Idaho National Engineering and Environmental Laboratory

INEEL/EXT-98-00780

August 1998

An Evaluation of the Cost/Benefits of Concrete Biodecontamination

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Prepared for the
U.S. Department of Energy
Office of Health and Environmental Research
Under DOE Idaho Operations Office
Contract DE-AC07-94ID13223

ABSTRACT

Two candidate technologies for decontamination of extensive areas of radioactively contaminated concrete, a biological technology and electro-hydraulic scabbling, that had been rated as "highly useful" in an earlier study were assessed more precisely. These technologies were compared to a base technology, scarification. The evaluation method was an adaptation of the Multi-Attribute Utility Technique (MAUT), a formal quantitative approach for analyzing decisions with regard to multiple objectives. The advantages of the biodecontamination technology were confirmed by this more precise quantitative analysis.

FOREWORD

This report was prepared by Fredrick F. Gorschboth, BDM International, Inc., at the request of the Biodecontamination Project Manager, Melinda A. Hamilton, Biotechnologies Department, Idaho National Engineering and Environmental Laboratory. The work was supported by the U.S. Department of Energy, Office of Health and Environmental Research (OHER), Subsurface Science Program. This support included access to research information on environmental microbiology, mixed contaminants, and information transfer methods. The purpose of this work was to develop a technique that provides a means of evaluating technologies, prioritizing programs, assessing comparative risks in decision making, and bridging the gap between technology development and basic research. This technique can be applied to environmental management problems. The author and project manager wish to acknowledge Dr. Frank Wobber, DOE, OHER, for his pioneering vision that lead to the development of this technique and for his support.

An Evaluation of the Cost/Benefits of Concrete Biodecontamination

BDM International, Inc.

Frederick F. Gorschboth

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EXECUTIVE SUMMARY

This study was undertaken to evaluate an innovative technology, biodecontamination, developed as part of the research program of the Idaho National Engineering Laboratory -- focusing on the possible benefits from its application to the problem of radioactive contamination of the concrete in the Department's facilities. In the course of the evaluation, a number of innovative technologies were screened to provide context for the assessment of the biological technology, a system of benefit determination was adopted, and a calculation of the cost/benefits of the candidate technologies performed.

The Candidate Technologies

In view of the widespread need for an effective technique for the decontamination of the extensive areas of radioactively contaminated concrete in the DOE complex, the Department evaluated various innovative decontamination technologies. A detailed assessment of thirty-one such technologies conducted by the Oak Ridge National Laboratory concluded that eight were of sufficient promise that they were preliminarily recommended for demonstration. Of these, the projected demonstration of four was determined to be "highly useful". One technology so judged was that of biological decontamination -- that on its face appeared to enjoy advantages in cost, worker health and safety risk reduction, and programmatic effectiveness. A review of the four candidate technologies indicated that sufficient cost data for comparison was lacking in one technology, and the applicability of another was too limited to warrant further investigation.

Consequently, a more precise assessment of the biological decontamination technology was undertaken, along with that of the remaining candidate, electro-hydraulic scabbling. Both of these technologies were then compared to a base technology (scarification) to project potential benefits from their adoption. This approach not only provided a quantifiable comparison between the two competing technologies, but at the same time, compared both with a current commercial baseline technology.

Evaluation Methodology

The technique employed for the evaluation was an adaptation of the Multi-Attribute Utility Technique (MAUT) -- a formal quantitative approach for analyzing decisions with regard to multiple objectives. The Program's objectives upon which this evaluation focused were effectiveness in achieving mission goals, reduction in risk for worker health and safety, and cost reduction. This technique provided a rigorous procedure for combining the technical assessments of scientists with the policy judgments of line managers into a prescribed set of decisions.

In utilizing this technique, the benefits of the candidate technologies, as compared with the baseline technology, were determined and quantified as dollar amounts (whether the benefits were originally monetary or non-monetary). Projected comparative costs of the candidate technologies were also calculated and compared with those of the baseline technology.

Findings

As a result of this evaluation, it was concluded that the qualitatively projected advantages of the biodecontamination technology were confirmed by the more precise quantitative analysis. Specifically, the total benefits projected to accrue from the adoption of biodecon technology were determined from an analysis of a given test scenario of decontaminating ORR's K-25. In this analysis, the aggregate projected benefits, both monetary and non-monetary, of adopting the biological and other candidate technologies -- compared with employing the baseline technology of scarification -- were calculated to be:

For the biological technology = $145.0 M

For the electro-hydraulic technology = (-)$7.46 M

It was recognized that the comparison was limited by the small number of candidate technologies vigorously screened, and by the fact that the assessment was a function of the assumptions and boundary conditions imposed upon the analysis. Nevertheless, the Study, in addition to subjecting the biodecontamination technology to a rigorous quantitative assessment in comparison to a current candidate technology, demonstrated a technique suitable for quantitatively comparing technologies with regard to both monetary and non-monetary benefits that could possibly accrue upon their adoption. This technique, the development of which was pioneered by Dr. Wobber in the course of his implementation of OHER's Subsurface Science Program, gives promise of providing a means not only for evaluating the costs/benefits of competitive technologies, but for prioritizing programs, and assessing comparative risks in decision-making -- by combining technical evaluations of scientists with the policy judgments of line managers into a prescribed set of competing objectives, and significant uncertainties. More significantly, the Study presented an example of successful technology transfer -- illustrating a bridge developed between a technology, biological decontamination as developed by basic research, and its application to a widespread contemporary program need, concrete decontamination.

BACKGROUND

Because of the changing national requirements resulting from the end of the cold war, and the concomitant decision to reduce the size of the U.S. nuclear weapons complex, the U.S. Department of Energy (DOE) began to implement a plan to deactivate, decontaminate, and decommission (D&D) a large number of aging, surplus facilities.

A major problem in the D&D effort is the decontamination of concrete since it constitutes a major construction component of the facilities undergoing D&D and has been extensively contaminated by a variety of hazardous chemicals, heavy metals, and radionuclides. As a result, facility closure/transition is often not possible until the concrete is either decontaminated or disposed of; and consequently, a major effort has been undertaken by DoD to address the concrete contamination of the facilities undergoing D&D. However in the past, to a large extent, only small-scale technologies were available for decontamination use, and for their limited requirements -- they proved adequate, and in fact, may still be appropriate for some tasks. On the other hand, exclusive reliance on these technologies could result in program deficiencies such as high costs and large waste volumes in the expanding D&D program.[1]

The extent of the future expansion of the Program can be anticipated by noting that the total area of contaminated concrete within the DOE complex is estimated to be in the range of 7.9×10^8 ft^2 or approximately 18,000 acres. The volume of contaminated concrete is estimated to be 6.7×10^6 ft^3. These estimates are based upon data from Hanford Facility (HANF), Fernald Environmental Management Project (FEMP), and Oak Ridge Reservation (ORR). The estimates are assumed to be low because they do not include complete information from Idaho National Engineering Laboratory (INEL), Savannah River Site (SRS), Portsmouth Gaseous Diffusion Plant (PORTS), Paducah Gaseous Diffusion Plant (PGDP) and Rocky Flats Environmental Technology Site (RFETS), all of which are expected to have similar amounts of contaminated concrete.

Consequently, the Program has a major requirement to develop a concrete decontamination process(es) to facilitate the closure/transition of buildings/facilities and to eliminate or decrease radiological worker exposure and environmental impact, and to minimize costs by limiting the volume of waste.

If concrete decontamination does not prove to be feasible, the primary final disposition would be to reduce the concrete to rubble for disposal as a radioactive waste.

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[1] U.S. DOE. 1993. *Laboratory Integration and Prioritization System.* ESH/PO, 1-1 Prioritization Office, U.S. Department of Energy, Washington, D.C.

INTRODUCTION

Many commercial technologies for concrete decontamination have been developed and applied. Traditional concrete decontamination methods include shot blasting, mechanical scabbling, detergent scrubbing, high pressure washing, chemical treatments, strippable coatings, clamshell scrapers, brushing, vacuuming and attacking cracks with jack hammers. However, the use of explosives, jackhammers, etc. has been a problem because of high worker exposure to contamination suspended in the dust. [2]

It is evident from past experience that the primary decontamination methods used to date have been pressure-washing techniques and various types of scabbling.[3] A small number of innovative technologies that give promise of greater effectiveness/cost savings relative to technologies currently available for addressing the concrete decontamination problem throughout the D&D life cycle have been developed -- and are proposed for demonstration.

This Study examines one of the most promising -- biodecontamination -- and arrays it against both baseline technology and other developing technologies that are candidates for demonstration, and ultimately, for adoption by DOE for large-scale concrete decontamination.

STUDY APPROACH

The specific objective of the Study is to evaluate the Benefits/Costs of the adoption of the biodecontamination technology in DOE's D&D Program vis-a-vis the Baseline Technology and other technologies that are considered viable candidates for demonstration. The Study is part of an ongoing effort by the DOE Office of Health and Environmental Research (OHER) Subsurface Science Program (SSP) to develop a means for evaluating innovative developments in basic research and prioritizing their transfer to meet current site requirements. The Environmental Science Research Center at PNNL, which has responsibility for facilitating technology transfer, greatly assisted in ensuring the success of the current effort.

As a boundary condition of the Study, the concrete contamination of ORO's K-25 facility was selected for theoretically determining the projected Benefits/Costs of the biodecontamination technology as opposed to the baseline technologies and other selected technologies considered as candidates for demonstration. K-25 contains 20 million ft^2 of concrete surfaces of various types -- all potentially contaminated -- and therefore, provided an ideal test bed for the evaluation.

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[2] *Ibid.*, 2-9.

[3] *Ibid.*, 2-13

In fact, ORR reports that technologies are needed to provide: [4]

1. More efficient concrete surface layer removal
2. Reduction of secondary waste from decontamination processes
3. Innovative systems for floor and wall decontamination
4. Decontamination of metals (Ni, Al, Pb and Hg)
5. Reduction of rubble waste

The current status of the ORR D&D Program (characterization, planning and some D&D) provides an opportunity for demonstration, and perhaps future application, of biological technology in the decontamination effort.

To carry out the evaluation of the biodecontamination technology, six facets of the examination were addressed:

1. Characterization of the biodecontamination technology
2. Identification and assessment of available candidate technologies for concrete decontamination
3. Formulation of a methodology for evaluating candidate technologies
4. Determination of relative benefits of biodecontamination and other selected technologies
5. Determination of projected costs of biodecontamination and other selected technologies
6. Determination of relative Benefits/Costs of biodecontamination and other selected technologies.

1. Characterization of the Biodecontamination Technology[5]

Biodecontamination is an innovative process that is currently being developed under a CRADA arrangement by the INEEL Biotechnology Group and British Nuclear Fuels to meet DOE needs (and as indicated above, to possibly meet the particular needs of ORO). Because the depth of removal of a contaminated surface can be controlled in the application of this technology, production of secondary waste, i.e. contaminated concrete, is greatly reduced and the occurrence of airborne contamination is eliminated. Estimated costs for the process range from 0.3 to 5.0% of those for different scabbling methods. As methods for application are developed, it is thought that the process will be usable for decontamination of incumbered (fitting, conduit, piping, etc.) floors and walls. Also, because of its "hands-off" operation, worker exposure to radiation and industrial accidents is expected to be greatly reduced.

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[4] U.S. DOE. 1995. *Contaminated Concrete: Occurrence and Emerging Technologies for DOE Decontamination.* DOE/ORO/2034, A-93. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

[5] L.O. Nelson. *Emerging Technologyfor Decontamination of Concrete Biodecontamination: An Innovative Process.* Private Memorandum, 1996. Idaho National Engineering Laboratory, Idaho Falls, Idaho.

Technological Basis for Process

The heart of the biodecontamination process is the naturally occurring microbial-influenced degradation (MID) of concrete. Three types of bacteria are known to promote MID of concrete. Of these, the sulfur oxidizing bacteria *Thiobacillus Thioxidans* was selected for use in the biodecontamination process. These naturally occurring, nonpathogenic, ubiquitous bacteria oxidize sulfur to sulfuric acid. They "stick" to the concrete surface by use of a naturally produced adhesive. Once on the surface, the bacteria continuously produce sulfuric acid at "microsite" locations. While the mechanism for decontamination is an acid-promoted deterioration of the concrete surface, the action of the bioprocess is not the same as that of using an industrial application of sulfuric acid. That process would require several applications of 30 L of a 10% solution of sulfuric acid to remove a 4 mm depth from a 1 m^2 area of concrete. Such a procedure would create a hazardous mixed waste. The bioprocess produces no effluents and affected concrete waste can be removed under controlled conditions.

Conditions to promote biodecontamination were developed in the laboratory some time ago. Data from early studies have been used to develop a field scale evaluation of the process. Currently, contaminated walls in the subbasement of the EBR-1 reactor building located at INEEL are being treated to demonstrate the process. The method is ready for full scale demonstration.

Cost Projections

The assumptions used to generate an estimate of costs for the process are shown in Exhibit 1, and the itemized result of the cost estimate is shown in Exhibit 2.

Exhibit 1
Assumptions Used in Cost Estimate for Biodecontamination of Concrete

Item	Assumption
Gel Application Rate	6,650 ft^2/hr. [1]
Labor Cost	$48/hr.
Gel/Thio Bacilli Cost	$0.98/lb or $9.90/gal [2]
Gel Coveage	1 gal/400 ft^2 [3]
Contamination Removal, once process is complete	6,650 ft^2/hr. [4]
Electricity Cost	$0.065/KWhr [5]

1. INEEL paint cost estimation software
2. BASF specifications
3. Sherwin-Williams paint coverage estimate
4. Contamination is assumed to be removed at the same rate at which the gel/bacilli mixture was applied
5. Local electric at peak time

Exhibit 2
Itemized Cost Estimate of Concrete Biodecontamination

Task/Description	Cost
Gel/Bacilli Application Materials (gel) Contaminant Removal - Process Complete Humidification of Area for 10 months (7200 hrs.)	\$48/hr * hr/6650 ft^2 = \$0.074/ft^2 1 gal/400 ft^2 * \$9.90/gal = \$0.025/ft^2 \$48/hr. * hr/6650 ft^2 = \$0.074 ft^2 7200 hrs *110 VAC * 5A * \$0.065/KWhr*1/3000 ft^2 * KWhr/1000 Whr = \$0.0858/ft^2
Total Cost	\$0.259/ft^2

2. *Identification and Assessment of Candidate Technologies*

In order to evaluate the Biodecontamination Technology with respect to the baseline technology and other candidate technologies for demonstration, it was necessary to identify and characterize the competing technologies. A list of such technologies was developed by ORNL[6] through assimilation and integration of information obtained from literature reviews, personal inquiries of commercial technology vendors, technology researchers and developers, and from prior experience of individual ORNL project team members. Although it was the focus of this task to look for emerging and/or innovative technologies, commercially available technologies were included for completeness. The latter technologies also served a more useful purpose in providing a basis for comparison with the biodecontamination technology. The results of the review identified thirty-one candidate technologies for concrete decontamination -- the characteristics of which are shown in Exhibit 3 below (a composite of tables from the ORNL Study).[7]

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[6] *Ibid.*

[7] ESH/PO, *op. cit.*

Exhibit 3
Characteristics of Candidate Technologies

Technology	Processing Rates	Estimated Costs			Limiting Condition	Problem Application
		Capital $	$ /ft. Operating	$ /hr. Labor		
Automated Brushing	Unknown	250K	300	Variable	Integrated filtering system	Not effective for fixed contaminants
Automated Grinding	15 ft^2/min	500K	Unknown	Variable	Development of vacuum system	Surface contaminants only
Biological	6650/2 ft^2/ hr.	NA	$0.259/$ft^2$	Included	Nutrient Availability	All surfaces, reduced risk, passive process
Detergent	Unknown	10K	1.00	Variable	Labor Intensive	Surface decontamination only
Centrifugal, cryogenic blasting CO_2	0.5 - 1.5 ft^2/min	200K	.075 - 0.75	Unknown	Waste handling of contaminated water	Surface decontamination only
Chelation	Variable	Unknown	1.0	Unknown	Selection of Chelating agents	Variable
Chemical Extraction	100 ft^2/hr.	5K	5	43.75/hr.	Depth of contaminants	Mixed results
Chemical Foams	Variable	50K	0.5 - 2.0	43.75/hr.	Ineffective with convoluted surfaces	Used as pretreatment
Chemical Gels	Unknown	50K	0.5 - 2.0	43.75/hr.	Complex Chemical System	Costly and Time Consuming
Chipping Hammer	20 yd/day	NA	Variable	Variable	Leaves rough surface, dust	Small inaccessible areas
Concrete Milling	Unknown	11K	0.75	43.75/hr.	Equipment not used for decontamination	Horizontal surfaces only
Compressed air, Cryogenic Blasting CO_2	0.5-1.5 ft^2/min	200K	0.075 - 0.75	Unknown	Waste handling of contaminated water	Surface decontamination only
CO_2 blasting	10-90 ft^2/hr.	300K	0.9 - 1.75	15-300	CO_2 in confined area, depth of contamination	CO_2 vaporizes, reduces waste

Technology	Processing Rates	Estimated Costs Capital $	$ /ft. Operating	$ /hr. Labor	Limiting Condition	Problem Application
Electro-hydraulic scabbling	20-40 ft^2/hr.	Unavailable	0.65 - 1.85	Variable	Airborne particles minimal	Applicable to floors only
Electrokinetic	Unknown	Unknown	Unknown	Unknown	Applicable to floors only	Applicable to floors only
Explosives	Unknown	50K	50	Unknown	Dust containment	Top 3-4" concrete
Flame Scarfing	Unknown	Unknown	Unknown	Unknown	Produces RA Airborne Particles	Differential Expansion and Spalling
Flashlamp Cleaning	120 ft^2/hr.	500	4.5 - 25	Included	Input from Xemon vendors critical	Surface decontamination only
Grit blasting	47 ft^2/hr.				Waste processing system	Rates depend on media/surface combinations
Hand brushing	Variable	Unknown	5-10	43.75/hr.	Includes labor	Labor intensive
Hand grinding	Variable	Unknown	0.5 - 1	Variable	Requires remote equipment	Limited to small areas
High pressure water	370 ft^2/hr.	50 -75K	0.06 - 2	43.75/hr.	Uses large amounts of water	Water recycling needed
Ice blasting	10-90 ft^2/hr.	60-155K	1	43.75/hr.	Needs remote operation	Limited to surface decontamination
Laser Ablation	85 ft^2/hr.	700K - 1M	Unknown	Unknown	Building prototype	Variable
Laser Heating	2.5 ft^2/min.	-	-	-	Used for metallic surfaces	Used for large areas with minimum of waste generation
Microwave Scabbling	40 ft^2/hr.	150K	Unknown	Unknown	Not available in private sector	Removes top layer of concrete
Plasma Torch	Unknown	100K	1	100	Spilling of concrete	Used to decontaminate hazardous surfaces
Plastic Pellet Blasting	4 ft^2/min	Unknown	0.2 to 2.15	43-63	Demonstration needed	Used as alternative to grit blasting
Scarification	200-400 ft^2/hr.	110K	5-12.6	43.75/hr.	Noise pollution	Collects 95% of debris

Technology	Processing Rates	Estimated Costs			Limiting Condition	Problem Application
		Capital $	$ /ft. Operating	$ /hr. Labor		
Shot Blasting	30-3000 ft^2/hr.	4M	0.04-5.02	43.75/hr.	Airborne debris waste processing	Removes 1/4" of concrete per pass
Soda Blasting	120-240 ft^2/hr.	Unknown	5-7	43.75/hr.	Multiple units required	For non-rad cleanup
Soft Media Blasting	60-100 ft^2/hr.	20K	10-12	43.75/hr.	Uses lots of water	Successful in mixed waste
Steam Cleaning	Unknown	50-75K	0.05 - 2	43.75/hr.	Uses lots of water	Not effective
Strippable Coating	100 ft^2/hr.	10K	1 - 1.4	43.75/hr.	Depth of Contamination	Application and removal times long
Supercritical CO_2	Unknown	150K	1	43.75/hr.	Optimizing pressure head speed	System optimization required
Superheated water	Variable	175K	0.05 - 2	43.75/hr.	Uses large amounts of water	Robotics and water recycling system needed
Ultrahigh pressure Water	1 ft^2/min	500K	2	43.75/hr.	Water recycling system	Robotics, non-rad contamination
Water Flushing	Variable	5K	1	43.75/hr.	Uses large amounts of water	Used for pre-treated surfaces

<u>Initial Screening of Candidate Technologies</u>[8]

The technologies identified by ORNL and presented in the compilation depicted in Exhibit 3 were then screened and evaluated with respect to:

- Their application to the four prinicipal categories of concrete evaluation:

    1. transferrable surface areas
    2. fixed surface areas containing contaminants at a depth of 1/8" or greater
    3. deep contamination beyond surface due to cracks and penetrations
    4. bulk contamination -- activated concrete -- and therefore, inappropriate for decontamination

[8] *Ibid.*, 4-2.

- Whether the technology was emerging or commercially available (innovative emerging technology was sought)

- Whether a field application was expected (based on technology requirements for active or projected decontamination programs)

- Liklihood of implementation (if there were no inhibiting regulatory or safety restrictions)

- Usefulness of demonstration

The technologies successfully passing the screening described above, and determined to have potential for application, were then further evaluated -- based on estimated costs, secondary waste generation and processing rates.

Technology Evaluation and Demonstration

The evaluation and matching processes described above were the basis for recommendations of technologies to be demonstrated.[9] Candidate technologies were qualitatively ranked, based on the relative ranking for each criterion, resulting in three different groupings: (1) demonstration is recommended, 2) demonstration may be considered, and (3) technology is removed from further consideration. Technologies in the first group were considered to provide the most potential benefit for decontamination of concrete within the DOE complex, and include biological decontamination, electro-hydraulic scabbling, electrokinetics, and microwave scabbling. For example, ORNL has concluded that "biological decontamination has the potential to decontaminate a wide range of problems (a large fraction of contaminated concrete), fits a niche that is not currently addressed (long-term passive treatment), and may provide potential cost savings and waste reduction.[10]

Technologies of the second group were considered to provide benefit to concrete decontamination, but with specific application (e.g. chemical extraction, chromographic strippable coatings, etc.).

Technologies in the third group include $C0_2$ blasting, ice blasting, plasma torch, etc. These technologies were removed from further consideration for two reasons. First, the technologies in the last group are essentially variations of baseline scabbling technologies and may be considered commercially available, therefore adding little benefit if demonstrated. Second, numerous commercial technology applications are available at lower costs for decontaminating the problem areas addressed by these technologies.

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[9] *Ibid.*, 4-4.

[10] *Ibid.*, 4-4.

Twelve technologies survived the screening process described, and of those, four were eliminated from consideration in this study on the basis of ORNL's low evaluation of their usefulness for demonstration. A categorization of the remaining eight technologies is presented in Exhibit 4 below. [11]

Exhibit 4
Results from Technology Demonstration Evaluation

Technology	Number of Applications [1]	Demo Usefulness [2]	Est. Cost Advantage[3]	Secondary Waste Reduction Advantage [4]	Processing Rates [5]
Biologial	6	High	High	High	Low
Chemical Extraction	7	Medium	Medium High	High	Medium
Chromographic Strippable Coatings	1	High	Unknown	High	Unknown
Electrokinetics	3	High	Unavailable	High	Low
Electro-hydraulic Scabbling	5	High	High	Medium	Low
Flash Lamp	6	Medium	Medium	High	Medium
Laser Ablation	4	Medium	Medium Low	High	Low
Microwave Scabbling	4	Medium High	Medium Low	Medium	Low

1. Seven problem areas were identified and used for comparison.
2. High ranking indicates an assumed greater benefit from a demonstration.
3. High ranking indicates an assumed process operation cost savings compared to baseline technologies, medium indicates minimal (or no) benefit and low indicates a higher process operation cost per unit. Capital cost was not included in the evaluation because these costs cannot be evaluated as unit costs and a specific application (extent of contamination to be decontaminated) is identified.
4. High ranking indicates an assumed reduction in secondary waste compared to baseline technologies, medium indicates minimal (or no) benefit, and low indicates increased secondary generation.
5. High indicates a faster processing rate compared to baseline technologies, medium indicates minimal (or no) benefit, and low indicates a slower processing rate.

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[11] *Ibid.*, 4-17.

Because a major objective of the Study was to determine the usefulness of demonstrating the biodecontamination technology -- as compared with other candidate technologies -- with respect to its potential benefit in decontaminating concrete within the DOE complex, technologies with less than a HIGH ranking for demonstration usefulness were then screened out.

Further, of those remaining, the chromographic strippable coatings technology was eliminated from consideration because of its single application, and electrokinetics because of the lack of available cost data.

Consequently, the biodecontamination technology was compared to the remaining candidate technology, electro-hydraulic scabbling; and the benefits/costs of both of these technologies were assessed - and compared to the baseline technology.

3. *Formulation of a Methodology for Evaluating Candidate Technologies*

Because the potential benefits to the Decontamination Program projected for the emerging candidate technologies (and their consequent demonstration usefulness) vary in accordance with the extent to which their application is effective in achieving the Department's objectives, it was necessary to first define those objectives, and then establish their achievement as the goal of the Program. Since the objectives represent disparate facets of the Program, a composite evaluation was required to integrate the various requirements and desired attributes of the Program.

A widely used approach for obtaining an aggregate measure of multiple attributes of, in this case a technology, is a specific adaptation of the Multi-Attribute Utility Technique (MAUT). Variations of this technique are employed by EPA in its Hazard Ranking System (HRS), by DoD in its Defense Priority Model (DPM), and by DOE in its Environmental Restoration Priority System (ERPS).[12]

The MAUT is a formal quantitative approach for analyzing decisions based on multiple objectives.[13] [14] [15] Underlying the approach is a rigorous process for combining the technical

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[12] National Research Council, 1994. *Ranking Hazardous-Waste Sites for Remedial Action.* National Academy Press, Washington, D.C.

[13] Keeney, R.W., and H. Raiffa. *Decisions with Multiple Objectives, Preferences Value Tradeoffs,* Wiley, New York, 1976.

[14] Keeney, R.W., *Value Focused Thinking,* Harvard University Press, Cambridge and London, 1992.

[15] von Winterfeldt, D and W. Edwards, *Decision Analysis and Behavior Reserach,* Cambridge University Press, Cambridge and New York, 1986.

assessments of scientists with the policy judgements of line managers into a prescribed set of decisions. The approach is applicable to situations in which there are many alternatives, competing objectives, and significant uncertainties.

The MAUT Process, as utilized in the Study, took the following form:

1. A set of fundamental objectives for the application of the candidate technologies were identified. These objectives established criteria for evaluating and comparing technologies.

2. A utility function was then defined to represent decision makers preferences regarding their willingness-to-pay to achieve benefits or avoid adverse impacts with respect to conflicting objectives. According to multi-attribute utility analyis, an additive function is appropriate for aggregating impacts upon different objectives if the measures established for the objectives are additive independent.

3. Measurement scales were then developed to quantify the degree to which the technologies would achieve the objectives.

4. Benefits were then calculated using an equation in the form:

$$Utility = \sum_{i=1}^{N} W_i U_i$$

   where the W's are "weights" that reflect the tradeoffs managers are willing to make between objectives, and the U's reflect the tradeoffs managers are willing to make between different levels of achievement of a single objective.

In the application of the technique, each technology was evaluated against each of the objectives -- measuring technology benefits rather than baseline conditions. The technique estimated the conditions that existed, first assuming that the technology had not been implemented (e.g. baseline cost), and then assumed that the technology had been implemented. The difference between the two judgements was used to measure the benefit of the technology according to each criterion.

After the technologies' impacts on the criteria were quantified, the impacts were converted into equivalent dollars based on the value judgements (weights) described above. The total benefit value of each activity was then compared to the estimated resources required to implement the technology. It would then have been possible to generate a benefit-to-cost ratio for each technology, to the extent that costs were known. Ranking of the technologies by this ratio could have made it possible for decision makers to determine the usefulness of the demonstration of the candidate technologies -- given constraints on funding and other resources.

4. *Determination of the Relative Benefits of Biodecontamination and Other Selected Technologies*

As indicated in the previous discussion of the methodology adapted to the evaluation of the candidate technologies, the assessment of the potential benefits from the implementation of these technologies was carried out in the following steps:

- Establishment of Fundamental Objectives
- Derivation of a Utility Function
- Formulation of Objective Achievement Level Scales
- Determination of Projected Improvements
- Quantification of Benefits

Details of the implementation of this methodology are presented below:

Establishment of Fundamental Objectives

In 1989, EM published its first five-year plan for cleaning up DOE's nuclear-related waste sites and for bringing its operating facilities into compliance with current environmental laws and regulations. The plan included the following four priority categories that were applied to environmental restoration and waste operations:

Priority 1:	Activities necessary to prevent near-term adverse impacts on workers, the public, or the environment
Priority 2:	Activities required to meet the terms of agreements between DOE and local, state and Federal agencies
Priority 3:	Activities required for compliance with external regulations not included in Priority 1 or 2
Priority 4:	Activities that are not required by regulation but would be desirable.

Based on these priorities, the following objectives were established for the DOE environmental restoration program and adopted in this study as a framework for technology evaulation.[16]

1. Worker health and safety
2. Public health and safety
3. Environmental protection
4. Safeguards and security
5. Regulatory Compliance
6. Public Concern

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[16] NRC, *op. cit.,* 180.

7. Achievement of mission objectives
8. Employee ability/efficiency
9. Motivated work force
10. Facilities and equipment management
11. Business and financial systems management
12. Employee motivation[17]

In selecting the criteria by which the technologies were to be evaluated, it was recognized that most of the benefit would be achieved in meeting the requirements of two or three criteria (because of the mutual inclusion or irrelevance of the other criteria). Further, only the first order effect of these criteria was calculated.

Based on the areas of interest indicated in DOE's qualitative ranking of the candidate technolgies, the following objectives were identified as those against which the technologies were to be evaluated:

- Worker health and safety
- Achievement of mission (program) objective
- Realization of cost savings

Derivation of Utility Functions

In this step of the methodology, a "utility function" was defined to represent decision makers preferences regarding their willingness-to-pay to achieve benefits or of avoiding adverse impacts of various types. As stated previously, according to multi-attribute utility theory, an additive function is appropriate for aggregating impacts on different objectives, if the measures established for objectives are additive independent. [18] As indicated previously, benefits of the technologies were to be calculated by a summation of the utilities, themselves the products of the tradeoffs managers were willing to make between objectives (W's or weights in the equation), and the tradeoffs managers were willing to make between different levels of achievement of a single objective (the U's of the equation).

Determination of Weights of Competing Objectives (W's)

The weights (W's) and single attribute functions (U's) were derived through a formal selection process with senior managers from participating laboratories (LANL, SNL, and LLNL). The weights obtained in this way were referred to as "unrefined weights" (meaning they did not necessarily represent any one laboratory, but were generally accepted by the laboratories for acceptable ranges of values).

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[17] *Ibid.*, 185.

[18] ESH/PO, *op. cit.*

These unrefined values are presented for reference in Exhibit 5 below.

Exhibit 5
Weights Used in the Benefits Assessment

Decision Objective	Weight	Rationale
Worker Health & Safety	$2.25 M	$2.25 million per worker. This value reflects management's willingness to pay to reduce the probability of an employee statistical death and is comparable to the value used by a wide range of federal agencies.
Public Health & Safety	$5.5 M	$5.5 million per member of the public. This value reflects management's willingness to pay to reduce the probability of a statistical death to a member of the public and is comparable to the value used by a wide range of federal agencies.
Environmental Protection	$10 M	This value reflects management's willingness to pay $10 million to prevent the permanent elimination of an endangered species.
Safeguards and Security	$45 M	This value reflects management's willingness to pay $45 million to prevent a security or safeguards incident resulting in loss, diversion or theft of category I or II quantities of SNM.
Regulatory Compliance	$25 M	This value reflects management's willingness to pay up to $25 million to prevent non-compliance resulting in criminal penalties.
Public Concern	$10 M	This value reflects management's willingness to pay up to $10 million to address items and issues of high public concern.
Achieve Mission Objectives	$100 M	This value reflects management's willingness to pay up to $100 million to prevent critical adverse mission impacts.
Employee Ability/ Efficiency	$0.1 M	$0.1M per worker. This value reflects management's willingness to pay to maintain a skilled workforce.
Motivated Workforce	$7 K	$7K per worker. This value reflects management's willingness to pay to maintain a motivated workforce.
Facilities & Equipment	$30 M	This value reflects management's willingness to pay up to $30 million to ensure facilities and equipment are equal to industry standards.
Business & Financial Systems	$30 M	This value reflects management's willingness to pay up to $30 million to ensure business and financial systems are equal to the highest industry standards.
Direct Cost Savings or Losses	N/A	$1 saved equals $1 benefit (assuming saving is immediate).

NOTE: Weights - A dollar amount for each decision objective representing the decision maker's willingness to pay to gain a benefit or avert risk. These amounts were used to convert impacts into equivalent dollars.

Determination of Objective Achievement Level Scales (U's)

As discussed, once the objectives and associated criteria were identified, and the trade-offs among those objectives were weighted (as indicated in Exhibit 5 above) a determination was made of the degree to which the technologies would achieve those objectives. The objectives against which the candidate technologies were evaluated have previously been identified as:

- Reduction in worker health and safety risk
- Achievement of mission (program) objective
- Realization of cost savings

Development of Work Packages

In order to project the level of objective achievement, a work package was developed for each objective comprising the specific goal and its components. Each candidate technology was then assessed in terms of the impact projected by its application with respect to the baseline technology as described below:

Work Package: *Worker Health and Safety Risk Reduction*

Specific Goal: Reduce risk to workers.

Since the desirability of a particular candidate technology with regard to worker health and safety risk is a function of its capability to reduce worker risk, a first order risk analysis was performed; the components of which were:

- Population at Risk
- Likelihood of Exposure
- Likelihood of Effect
- Severity of Effect

According to the following relationship:

Risk = Population at risk x likelihood of exposure x likelihood of effect x severity of effect

The analysis comprising these components was then performed for the three different technologies under evaluation:

CASE I:	The Baseline (Scarification -- a baseline technology identified by ORO)
CASE II:	Electro-Hydraulic Scabbling (the remaining candidate for screening)
CASE III:	Biological

The case analysis is presented below.

CASE I: Baseline (Test Case at ORR K-25 using scarification)

Population at Risk: Two-man teams for period of treatment

Likelihood of Exposure: Number of hours of exposure

6.7×10^4 hours for cleanup of 20 10^6 ft^2 (at 300 ft^2 /hr) or 34 man/years x 2 (Two-man teams) = 68 man yrs. of exposure

Likelihood of Effect: Assumed one chance in a thousand for an incident per year (.001) x 68 (man years) = .068

Severity of Effect: Moderate (See Exhibit 6).

CASE II: Electro-hydraulic scabbling

Population at Risk: Two man teams for period of treatment.

Likelihood of Exposure: Number of hours of exposure.

6.7×10^5 hours for cleanup of 20×10^6 ft^2 (at 30 ft^2/hr) or 340 man/years x 2 (Two-man teams) = 680 years of exposure

Likelihood of Effect: Assumed one chance in a thousand for an incident per year (.001) x 680 = 0.68

Severity of Effect: Moderate (See Exhibit 6).

CASE III: Biological

Population at Risk: Two-man teams for period of treatment.

Likelihood of Exposure: Number of hours of exposure

67×10^3 hours for application and cleanup of 20×10^6 ft^2 (@ 6650/2 ft^2/hr) or 3.0 man years x 2 (Two-man teams) = 60 man years of exposure

Likelihood of Effect: Assumed one change in a thousand for an incident per year (.001) x 60 (man years) = .006 incidents

Severity of Effect: Moderate (See Exhibit 6)

As seen in the case studies above, the determination of the probability of incidence appeared tractable, given the projections integrated into the analysis. However, to determine the degree of achievement of the objective of risk reduction by the application of a particular technology, it was necessary to determine, as well, the severity of effect of that technology. This determination required a measurement scale that related a qualitative scoring of impact to a corresponding determination of the relative degree of achievement of the goal of reducing risk to workers. As a result of the tradeoff analysis of the DOE laboratories, the value judgements for health and safety risk were incorporated in severity scales, and are presented in Exhibit 6 below.

Exhibit 6
Value Judgments for Health and Safety Risk Scales for Severity of Effect

Score	Severity of Effect Description	Relative Weight
0	No effect.	0
1	Minor effect. Minor injury/or temporary discomfort (e.g. cuts, bruises, minor burns, etc.)	0.0001
2	Moderate effect. Moderate injury or illness, but the effects are not long-term (effects last one year or less) or life threatening (e.g. broken bones, torn ligaments, moderate burns, etc.)	0.01
3	Serious effect. Permanent debilitating injury or serious long-term illness (effect last 5 years or more) (e.g. permanent loss of hand, leg, eye, third-degree burns, etc.)	0.1
4	Very serious. Death or permanent and near total loss of quality of life (e.g., death, coma, quadriplegic, disabling birth defects)	1

The assessments of the components of objective achievement by the candidate technologies were then aggregated and arrayed against each other to determine the degree to which each candidate technology achieved the reduction of worker health and safety risk. A comparison of technology achievement is presented in Exhibit 7 below.

Exhibit 7
Relative Objective Achievement (U_H) Regarding Health & Safety Risk

Objective Component **Candidate Technology**	**Population at Risk (Persons)**	**Likelihood of Exposure (Man/years)**	**Likelihood of Effect Incidents**	**Severity of Effect (Moderate Relative Weight)**	**Technology Risk U_H**
Baseline	2	68	0.001.	0.01	$6.8 \times 10^{-4}(UH_B)$
Electro-Hydraulic Scabbling	2	680	0.00.1	0.01	6.8×10^{-3} (UH_E)
Biological	2	6.0	0.001	0.01	6.0 x 10-5 (UH_{Bi})

Work package: *Achievement of Mission (U_M)*

Specific Goal: Improve effectiveness of decontamination program.

There are essentially two factors that are determinative in evaluating the effectiveness of the candidate technologies for concrete determination; the number of problem categories for which the technology is suitable, and the time required for the decontamination of the specific area -- using the candidate technology.

The analysis of these two components of the evaluation took the following form:

U_M (Objective Achievement) = UM_A (Number of Applications Value Judgment) +

UM_C (Schedule Progress Value Judgment)

Number of Applications

DOE identified seven categories of contamination against which the candidate technologies were evaluated: transferable surface areas, bare and painted floors, bare and painted walls and ceilings, basins and pools, and deep contamination (cracks and penetrations). It is estimated that the last category (deep penetrations) accounts for only 5% of the K-25 contaminated areas. For purposes of the Study, and in lieu of conclusive data regarding the distribution of contamination of K-25, the remaining areas of contamination have been postulated as being equally divided among the six categories.

One component of the measurement of the effectiveness of the candidate technology therefore was the number of categories of contamination (assuming they are equivalent -- with the exception of deep penetration) that the technology under evaluation could address.

Impact on Completion Time

The other measurement of effectiveness of candidate technologies was their projected success in meeting or exceeding the scheduling requirements of the decontamination program. The schedule against which these technologies was evaluated was the projected completion time for the decontamination of K-25 using baseline technology (scarification).

As in the previous analysis of the Worker Health and Safety Work Package, the evaluation of the three technologies was performed in parallel for all three cases, as detailed below.

CASE I: Baseline (Test Case at ORR, K-25, using scarification)

Number of Applications: 3 - Fixed contamination in floors (bare and painted) and containment problems (basins, pools)

Impact on Program Completion Time: Baseline time for completion -- 6.7×10^4 hours for clean up of 20×10^6 ft^2 (@ 300 ft^2/hr)

CASE II: Electro-Hydraulic Scabbling

Number of Applications: 4 - Transferrable surface areas, fixed contamination in floors, (bare and painted) and containment problems (basins, pools).

Impact on Program Completion Time: Time for completion for this technology -- 6.7×10^5 hours for clean up of 20×10^6 ft^2 (@30 ft^2/hr)

CASE III: Biological

Number of Applications: 6 - Transferrable surface areas, fixed contamination in floors, (bare and painted) walls and ceilings (bare and painted) and containment problems (basins, pools).

Impact on Program Completion Time: Time for completion for this technology -- 6.0×10^3 hours for clean up of 20×10^6 ft^2 (@ 3325 ft^2/hr)

As indicated previously, DOE has identified seven categories of concrete contamination. In the case analysis above, the number of categories addressable by each of the candidate technologies under evaluation (and the baseline technology) was determined. A measurement of the extent of addressable contamination, therefore, provided one means of determining technology effectiveness. Value judgments with respect to the applicability of technologies to decontamination categories were incorporated into an effectiveness scale, as presented in Exhibit 8 below.

Exhibit 8
Value Judgments for Effectiveness Scale Relating to Technology Applicability

Score	Technology Applicability Effectiveness	Relative Weight
7	Applies to all categories of contamination	1.0
6	Applies to 6 of 7 categories (excluding deep penetration)	0.95
5	Applies to 5 of 7 categories (excluding deep penetration)	0.79
4	Applies to 4 of 7 categories (excluding deep penetration)	0.63
3	Applies to 3 of 7 categories (excluding deep penetration)	0.47
2	Applies to 2 of 7 categories (excluding deep penetration)	0.31
1	Applies to 1 of 7 categories (excluding deep penetration)	0.16

The other measurement of technology effectiveness, success in meeting scheduling requirements, was carried out by making value judgements with respect to schedule compliance in the implementation of the decontamination program and incorporating them into an effectiveness scale, presented in Exhibit 9 below.

Exhibit 9
Value Judgments for Progress Toward Implementing the Decontamination Program Scales

Score	Technology Applicability Effectiveness	Relative Weight
3	The program is completed 3 or more years ahead of schedule	0.1
2	The program is completed 2 years ahead of schedule	0.09
1	The program is completed 1 year ahead of schedule	0.067
0	The program is completed on schedule	0
-1	The program is completed 1 year behind schedule	-0.67
-2	The program is completed 2 years behind schedule	-0.9
-3	The program is completed 3 or more years behind schedule	-1.0

The assessment of the components of objective achievement by the candidate technologies were then aggregated and arrayed against each other to determine the degree to which each candidate technology achieved effectiveness in achievement of mission. A comparison of technology achievement is presented in Exhibit 10 below.

Exhibit 10
Relative Objective Achievement (U_M) Regarding Mission Achievement

Objective Component / Technology	Number of Applications	Technology Effectiveness UM_A	Schedule Compliance	Technology Effectiveness UM_C	U_M
Baseline	3	0.47	On schedule	0	0.47
Electro-Hydraulic Scabbling	4	0.63	>3 yrs. behind	-1.0	-0.37
Biological	6	0.95	>3 yrs. ahead	0.1	1.05

It should be pointed out that in determining the degree to which the achievement of mission objective was projected (U_M), the component effectiveness measures were additive (UM_A and UM_C) since the measures established for these were additive independent.

5. Determination of the Relative Projected Costs of Biodecontamination and Other Selected Technologies

In the course of projecting costs for the candidate technologies (and the baseline technology as well), a significant aspect of the cost analysis - cost reduction - proved most determinative. In addition, this aspect of cost projection conformed to a major objective of The Program, and consequently, was the cost component evaluated. In this evaluation, cost reduction was treated as a benefit and assessed in the same manner as the benefits described above.

Thus, a work package was developed; and each candidate was then assessed in terms of the cost reduction potential projected by its application -- in comparison with the baseline technology (scarification).

Work Package: *Cost Savings (U_S)*

Specific Goal: Reduce program costs by adopting candidate technology

Unlike the possible cost savings that must be imputed from the reduction in worker health and safety risk and enhanced mission achievement, it is possible to project potential direct cost savings accruing from the adoption of the candidate technologies under evaluation. The basis of such projections was the determination of operating and labor costs (capital costs were unavailable) of the candidate technologies in comparision with the costs of the baseline technology. As a basis for assessment, the comparative costs were calculated for those contaminated areas of K-25 for which the baseline and the two candidate technologies were applicable (fixed contamination in floors, bare and painted, and containment problem areas) constituting 3/7 of total K-25 contamination. The analysis of the two components of cost took the following form:

Technology Cost = Operating Cost (Area/Cost/ft^2) +

Labor Cost (Area/Processing Rates x Labor Rates)

As in previous evaluations, the cost analysis of the three technologies were performed in parallel for all three cases, as detailed below.

CASE I: Baseline (Test Case at ORR, K-25, using scarification)

Operating Cost: Applicable Contaminated Area x Cost/ft^2

$3/7\ (20 \times 10^6\ ft^2)\ (\$10/ft^2) = \$8.6 \times 10^7 = \$86 \times 10^6$

Labor Cost: Number of Hours for Cleanup x Labor Rate

$(3/7)(6.7 \times 10^4)(\$43.75/hr) = \$123.1 \times 10^4 = \$1{,}230{,}000$

Baseline Cleanup Cost: $86,000,000 + $1,230,000 = $87,230,000

CASE II: Electro-hydraulic Scabbling

Operating Cost: Applicable Contaminated Area x Cost/ft^2

$3/7\ (20 \times 10^6\ ft^2)\ (\$1.25/hr) = \$10.7 \times 10^6 = \$10{,}700{,}000$

Labor Cost: Number of Hours for Cleanup x Labor Rate

$(3/7)(6.7 \times 10^4)\ (0) = 0$ (Included in operating cost)

Electro-Hydraulic Scabbling Cleanup Cost: $10,700,000

CASE III: Biological

Operating Cost: Applicable Contaminated Areas x Cost/ft^2

$(3/7)(20 \times 10^6 \text{ ft}^2)(0.259 \times 10^2/\text{ft}^2) = \$2.22 \times 10^5 = \$222,000$

Labor Cost: Number of Hours for Cleanup x Labor Rates

$(3/7)(6.7 \times 10^4)(0) = 0$ (Included in operating cost)

Biological Cleanup Cost: $222,000

The assessment of the components of cost were then aggregated and arrayed against each other to determine the degree to which each candidate technology achieved projected cost reduction. A comparison of projected technology cost reduction is presented in Exhibit 11 below.

Exhibit 11
Relative Objective Achievement (U_S) Regarding Cost Reduction

Cost Component / Technology	Operating Cost $	Labor Cost $	Technology Total Cost $ U_S
Baseline	86.0×10^6	1.23×10^6	87.23×10^6
Electro-Hydraulic Scabbling	10.7×10^6	0	10.7×10^6
Biological	2.22×10^5	0	2.22×10^5

6. Determination of Relative Benefits/Costs of Biodecontamination and Other Selected Technologies

Since the technologies under evaluation are candidates for demonstration and perhaps future utilization in the decontamination program, their assessments were conducted in comparison with a current baseline technology (for this study, scarification - as previously discussed). The relative achievements of the candidate technologies with respect to the objectives of the decontamination program are presented in Exhibit 12 below.

Exhibit 12
Technology Objective Achievement Relative to Baseline

Relative Objective Achievement / **Technology**	**Cost** U_S $	**Cost Savings Re Baseline** $	**Worker Risk** U_H $	**Risk Reduction Re Baseline** $	**Mission Achievement** U_M $	**Mission Achievement Re Baseline** $
Baseline	Us_B 87x23x10^6	NA	UH_B 6.8x10^{-4}	NA	UM_B 0.47	NA
Electro-Hydraulic Scabbling	US_E 10.7 x 10^6	US_E -US_B 76.53x10^6	UH_E 6.8x10^{-3}	UH_E - UH_B (-)61.2x10^{-4}	UM_E -0.37	UM_E - UM_B -0.84
Biological	US_{BI} 2.2 x 10^5	US_{BI}-US_{Bi} 87.0 x 10^6	UH_{BI} 6.0x10^{-5}	UH_{BI}-UH_{Bi} 51.2x10^{-4}	UM_{BI} 1.05	UM_{BI}-UM_{Bi} 0.58

Quantification of Benefits

To determine the projected cost benefits accruing from the adoption of the candidate technologies, it was necessary to quantify the achievement of the program's objectives by these technologies.

This determination was made by using a variation of the Utility equation previously discussed, in the form:

$$ObjectiveBenefits = \sum_{i=1}^{N} W_i U_i$$

where the W's reflect the trade-offs managers were willing to make between completing objectives. The trade-offs were converted into dollar equivalents -- as presented in Exhibit 5. Similarly, the trade-offs managers were willing to make between different levels of achievement with respect to individual objectives by candidate technologies were likewise made, and are summarized in Exhibit 12. The benefits projected for the candidate technologies were then calculated in accordance with multi-attribute utility analysis theory as indicated below.

For the Biological Technology:

$$B_B = WH_{Bi}\ UH_{Bi} + WM_{Bi}\ UM_{Bi} + \triangle S_{Bi}$$
$$= (\$2.25M)(51.2x\ 10^{-4}) + (\$100M)(0.58) + \$87.0\ M$$

$$= \$.011\ M + \$58\ M + \$87.0\ M$$

$$B_B = \$145.011\ M$$

For the Electro-hydraulic Technology:

$$B_E = WH_E\ UH_E + WM_E\ UM_E + \triangle S_E$$
$$= (\$2.25M)(-61.2\ x\ 10^{-4}) + (\$100M)(-0.84) + \$76.53\ M$$

$$= \$(-.001\ x\ 10^6) + (-\$84x10^6) + \$76.53\ x\ 10^6$$

$$B_E = -\$7.46\ M$$

Where:

B_B are the aggregated benefits of the biological technology
WH_B is the value judgment of the effectiveness of the biological technology for reducing worker risk.
UH_B is the relative weight of risk reduction.

WH_B is the value judgment of the effectiveness of the biological technology for achieving program mission.

UM_B is the relative weight of program achievement.

Δ_{SB} is the cost reduction projected for the biological technology in comparison with the baseline technology (scarification)

and

WH_E is the value judgment of the effectiveness of the electro-hydraulic technology for reducing worker risk.

UH_E is the relative weight of risk reduction.

WM_E is the value judgment of the effectiveness of the electro-hydraulic technology for achieving program mission.

ΔM_E is the relative weight of program achievement.

ΔS_E is the cost reduction projected for the electro-hydraulic technology in comparison with the baseline technology (scarification)

FINDINGS

The findings of the Study projected potential cost reductions and non-cost benefits that could result from the adoption of a biological technology for the decontamination of concrete. The benefits were derived from an analytic technique that was employed to not only calculate cost reductions, but to quantify, as well, non-cost benefits reflecting program objective achievement. In the course of the Study, various assumptions were made and certain boundary conditions were imposed as the analysis progressed. The quantified benefits and the conclusions that can be drawn from the assessment, along with the assumptions and boundary conditions imposed upon the analysis, are summarized below.

Assumptions

As a basis for the analysis, the following assumptions were made:

- That the decontamination of ORO-25 provided a reasonable and valid arena for evaluating competing candidate technologies;
- That the thirty-one technologies determined by ORO to be useful for concrete decontamination provided a representative set of available technologies;
- That the results of the initial screening of these technologies provided a reasonable mix of innovative technologies from which those suitable for demonstration could be selected;
- That the further screening of the technologies to those employed in the analysis was valid for technology comparison, in view of the lack of cost data and the limitations of applicability of the other technologies that were rated as highly favorable for demonstration;
- That the major objectives of the demonstration and adoption of innovative technologies for the concrete decontamination program are: enhanced performance of cost reduction, and lessening of worker health and safety risk;
- That the Multi-Attribute Utility Technique (MAUT) is valid and applicable to the evaluation;
- That the benefit determination, based on the impacts of the candidate technologies on different objectives are additive, since the measures established for the achievement of objectives are additive independent.

Boundary Conditions

The evaluation performed in the Study was bounded by the following analytic criteria:

- That the assessment of cost reductions among the candidate technologies was to be limited to cost reductions possible in the contaminated areas in which the assessed technologies were applicable. This limitation resulted in a diminution of cost reductions that would have been projected had the cost differentials between the candidate technologies been applied to the entire area of contamination.

  On the other hand, this underevaluation of cost savings was, to some degree, compensated for in the calculation of benefits attributed to improved effectiveness of the decontamination program - a function of the number of contamination categories addressable by the candidate technologies.

- That because data regarding capital costs were not available for all of the technologies being evaluated, potential cost differences between the competing technologies in this regard could not be ascertained.

- Consequently, a determination of ROI's with respect to the adoption of the candidate technologies was not possible.

Benefits

As determined in the course of the analysis presented previously, the projected benefits of the candidate technologies, biological, and electro-hydraulic scabbling -- with respect to the baseline technology (scarification) -- took the following form:

The total benefits projected to accrue from the adoption of the biological technology were calculated to be $145.01 M.

The total benefits projected to accrue from the adoption of the electro-hydraulic scabbling technology were calculated to be $-7.46 M.

It should be pointed out that the negative value ($-7.46 M) of benefits attributed to the adoption of electro-hydraulic scabbling indicated that the overall benefit accrual of that technology would be less than that of the baseline technology (despite potential cost savings) with which both candidate technologies were compared. This determination essentially reflected the difference in projected non-monetary benefits (specifically, the difference in processing time between electro-hydraulic scabbling and scarification). The significantly greater processing time required for electro-hydraulic scabbling would be expected to increase exposure time for workers and diminish the program's capacity for meeting schedule requirements -- as established by the baseline technology (scarification).

A further refinement in the determination of the projected accrual of benefits could be made by incorporating a time dimension of the accrual into the assessment. This time factor would impact both the monetary benefits (costs reduction) and the non-monetary benefits.

Monetary Benefits

The final component of the benefit calculation, Cost Savings (U_S) was a function of the projected costs of the candidate technologies. It is common practice when evaluating long-term projects with very different funding profiles over time to use discounting methods to reduce time-streams of cost into a single numeraire. This would enable consistent and logically sound comparison of projects. Discounting future costs would account for the preference to defer expenditures (all things being equal) due to the time value of money. Discounting could also be used to account for the preference for achieving benefits sooner rather than later. In both cases, discounting would be applied to calculate the Net Present Value (NPV) of project costs and project benefits.

For project costs, a cost in real current dollars (i.e. no adjustment for inflation) would be required as input for each year during which the project requires funding. The NPV of project costs could then be calculated using the following equation: [19]

$$C_{NPV} = \sum_i \frac{C_i}{(1+r_c)^i}$$

where C_{NPV} is the NPV of project costs, C_i represents project costs in year i, and r_c is the appropriate discount rate on costs reflecting the time value of money.

A real discount rate of 5% was chosen and is believed to be consistent with values recommended by various government agencies. The implications of various discount rates are summarized in Exhibit 13 below.[20]

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[19] *Ibid.*, 7.

[20] *Ibid.*, 6.

Exhibit 13
Implications of Alternative Discount Rate on Project Costs

($ in M)	What would I be willing to spend today to avoid spending $10M in ...		
Real Discount Rate	**5 Years**	**10 Years**	**20 Years**
1%	9.5	9.1	8.2
5%	7.8	6.1	3.8
10%	6.2	3.9	1.5
15%	5.0	2.5	0.6

This refinement in the calculation of costs, and consequently, the cost-saving benefit could be more realistically applied after a project is developed - based on a successful demonstration of the candidate technology.

Non-Monetary Benefits

Similarly, a refinement of those values could be made in the determination of the non-monetary benefits by discounting these benefits to account for the preference to achieve immediate benefits and address urgent risks, all things being equal. The benefits evaluation employed in this Study's analysis would allow the representation of the time dimension of the benefits using a somewhat simplified scheme. To utilize this approach, benefit criteria were grouped into three classes depending upon the degree of complexity required to appropriately capture timing issues: those requiring a special model of timing, those requiring a model representing the time until an impact occurs, and those requiring a model representing the time until impact occurs as well as the duration of impact. Each type of model is discussed briefly below.

No Timing Model Needed

The criterion of "progress toward completion" would not require any detailed timing model. It was assumed that the time of implementation was only important to the extent that it related to schedule performance. Since schedule performance was already measured in timing of completion measurement scales (Exhibit 9), no special timing model would be needed.

"Time Until Impact" Model Needed

The Worker Health and Safety Risk Reduction criterion would require a timing model that would account for the preferences for addressing immediate risk problems over more distant problems. The idea was that the time until an impact on health and safety risk would occur should be used to discount the value of addressing a risk problem: if it occurs now it would receive full value; if it occurs in the future, it receives some discounted value based on how far in the future it occurs.

"Time Until/Duration of Impact" Model Needed

The remaining criterion would account for the various types of annual risks that could start now or some time in the future and that could last for one or many years. These types of impacts would require a representation of both the time until a risk occurs and the duration of that risk. In this case, for each year during which a risk occurs, the risk would have to be discounted to account for the value of addressing risks in that year relative to the value of addressing identical risks that would occur immediately.

For all of the criteria for which some type of timing model would be necessary, an approach for discounting project benefits identical to that for discounting project costs would be used. That is the Net Present Value (NPV) of a future stream of benefits would be calculated as:[21]

$$B_{NPV} = \sum_i \frac{B_i}{(1+r_b)^i}$$

where B_{NPV} is the NPV of project benefits for a particular criterion, B_i represents project benefits for that criterion in year i in current dollars (calculated based on scores and the value judgments determined previously, and r_b is the appropriate discount rate to apply for that criterion.

The only additional complication in calculating the NPV of project benefits would be that the scores for timing and duration of impacts would have to be analyzed to determine appropriate values of the B_i. For example, if a project produced an annual risk reduction that would be worth \$x/year today, but if that risk reduction would not start for 3 years and would last for 2 years, then $B_o = 0$, $B_1 = 0$, $B_2 = 0$, $B_3 = x$, $B_4 = x$, $B_5 = 0$, $B_6 = 0$. The equation above, given these values for B_i, would yield the NPV of the project's benefits for that particular risk reduction criterion.

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[21] *Ibid.*, 7.

It is assumed that the discount rate applied to project costs should be the same as that applied to other cost impacts. For risk and other non-monetary impacts, it was decided that the model should be capable of using a different discount rate. However, based on a consideration of various discount rates for project benefits, a discount rate of 5% (identical to that chosen for costs) was deemed to be reasonable. Thus, though the model could theoretically incorporate different discount rates (or even a discount rate of o, corresponding to no discounting) for project benefits, in practice it was decided that identical discount rates would be used for project benefits and costs. Implications of various risk discount rates are summarized in Exhibit 14 below. [22]

Exhibit 14

Implications of Alternative Real Discount Rates to Account for Risk Urgency

(In statistical fatalities)	**How large a future risk would I be willing to accept to eliminate a current risk of 1 statistical fatality, if the future risk occurred in ...**		
Real Discount Rate	**5 Years**	**10 Years**	**20 Years**
1%	1.1	1.1	1.2
5%	1.3	1.6	2.7
10%	1.6	2.6	6.7
15%	2.0	4.0	16.4

Again, as with cost discounting, this refinement in risk determination and trade-off could only be validly approached in terms of a real project after a successful demonstration of the candidate technology.

It should be pointed out that the discounting refinement in the assessment of the cost/benefits derived from the use of various decontamination technologies, although providing a time dimension and perhaps enhanced precision in the determination, should not be considered a convenient mechanistic solution to decision-making in the selection of a suitable technology. For example, although a project might have a need for a technology that would provide the means for immediate clean-up, such a requirement is generally limited in scope. Moreover, the utilization of an immediately acting technology, albeit more expensive and perhaps more hazardous, would not preclude the use of more beneficial, though longer-acting biological process for the remaining areas of contamination. In fact, the passive, more benign, more economical biotechnology could be implemented in parallel -- providing, as an added dividend, the reduction in the extent of contamination that would have to be addressed by other

[22] *Ibid.*, 7.

technologies. Thus, the possible pairing of the biodecontamination technology with other more hazardous, but more immediately effective, technologies would remain a program option that should be considered in any long-term decontamination program.

CONCLUSIONS

As a result of the analysis performed in the course of this study -- based on the assumptions and value inputs, and bounded by the conditions described above -- it was concluded that:

- The methodology developed for, and utilized in, the evaluation of the biodecontamination technology for concrete successfully integrated its costs/benefits, both monetary and non-monetary, and related those benefits to the project's objectives. Further, that this evaluation scheme would be applicable to the similar selection and prioritization of technologies, projects, problem solutions -- when the selection is bounded by schedule demands, regulatory compliance, resource ceilings and technology limitations. The relationship and interfacing of these factors as developed by this methodology is depicted in Exhibit 15.

- The evaluation of the biodecontamination technology utilizing this methodology, correlated costs and benefits of the competing candidate technologies -- benefits that were functions of the extent that the adoption of the candidate technologies enhanced the achievement of the goals of the decontamination program.

- The determination of the advantages of utilizing the biological process for concrete decontamination provided a well-documented example of successful technology transfer from basic research (carried out by the Surface Science Program of the Office of Health and Environmental Research) to a major problem of the Department.

- The analysis confirmed the qualitative assessment of the biological approach that concluded that it provided clear advantages in its capacity for reducing worker health and safety risks, enhanced achievement or program goals and reducing costs -- major objectives of the decontamination program.

- The adoption of the biological process for concrete decontamination has the potential for yielding sufficiently enhanced benefits in comparison with other candidate technologies that a demonstration of the biodecontamination technology is strongly recommended.

Exhibit 15

Relationship Between Technologies' Cost/Benefits and Program Objectives

Cost Components		Total Costs	Technology	Total Benefits	Benefits/Objectives	
Capital Costs	Unknown	$10.7 M	Electro-Hydraulic Scabbling	$-7.46 M	$-0.0001 M	Risk Reduction [2]
Labor Costs [1]	NA				$-84.0 M	Mission Achievement [2]
Operating Costs	$10.7 M				$75.6 M	Cost Reduction [2]
Capital Costs	Unknown	$0.22 M	Biodecontamination	$145.0 M	$0.011 M	Risk Reduction [2]
Labor Costs [1]	NA				$58.0 M	Mission Achievement [2]
Operating Costs	$0.22 M				$87.0 M	Cost Reduction [2]

1 - Included in operating costs.

2 - As compared to Baseline Technology (Scarification)