank Waste Remediation System. With support from Westinghouse Hanford Company and DOE's Environmental Management Office of Technology Development, the IRG explored numerous issues related to SST waste retrieval. After recommending that formal decision-aiding methods be utilized, the IRG worked with decision analysts from Applied Decision Analysis, Inc., to develop the basic elements of a methodology. The methodology was then illustrated by conducting a sample application to the SSTs.[1]

II. DESCRIPTION OF THE WORK

The evaluation methodology consists of three major components: (1) a decision pyramid and strategy table, used to establish the scope of the analysis and to select the strategies to be evaluated; (2) an objectives hierarchy, associated performance measures, and set of importance weights, used to specify a multiattribute utility function for the evaluation; and (3) a decision tree, used to conduct the evaluation.

Figure 1 illustrates a decision pyramid. A decision pyramid distinguishes the various levels of the decisions that must be made. The shaded area indicates the focus of the sample application: (1) Which technologies to develop for in-tank retrieval and leak control? (2) Which type or class of tank to select for technology demonstrations? (3) What characterization activities to conduct? (4) Which technologies to apply? (5) How to accomplish intermediate storage of retrieved waste? (6) What closure activities to conduct? Listed above the shaded level are higher-level decisions that are taken as "givens." For example, the sample evaluation assumes that retrieving SST waste is the appropriate means for addressing tank problems. The accuracy of analysis results always depends on the validity of such higher-level assumptions. The lowest portion of the pyramid lists subordinate, more detailed decisions that must be made depending on the choices for the decisions in the shaded area. Where necessary, "baseline" choices are made for

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such lower-level decisions so as to provide assumptions necessary to evaluate the shaded-area decisions.

Table 1 shows a strategy table identifying several options for the decisions to be evaluated. For example, the first column lists options for retrieval system technologies development. These include (a) hydraulic technologies (e.g., high-pressure water jets with associated pumping systems to remove the waste as a slurry), (b) pneumatic systems (e.g., high-velocity air jets with cyclone separators), (c) mechanical systems (e.g., articulated arms with end-effectors to break up the waste and bucket elevators to retrieve it), (d) conventional mining technologies (which would allow waste retrieval after entering the tank through its bottom or sides), and (e) combination technologies (e.g., a hydraulic/mechanical system wherein a mechanical arm would be used with sluicing end-effectors).

The various options for each decision from the strategy table can be combined in many ways. For example,

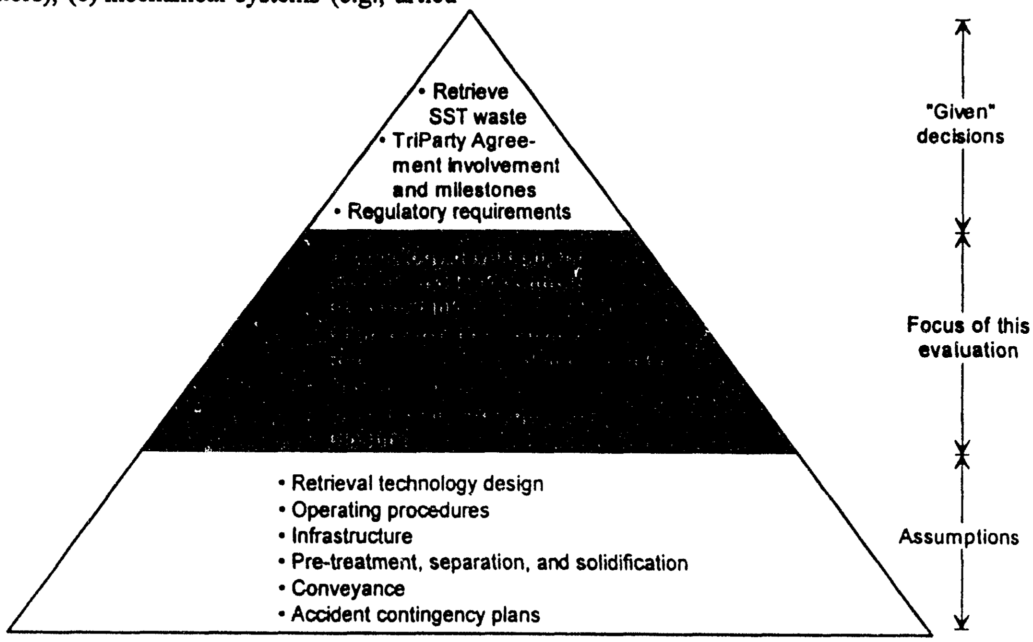

Figure 1. SST Waste Retrieval Decision Pyramid

Table 1. SST Waste Retrieval Strategy Table

KEY DECISIONS						
Technology Development		Class of Tank*	Characterization Activities	Retrieval System for Demo	Intermediate Storage	Closure
Retrieval System	Leak Control					
Hydraulic Pneumatic Mechanical Mining Hydraulic and mechanical	None Liquid control and detection Ex-tank barrier Gelling fluid	Sludges Salt cake Mixture Concrete-like	Physical properties Tank leakage Chemical, radiological properties Physical properties and tank leakage	Hydraulic Pneumatic Mechanical Hybrid Mining	New tanks Existing tanks	None Remove tanks Remediate contaminated soils Remove tanks and remediate contaminated soils

* Class may include a description of safety issues (ferrocyanide, flammable gas, organic sales, high heat)

one strategy is: develop hydraulic retrieval technologies with leak control and detection systems, chose a sludge tank for the demonstration, characterize the physical properties of the tank, use new tanks for intermediate storage, and have no special activities at closure, but with tank removal as a closure requirement. The strategy table is used to piece together a set of reasonable, distinct combinations of options that span the range of possibilities. Theoretically, all options could be evaluated, but the use of the strategy table helps reduce the amount of analysis because combinations that are similar can be combined and obviously inferior strategies can be eliminated.

Figure 2 shows a decision tree developed for the sample evaluation. With decision trees, square and circular nodes correspond to key decisions and uncertainties, respectively. The order of the nodes from left to right shows the sequence in which decisions must be made and uncertainties will be resolved. Branches emanating from decision nodes represent the alternatives available at points of decision, and branches from uncertainty nodes indicate possible outcomes to uncertainties. The decision tree provides a "road map" for what might happen depending on what choices are made and how uncertainties are resolved. In this way, the decision tree provides a detailed description of the problem to be solved. As will be described below, a decision tree also provides a means for solving the problem to identify optimal decision strategies.

The tree in Figure 2 is restricted to four decision nodes, (1) the selection of technologies for development, (2) the choice of a type of tank for a technology demonstration, (3) the selection of a specific retrieval system for the demonstration, and (4) the selection of retrieval systems for other tanks in the same class. Three alternative hydraulic retrieval systems are considered: (h1) installing a leak detection system and retrieving waste using a method termed past practice sluicing (PPS), which involves spraying water from a nozzle mounted on a mechanical mast and pumping out the resulting slurry; (h2) using PPS with leak detection plus subsurface barriers; and (h3) using a confined sluicing method

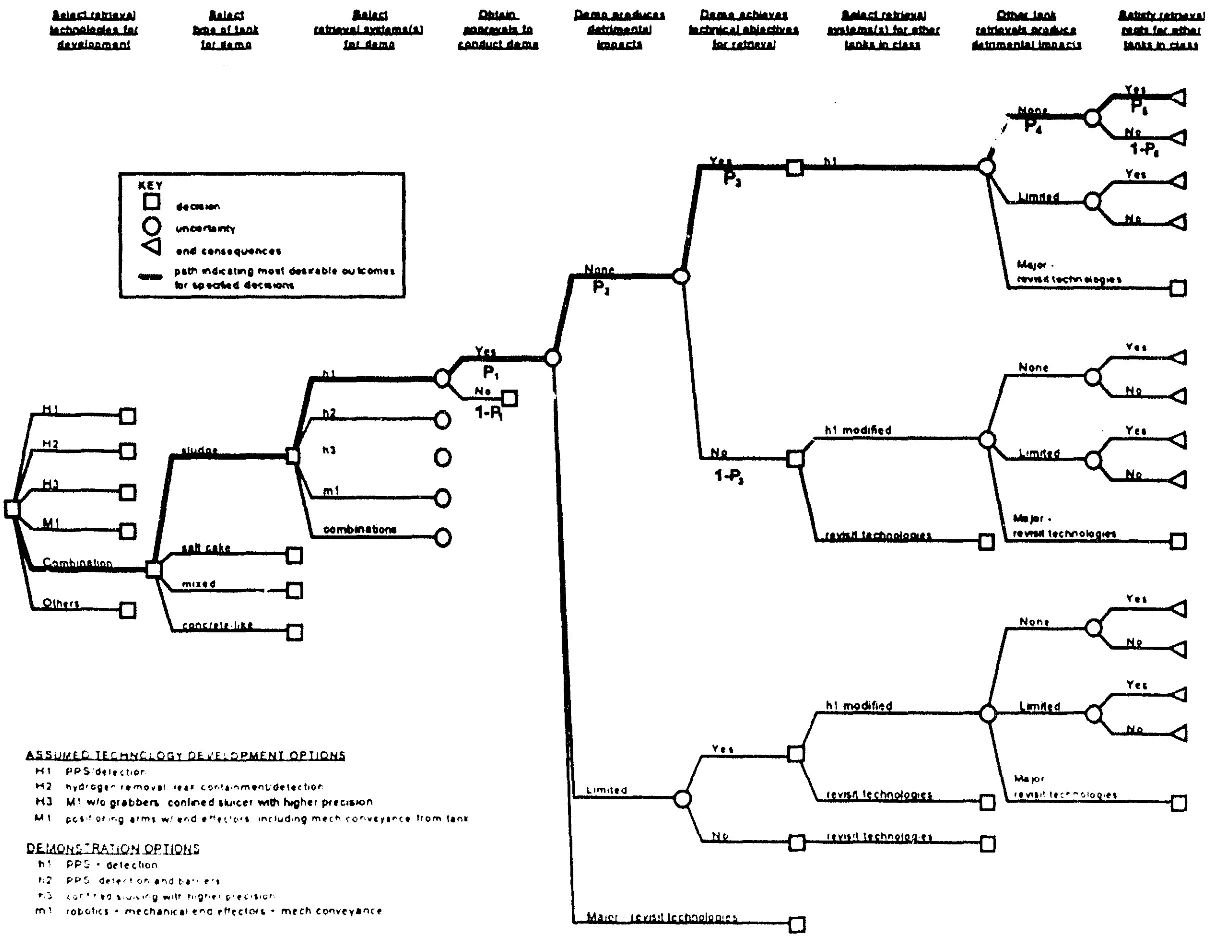

Figure 2. Typical Decision Tree Developed for the Analysis

involving high-precision positioning and multiple high-pressure, low-flow nozzles with a vacuum suction system to remove water and waste. In addition, one mechanical system is considered: (m1) a telescoping, articulated arm with end effectors and a bucket or grabber to move waste out of the tank on a batch conveyance system.

Note that the tree in Figure 2 is only partially drawn. It displays only those choices and uncertainties corresponding to a strategy wherein a combination of retrieval technologies are simultaneously developed and a sludge tank is selected for the initial technology demonstration. Similar decision trees were developed to represent other strategies. The notations P_1, P_2, etc., shown under branches emanating from uncertainty nodes, denote the probabilities that would be assigned to the outcomes represented by the branches conditional on the outcomes and decisions leading to those branches. The path through the tree shown in bold represents the case where every uncertainty results in a desirable outcome. The probability of this path, P_S, is the product of probabilities associated with each of the necessary desirable outcomes: $P_S = P_1 \cdot P_2 \cdot P_3 \cdot P_4 \cdot P_5$.

A decision tree, such as that shown in Figure 2, may be "solved" to identify an optimal alternative for the initial decision (which technologies to develop) and optimal alternatives for subsequent decisions contingent on the outcomes to intermediate uncertainties. The approach requires assigning (1) probabilities to each outcome for each uncertainty in the tree and (2) "utilities" (numbers representing relative desirability) to each end point of the tree. According to decision theory, the preferred alternative at each decision node is the one having the highest expected utility. Expected utilities for each node in the tree are calculated using a "rollback" procedure. Starting with the utilities assigned to the end points of the tree, the expected utility for an uncertainty node is obtained by multiplying the utilities associated with the branches times the corresponding probabilities and adding. The expected utility at each decision node is the highest utility associated with any alternative.

Decision analysis literature describes methods for estimating probabilities based on expert judgment[2] and methods for assigning utilities to reflect decision-maker preferences.[3] The formal process of eliciting probability numbers from experts is called "probability encoding." The process of assigning utilities involves developing a multiattribute utility function. Probability encoding and multiattribute utility analysis have been used previously to support DOE decisions.[4,5]

Note that probabilities and preferences for possible outcomes would be desirable inputs to the planning process regardless of whether a formal decision analysis approach is used. Decision makers need to know how confident experts are in the capabilities of various options. They also need to know what experts think about other relevant uncertainties, such as the likelihood of specific closure requirements. Probabilities provide an unambiguous language for conveying judgments regarding uncertainties. The statement "expert A believes the probability is 0.75" is much more useful for decision makers than "he thinks the technology will probably succeed." Similarly, assessing the desirability of possible outcomes is crucial to determining whether the risks associated with alternative strategies are acceptable. Expressing the necessary value judgments in the form of utilities documents those judgments and ensures that the same preference structure is applied consistently to all alternatives. The benefit of the decision tree is that it provides a defensible logic for using these key decision components to find an optimal decision strategy.

A complete decision-tree evaluation was not conducted as part of the IRG effort; however, the IRG did explore and test several potentially useful methods for generating the necessary inputs for a full evaluation. For example, to facilitate and improve the assessment of complex probabilities, influence diagrams[6] are often recommended. Figure 3 shows an influence diagram designed to support the estimation of P_3, the probability that the initial demonstration will achieve the technical objectives of retrieval. Such diagrams are constructed using a top-down approach. Tank characteristics, technology considerations, and other factors relevant to the uncertainty to be assessed are successively identified and their influence on other variables designated with connecting arrows. Rectangular nodes in the figure indicate those factors judged by the IRG to be the most critical—they are the factors judged to vary most depending on the selected retrieval technology and the factors to which the level of technical achievement is most sensitive.

Constructing an influence diagram before estimating probabilities serves several purposes. It helps ensure a systematic, balanced exploration of issues and encourages participants to articulate and share their views regarding cause-effect and other relationships. Once constructed, the diagram provides a "knowledge map" summarizing understanding and indicating chains of reasoning for supporting specific assessments. For example, the diagram in Figure 3 suggests that useful

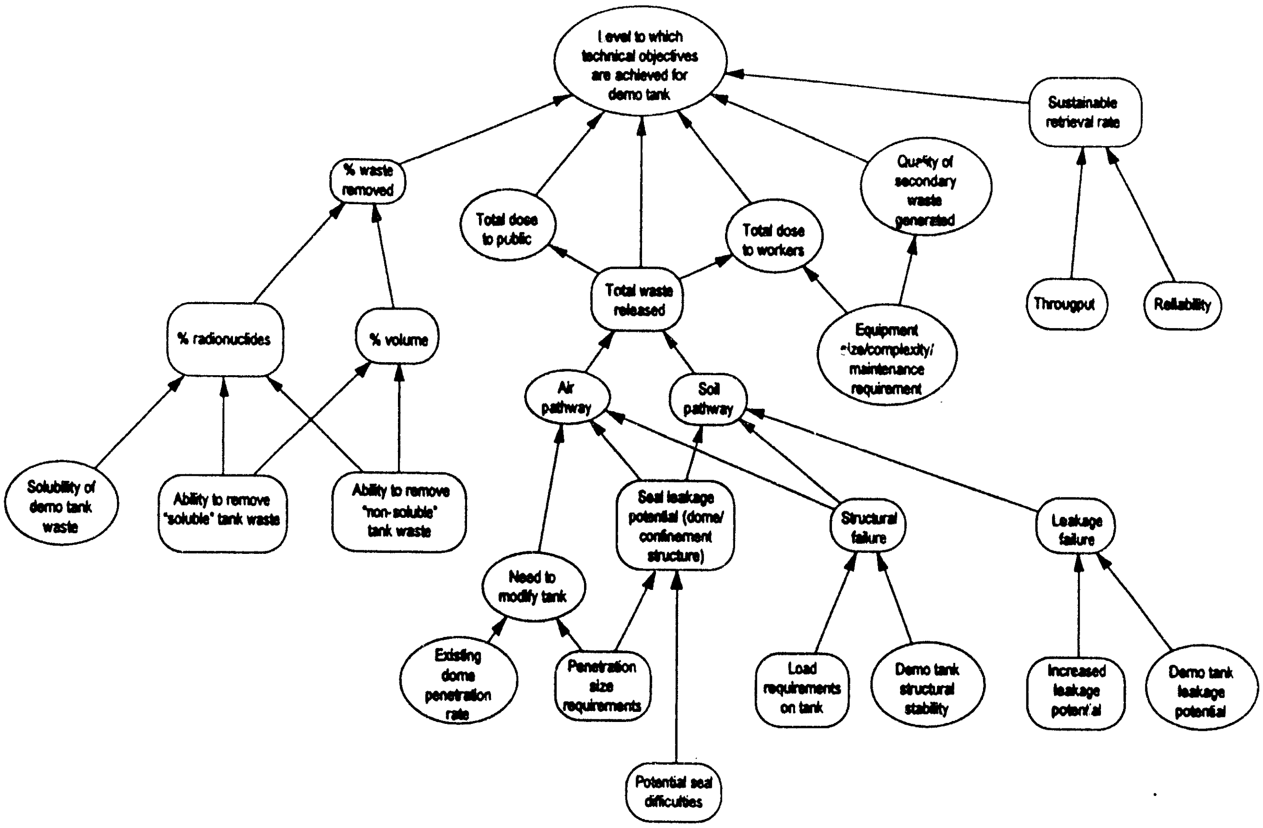

Figure 3. Influence Diagram for Probability P_3

Table 2. Technology Ranking and Assessed Probabilities of Technical Success in the Demonstration

		Group Average*			
		h1	h2	h3	m1
% Waste Removed	1) Ability to remove "soluble" waste	1.0	1.0	3.0	4.0
	2) Ability to remove "non-soluble" waste	3.0	3.0	2.0	1.0
Total Waste Released	3) Penetration size requirements	1.0	1.7	2.7	4.0
	4) Sealing difficulties	1.0	1.0	3.0	3.7
	5) Load requirements	1.0	2.3	2.7	3.7
	6) Increased leakage potential	3.7	2.7	2.3	1.0
Sustainable Retrieval Rate	7) Throughput	1.0	1.7	2.3	3.7
	8) Reliability	1.0	2.3	2.7	4.0
	Overall Rank	1	2	3	4
	Overall Probability (P_3) of Achieving Technical Success	0.97	0.94	0.91	0.86

* Entries denote IRG judged rankings of alternative systems with respect to relevant factors. Identical entries in a row indicate a tie. Non-integer ranks (e.g., 1.7) result from averaging judgments across participants

criteria for determining the achievement of demonstration objectives are (a) the percent of waste removed, (b) total waste inadvertently released, and (c) the sustainable retrieval rate. As illustrated, the critical factors for determining percent of waste removed are the ability of the technology to remove (1) soluble waste and (2) non-soluble waste. The critical factors for waste released are the technology's (3) penetration size requirements, (4) potential for sealing difficulties, (5) load requirements, and (6) potential for increasing tank leakage. Finally, the critical factors for retrieval rate are (7) throughput and (8) system reliability.

The IRG used the Figure 3 influence diagram and formal probability encoding methods to generate illustrative probability estimates for each of the basic retrieval systems. First, each IRG member ranked the systems with regard to each of the critical factors in the influence diagram. The resulting rankings, . averaged across individuals, were then used as a guide for the assignment of probabilities. Table 2 shows the average rankings and consensus probabilities. As indicated, each system was estimated to provide a high probability of technical success (assuming it produces no detrimental impacts). The differences between the estimates are relatively small; however, the highest probability (.97) was assessed for h1 (PPS with leak detection).

III. RESULTS AND CONCLUSIONS

The observations and conclusions derived by the IRG include:

1. There are many possible paths (sequences of decisions and outcomes as represented in a decision tree) toward solution of the SST problem. Initial choices (e.g., the decision to develop a specific retrieval system technology) affect later options, costs, and the likelihood of obtaining favorable outcomes to subsequent choices. The difficulty is in identifying a sequence of choices that will maximize the probability of successfully removing tank waste while minimizing the possibility of unacceptable detrimental outcomes.

2. Each step in the process must achieve a very high probability of success to obtain a high probability for overall success. For example, to obtain a 95% chance of overall success with the path highlighted in Figure 2, the probabilities of success for P_{1-5} must average at least .99, with no individual probability less than .95.

3. Following or applying parallel paths in technology development and even in technology demonstrations can significantly increase the overall chance that a class of tank (i.e., tanks containing similar waste) will be satisfactorily remediated with no major detrimental or limited outcomes.

In conclusion, the IRG recommended that a decision analysis of retrieval systems technologies be conducted. Among the benefits expected were that the approach would:

- ✓ increase the likelihood of retrieval success;
- ✓ increase program credibility;
- ✓ help focus debate through the use of sensitivity analyses that indicate the assumptions and uncertainties to which decisions are sensitive;
- ✓ direct information collection activities through the use of value-of-information analyses; and
- ✓ provide a valuable, well-documented basis for the ultimate retrieval decisions to be made.

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