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RISK-BASED SYSTEMS ANALYSIS FOR EMERGING TECHNOLOGIES: APPLICATIONS OF A TECHNOLOGY RISK ASSESSMENT MODEL TO PUBLIC DECISION MAKING

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ABSTRACT

The risk-based systems analysis model was designed to establish funding priorities among competing technologies for tank waste remediation. The model addresses a gap in the Department of Energy's (DOE's) "toolkit" for establishing funding priorities among emerging technologies by providing disciplined risk and cost assessments of candidate technologies within the context of a complete remediation system. The model is comprised of a risk and cost assessment and a decision interface. The former assesses the potential reductions in risk and cost offered by new technology relative to the baseline risk and cost of an entire system. The latter places this critical information in context of other values articulated by decision makers and stakeholders in the DOE system. The risk assessment portion of the model is demonstrated for two candidate technologies for tank waste retrieval (arm-based mechanical retrieval - the"long reach arm") and subsurface barriers (close-coupled chemical barriers). Relative changes from the base case in cost and risk are presented for these two technologies to illustrate how the model works. The model and associated software build on previous work performed for DOE's Office of Technology Development and the former Underground Storage Tank Integrated Demonstration, and complement a decision making tool presented at Waste Management 1994 for integrating technical judgements and non-technical (stakeholder) values when making technology funding decisions.

INTRODUCTION

Because of the extraordinary uncertainty inherent in research and development (R&D) activities, decision-makers must choose among still undeveloped or partially developed products for roles in large and complex technical systems, such as for high-level waste tank remediations for the U.S. Department of Energy (DOE). They must attempt to make funding decisions about appropriate technologies within tight timeframes. Decision-makers who have fiscal responsibility for program budgets have difficulty in determining whether the technology provides sufficient benefit to the overall system to warrant its development. Unfortunately, the tools to accomplish these tasks have proven cumbersome. Current systems engineering or environmental impact statement analyses that address entire systems are larger and more costly than is practical for the multiple, highly detailed decisions required to guide a technology development program. Also, these more complex models are not typically amenable to online sensitivity analyses, which are required when there are expert disagreements in predictions of a new technology's performance under varying conditions. In addition, a number of good activities are underway to improve stakeholder involvement in the decision-making process for choosing technologies, which adds the dimension of increased inputs into the process.

Because of this complexity and uncertainty, the current decision-making processes often suffer from a lack of disciplined assessment of the factors, particularly of the potentials for risk and for cost-reduction, which are usually considered by all parties to be critical. The current processes can lead to biased judgements because the technologies are rarely evaluated in a systems context.

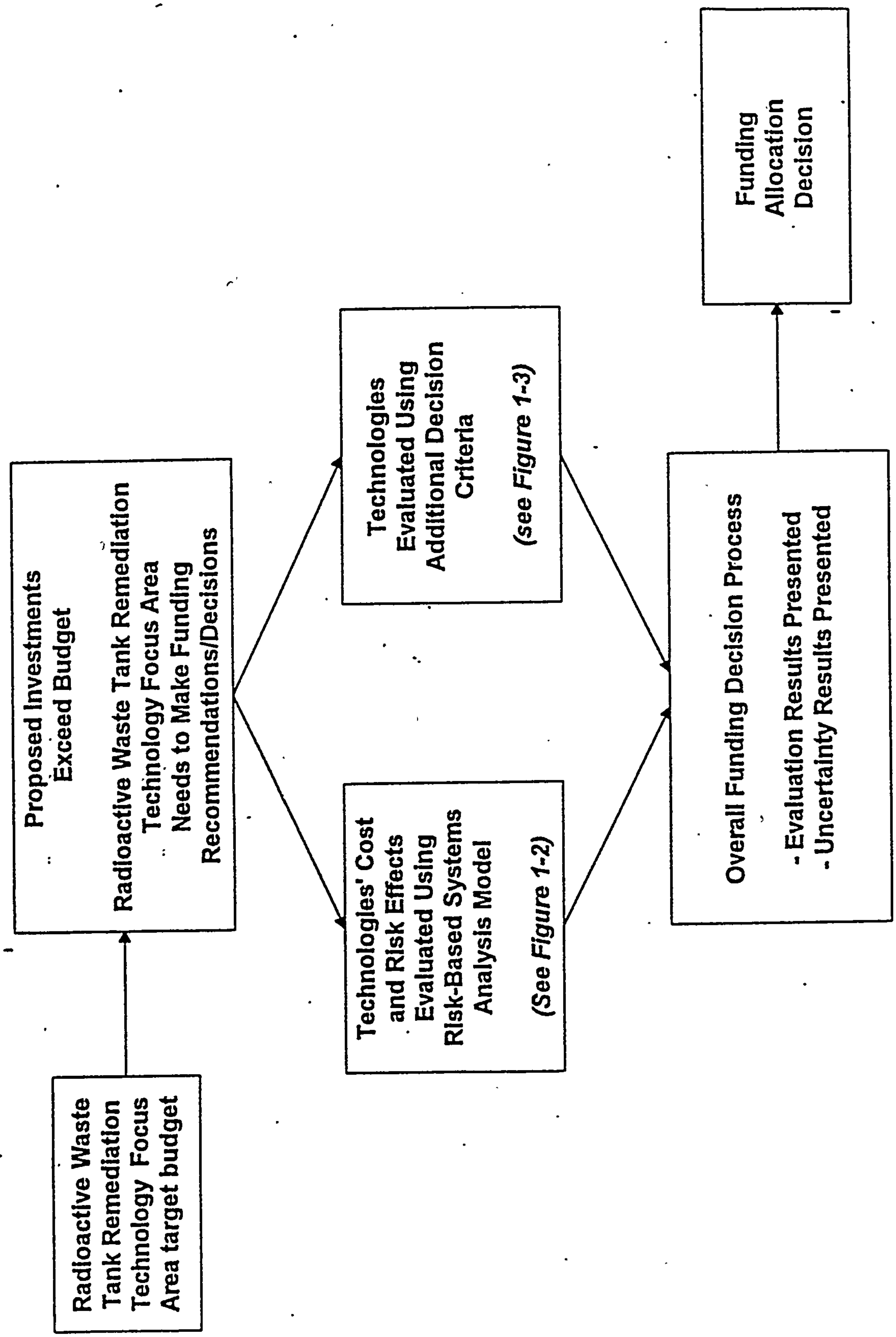
The Risk-based Systems Analysis Model, a computer-based model for assessing emerging technologies, addresses these gaps in the decision-making tools available for selecting what technologies to fund when those technologies must function as part of a large and complex system. It provides a simplified systems perspective that is more practical for technology decisions than are the more complicated systems engineering models. It combats biases in judgment by summarizing system-level information that is difficult for experts to consider when assessing individual technologies. It accommodates differences of opinion in assumptions or predicted performance through sensitivity analysis. Finally, the interface is easy to display and understand, which makes this model useable on-line in forums involving multiple decision makers, including public stakeholders and regulators who want to see (or have the opportunity to assess and differentially weight) how a technology performs on a broad range of variables.

RISK-BASED SYSTEMS ANALYSIS MODEL DESCRIPTION

The model uses a structured systems methodology for estimating the risks and the costs of new technologies for remediating DOE underground storage tanks (UST) relative to a base case. Figure 1 describes the envisioned decision making process underlying the model. The base case establishes a flowsheet and material balance for all stages of a baseline UST remediation (the Hanford technical strategy is currently modeled). The model incorporates new technologies (test cases) into this complete remediation system to allow a disciplined assessment of changes in the risk and cost of specific functions as well as overall system risk and cost. The values for each module are summed to provide total system values. Potential risks to workers and to the public associated with both routine and failure conditions are currently represented. These data are combined with additional decision variables (e.g., program schedule) and stakeholder values (e.g., economic impacts, final land use) to ensure that risk factors are placed in a broader decision context. Where data are not available, risk and cost analysis are performed for each module using available data, expert judgment, and simplifying assumptions.

Figure 1 [Fig 1-1,Technology Funding Decision Making Process]

Figure 1-1. Technology Funding Decision-Making Process.



The assessment methods selected had to be:

- comprehensive and "cradle to grave" in scope,
- easy for decision makers to understand,
- easy to apply early in the technology evaluation process (when limited information is available), and
- amenable to changes in assumptions or estimates to facilitate discussion among users.

System Characterization

System characterization requires that all of the major processes and process streams be identified and that an overall material balance be established. First, the major processes are labeled as unit operations. Each unit operation is described in terms of the information categories listed in Table 1.

It is particularly important that all process streams that discharge to the environment (air or water) be characterized, as these are the primary contributors to the public risk values. This information is used to estimate routine worker radiation exposure and potential for and severity of accidents associated with each unit operation, under both routine and nonroutine conditions.

Table 1. Unit Operation Descriptions.

REQUIRED INFORMATION CATEGORIES
General Description
Number of Individual Components (tanks, pumps, filters etc.)
Size/Capacity of Each Component (m, m^2, m^3)
Unit Operation Lifetime (years)
Operating Efficiency (%)
Radiation Level (High, Low, Cold)
Total Direct Labor Man-hours (hours)
Temperature (°C)
Pressure (psi)
pH/Acidity/Alkalinity
Energetic Reaction Potential (seven categories from Very Low to Very High)
Process Stability (High, Medium, Low)
Waste Form (solid, liquid, gas)
Solids in Waste (%)
Organics in Waste (%)
Flammability (seven categories from Very Low to Very High)
Number of (HL[a], LL[b], & Cold) Mechanized Parts per Unit
Number of (HL[a], LL[b], & Cold) Isolated Process Steps per Unit
Number of Installation Activities (e.g. install 20 mixer pumps)
Number of Items Requiring Decontamination
Number of Items Requiring Decommissioning and Disposal

[a] HL - high-level, assumed to require remote handling
[b] LL - low-level, assumed to allow contact handling

The unit operations are grouped into functional groups labeled as modules. The model's baseline risk assessment consists of 13 modules that encompass the complete set of tank remediation functions, including waste retrieval, treatment, disposal, and tank and facility decontamination and decommissioning. Each module is a group of similar or related process steps linked to a specific technology, and is comprised of one or more unit operations or major components. The modular format allows users to add or replace modules to define the test cases and provides a practical breakdown of overall system risk and cost. Figure 3 shows the process flow defined by the modules for the base case. The model's modular format provides a mechanism by which new modules can be added or modules can be modified to form test cases. This facilitates the incorporation and comparison of the impacts of new technologies with the baseline.

Figure 2
[Fig 3-2, Base Case Top-Level Flow Diagram]

Following organization of the modules into an overall flow diagram, stream flows between modules are identified and labeled. Then, a material balance is completed for all critical streams entering and leaving each module in terms of the total liquid mass, total solids mass, total water mass, and mass of contaminants of concern.

Risk Evaluations

The objective of the model's risk calculation is to provide a consistent basis for qualitatively evaluating the potential influence that alternative technical modules may have on overall health risks associated with the remediation system. The specific steps involved in the risk assessment portion of the model are shown in Figure 2. The risk assessment spans both operational and post-operational phases of remediation and addresses all potentially significant sources of contamination and all potential contaminant receptors. Potential risks associated with both routine and failure conditions affecting both

Figure 3 [Fig 1-2, System Risk Analysis Model Process]

workers and the public are addressed.[1] Calculational methods were selected that are consistent with the fact that they will be applied early in the technology evaluation process, when limited or only qualitative information will be available regarding technology characteristics. The specific methods selected for demonstrating the model were chosen for their ease of application and familiarity; they may (and, in some cases, should) be further reviewed and modified. See Peters et al. (1994) for the detailed calculations.

Health risks are calculated for six variables:

- for workers and for the general public,
- for routine and failure events, and
- for two timeframes:
  - near-term exposures associated with the active installation and operational phases, and
  - future public exposures associated with residual contamination and disposed wastes following completion of the active operations.

In the case of workers, health related impact is evaluated in terms of radiation dose to individual

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[1] The risk calculations do not currently address the risks of physical injuries that can occur during construction or other industrial activities associated with the installation or operation of the technology. Because these risks can be significant, they will be addressed in future revisions of the model.

Figure 3-2. Base Case Top-Level Flow Diagram.

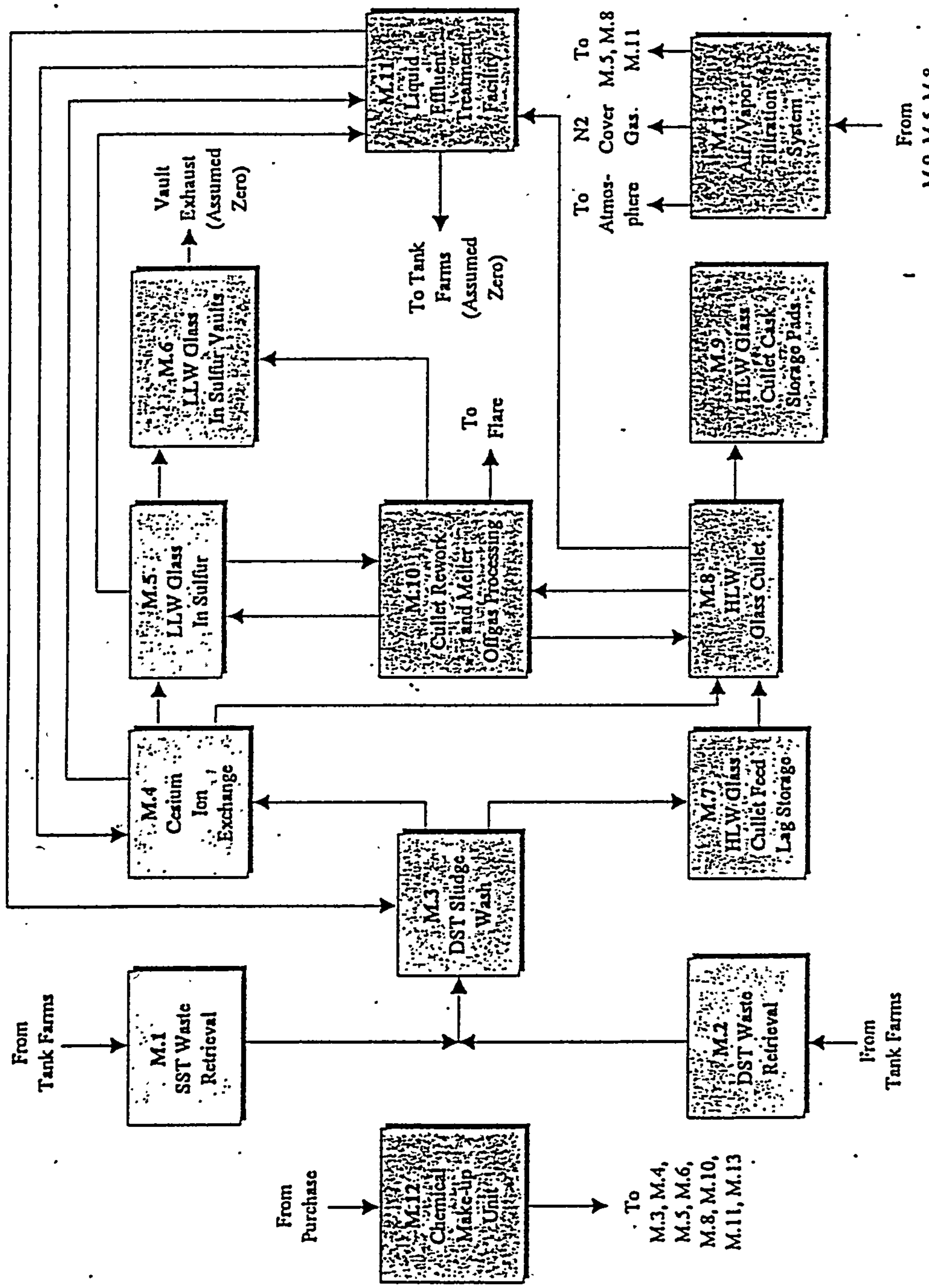
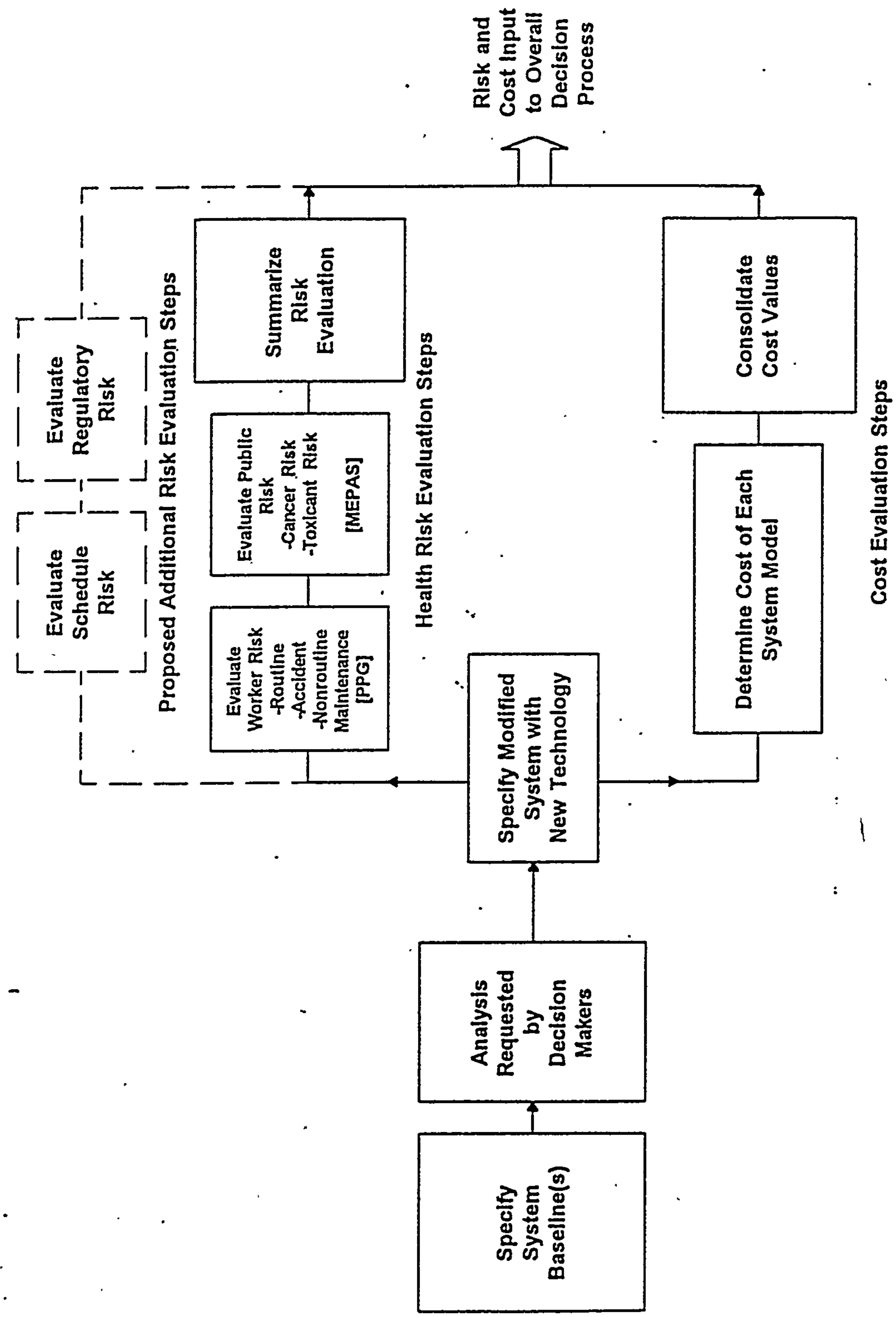


Figure 1-2. System Analysis Model Risk and Cost Evaluations.



members of the work force. In the case of the public, health related impact is addressed in the context of a maximally exposed individual's (MEI) (1) incremental increase in risk (probability) of death from cancer and (2) hazard index (HI), which is the ratio of calculated toxic material exposure to the toxic material reference doses. Routine risks to the public are currently estimated using the Multimedia Environmental Pollution Assessment System (MEPAS) computer code (Droppo et al., 1989).
For identifying and evaluating potential failure events, there are standard safety analyses, but they require a minimum level of facility and process information that is not available for these technology evaluations. Thus, a subjective approach was selected that relies on expert judgement: Risks to workers and failure risks are determined using a Priority Planning Grid (PPG), developed under DOE funding and commonly used at the Hanford Site. This process uses qualitative frequency consequence values (unitless) that have been derived from selected elements of the relative ranking system implemented in the PPG. The PPG has established eight levels of consequence (ranks), within which nine impact attributes are compared. The attributes of interest for the model risk evaluation are public safety, worker safety, environmental contamination, and cost.

Results generated by the risk calculations, while given as discrete numerical quantities, should not be viewed as estimates of actual or potential human health risk associated with the tank waste remediation technologies. The calculation results are intended to support consistent *comparative* evaluations of the influence that alternative technologies may have on overall system risk, and should be viewed as qualitative estimates only.

Cost Calculations

Cost information is required to provide a basis for direct comparisons of alternatives in terms of overall cost and cost-benefit. The model measures benefit in terms of risk reduction. Given the high uncertainties in risk and cost data available for emerging technologies, costs were appropriately estimated using relatively simple cost estimating software and best engineering judgement. All costs are converted into Total Net Present Worth (TNPW) and 1994 dollars. The complete waste retrieval, treatment, and decontamination and decommissioning (D&D) process is assumed to take 13 years (10 years processing and 3 years D&D). A 10% discount rate was assumed for conversion of costs to TNPW.

The following costs are calculated:

- capital (facility design, purchase and construction, and equipment purchase and installation),
- chemical (bulk chemicals added to the system),
- labor (exempt,nonexempt,and bargaining unit personnel),
- utilities (steam and electricity),
- CENRTC and GPP (capital equipment not related to construction and general plant process),
- R&D,
- disposal (for low-level and high-level waste only), and
- D&D (decontamination and decommissioning of all tanks and facilities when remediation is complete).

System Analysis Model Software

The System Analysis Model Software is a linked system of Microsoft Excel 4.0 spreadsheets that provide the user with a computerized directory of the flow processes being evaluated by the model. By using the mouse to click on a series of buttons or menu items, the user can call up a particular case (i.e., the Base Case, Test Case I, or Test Case II), display a complete flow diagram of any module within the given case, and then find out more information about the module and any unit operations within the module. Available information also includes the set of assumptions used to characterize the module, the details of the mass balance at that point in the model, and the results of the risk analysis and the cost analysis. This layered information system, which displays only as much information as required by the user, will allow the user to easily compare modules, unit operations, and risk/cost analyses results for different system configurations. It also provides access to any of the critical assumptions or parameters, making the process transparent. This serves both educational and negotiation purposes: non-experts can view the critical parameters throughout the model and experts can test alternative assumptions or judgements of performance.

EXAMPLE RISK ASSESSMENT RESULTS

The model has been demonstrated using the Hanford Tank Waste Remediation System as a base case, with two retrieval technologies for test cases: an arm-based retrieval system and close-coupled chemical sub-surface barriers. Complete descriptions of these test technologies are provided in Peters et al. (1994).

Table 2 shows the relative contributions of each module to the base case system risks and costs. Comparisons of the base case to each of the test cases is presented in relative terms in Table 3.

Table 2
[Table 2, Volume 1: Module Contributions to Base Case Risks and Costs]

Table 3. Relative Test Case Changes to System Risk and Cost from the Base Case.

		Test Case I (Barriers)	Test Case II (Robotic)
Risk Element	Operational Phase Public Cancer Risk	—	—
	Disposal Phase Public Cancer Risk	-41%	-52%
	Operational Phase Public Toxicant Hazard Index	—	—
	Disposal Phase Public Toxicant Hazard Index	-47%	-61%
	Collective Worker Routine Radiation Dose	+2%	+27%
	Accident Risk	<1%	<1%
	Nonroutine Maintenance Risk	<1%	+2%
Cost Element	Total Net Present Worth	+24%	+19%

Table 3 shows, for example, that Test Case I (a close-coupled barrier) promises to reduce by 41% the chance that the MEI will get cancer, reduce by 47% the chance that the MEI will be harmed by toxicants, increase by <1% the accident risk, and increase by 2% the collective routine worker radiation dose. These reductions are achieved at a 24% increase in cost, or an addition of $3,300,000,000. In contrast, at slightly less cost increase (19%, or $2,500,000,000), Test Case II (robotic sluicing) may provide relatively greater risk reductions to the public. We cannot confidently conclude from the level of analysis in the model that a test case will reduce the incidence of cancer by a specific amount, only that it will do so to a greater or lesser extent than will the baseline.

Table 2. Module Contributions to Risk and Cost - Base Case.

Risk and Cost Elements	Modules	M.1 SST Waste Retrieval	M.2 DST Waste Retrieval	M.3 DST Sludge Wash	M.4 Cesium Ion Exchange	M.5 LLW Glass in Sulfur	M.6 LLW Glass in Sulfur Vaults	M.7 HLW Lag Storage	M.8 HLW Glass Cullet	M.9 HLW Glass Storage Pad	M.10 Rework and Offgas	M.11 Liquid Effluent Treatment	M.12 Chemical Make-up Unit	M.13 Air/Vapor Filtration System	Total Contribution by Element
Risk Element	Operational Phase Public Cancer Risk	—	—	—	—	—	—	—	—	—	—	—	—	100%	100%
	Disposal Phase Public Cancer Risk	79%	21%	—	—	—	—	—	—	—	—	—	—	—	100%
	Operational Phase Public Toxicant Hazard Index	—	—	—	—	—	—	—	—	—	—	—	—	100%	100%
	Disposal Phase Public Toxicant Hazard Index	91%	9%	—	—	—	—	—	—	—	—	—	—	—	100%
	Collective Routine Worker Radiation Dose	18%	4%	9%	10%	9%	7%	6%	11%	10%	6%	6%	—	3%	100%
	Accident Risk	29%	3%	< 1%	3%	29%	<1%	3%	29%	<1%	<1%	<1%	1%	<1%	100%
	Nonroutine Maintenance Risk	4%	4%	< 1%	1%	28%	9%	2%	38%	<1%	10%	<1%	2%	1%	100%
Cost Element	Total Net Present Worth	11%	4%	3%	5%	12%	4%	<1%	28%	25%	5%	<1%	<1%	2%	100%

— Non Contributor

DECISION INTERFACE

The ultimate value of this model is to provide decision makers with a tool for identifying development efforts which, if successful, would provide significant overall benefit with the lowest possible cost. Worker and public risk are two critical components of overall benefit, but they are not the only relevant factors. McCabe et al., have argued that decision makers and stakeholders wish to consider environmental impacts, schedule, socio-political issues (e.g., positive economic impact), other aspects of technical performance (e.g., ease of implementation), and regulatory compliance when assessing new technology (McCabe, et al., 1992). Stakeholders at the Hanford site, which has the biggest UST remediation problem, have identified a core set of 14 values that they want to guide remediation decisions. Other stakeholder involvement exercises have uncovered additional values that may be discriminators for technology development decisions. (Armacost, et al., 1994).

Thus, risk and cost are two of several critical decision criteria. However, they are the most technically complex, a big stakeholder concern, and arguably the hardest to judge. Nevertheless, risk and cost reduction are considered by all parties to be critical criteria for sound technical funding decisions. Most decision-makers will consider risk, cost, and some additional criteria. Figure 4 illustrates one such set of variables.

The current decision-making processes often suffer from a lack of disciplined assessment of these critical factors because their inherent complexity and uncertainty can lead to biased judgements and because the evaluation of the technologies is rarely placed in a systems context. The model would allow and encourage disciplined assessments by emphasizing the following decision process activities:

- criteria elicitation,
- criteria evaluation,
- application of alternate weighting schemes to reflect different value sets,
- dialogue/feedback opportunities between users of the technology, technical experts, regulators, and other stakeholders, and
- broadly reviewed recommendations on funding priorities to DOE.

Although the model provides a rigorous method for assessing risk and cost, it can also be expanded to apply a similar degree of rigor to environmental impacts, schedule, and regulatory compliance. Judgments of other criteria deemed important by decision makers can be elicited from experts, stakeholders or published reports.

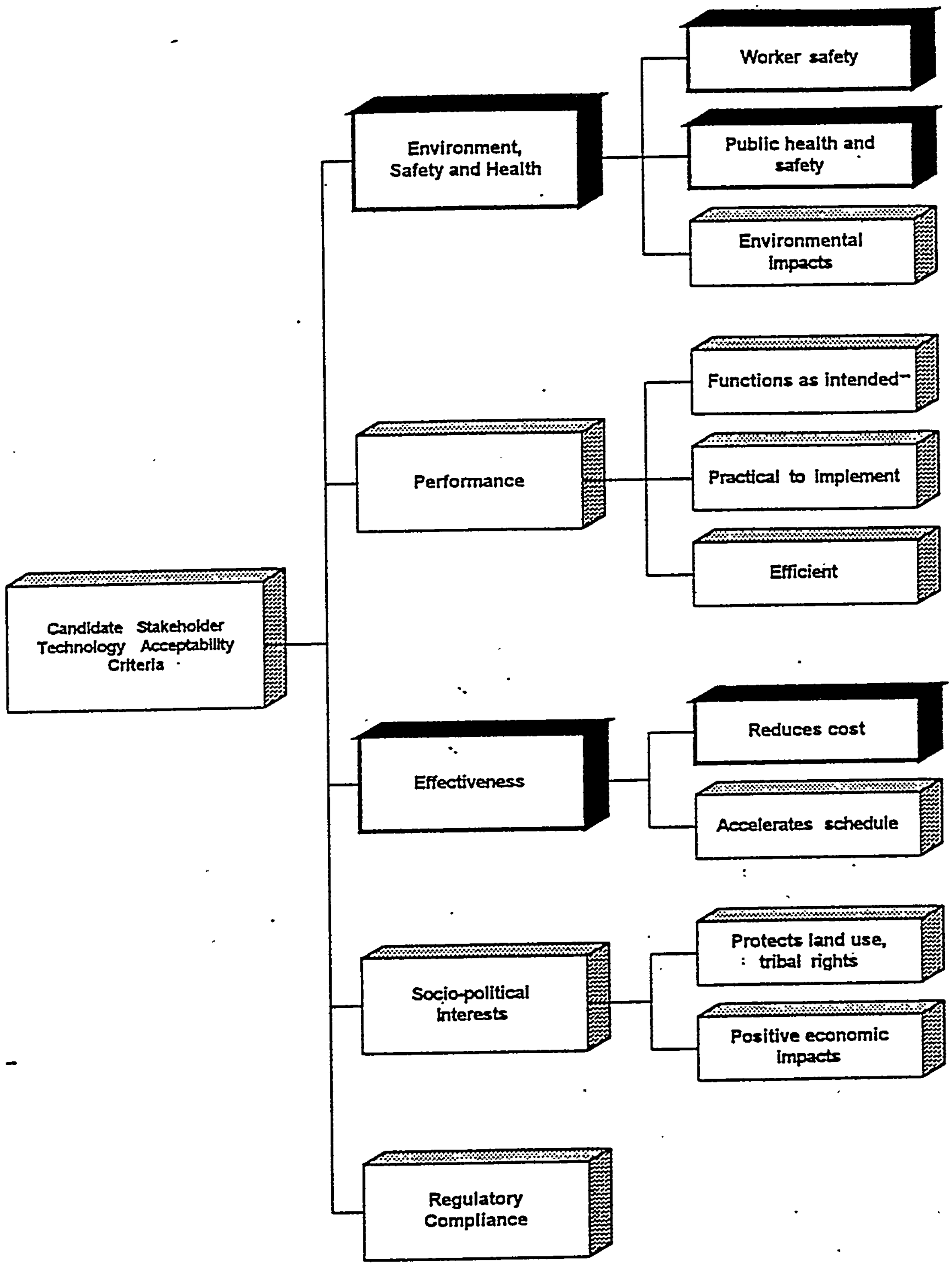
Figure 4 Decision Interface for Prioritizing Technology
[Fig 3: Additional Stakeholder Values]

SUMMARY AND CONCLUSIONS

The Risk-Based System Analysis Model provides a framework for evaluating the risk and cost of new technologies relative to a baseline remediation plan. The general approach incorporates new technologies into complete remediation systems to allow a disciplined assessment of overall system risk and cost. Risk and cost data can then be combined with additional decision variables, and evaluated from multiple perspectives (stakeholders, technologists, etc.) to produce a disciplined assessment of emerging technologies.

Application of this model will ensure that funding priorities reflect the risk/cost tradeoffs, stakeholders can understand the basis for risk/cost assessments, the final recommendation will consider

Figure 1-3. Additional Stakeholder Values.



risk and cost in the context of additional stakeholder/user concerns, and the decision process itself will enhance the dialogue and understanding of the different parties (technical experts, stakeholders, users, etc.). In that way, it should be a practical tool for building consensus among users, technologists, stakeholders, and final decision-makers.

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