AFIT/GEE/ENS/93S-2

AD-A270 460

(1)

DEVELOPMENT OF A
MULTICRITERIA DECISION MODEL
FOR PRIORITIZING AIR FORCE
ENVIRONMENTAL RESTORATION PROGRAM PROJECTS

THESIS

Thomas E. Ellingson, B.S.
T. Gene Gallogly, B.S., M.B.A.

AFIT/GEE/ENS/93S-2

Approved for public release; distribution unlimited

The views expressed in this thesis are those of the authors and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

AFIT/GEE/ENS/93S-2

DEVELOPMENT OF A MULTICRITERIA DECISION MODEL FOR PRIORITIZING AIR FORCE ENVIRONMENTAL RESTORATION PROGRAM PROJECTS

THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in

Engineering and Environmental Management

Thomas E. Ellingson, B.S.

T. Gene Gallogly, B.S., M.B.A.

September 1993

Approved for public release; distribution unlimited

THESIS APPROVAL

STUDENTS: Thomas E. Ellingson CLASS: AFIT/GEE/ENS/93S-2
T. Gene Gallogly

THESIS TITLE: DEVELOPMENT OF A MULTICRITERIA DECISION MODEL FOR PRIORITIZING AIR FORCE ENVIRONMENTAL RESTORATION PROGRAM PROJECTS

DEFENSE DATE: 12 AUG 93

GRADE:

COMMITTEE:	NAME/TITLE/DEPARTMENT	SIGNATURE
Advisor:	Yupo Chan Professor of Operations Research, ENS	
Reader:	Michael L. Shelley Asst Prof Eng & Env Mgt	
Reader:	Guy S. Shane Associate Prof Mgt & Org Behavior	
Reader:	Mark N Goltz Assoc Prof Eng + Env Mgt	
Reader:		

Preface

The purpose of this study was to develop a multicriteria decision model to aid the Air Force in prioritizing Installation Restoration Program projects. The need for research on this subject has been expressed by many individuals, ranging from project programmers at the base level, to environmental restoration experts at the Major Command and Air Staff levels, to the Deputy Assistant Secretary of the Air Force for the Environment.

This research was accomplished using a Delphi process and a multiattribute utility theory questionnaire. We would like to gratefully acknowledge the time and effort expended by those who participated in our questionnaires. We would also like to thank our readers, Lt. Colonels Mark Goltz and Mike Shelley, for their insightful guidance on the environmental aspects of our work, and Dr. Guy Shane for his enthusiastic support, his assistance with the Delphi technique, and his editorial efforts. A special thanks must also go to our faculty advisor, Dr. Yupo Chan, who patiently endured the process of teaching us multicriteria decision making. Without his dedication, support, and guidance, this research effort would not have been possible.

An Air Force Institute of Technology thesis is a very time consuming and mentally taxing effort. Many hours are spent reading background material, gathering and analyzing

data, and documenting results. Often our scholastic responsibilities required that we spend more time with our books than with our loved ones. For their support and understanding, we would like to thank our families.

Gene would especially like to thank his wife Tami for maintaining the family single-handedly during the times he was preoccupied with schoolwork. He also promises to spend more time with his children; Katie, Erin, Craig, Kelsey, and Jenni; now that we have completed our work.

Tom would like to give special thanks to his parents, Don and Mary Ellingson for their confidence, love, and teaching, not just during the past year and a half, but over the last twenty-seven years. Also, a very special thanks to his fiancé Donna Esterbrook for her contributions to this effort, for enduring the time spent apart, and most of all, for promising to share her life.

T. Gene Gallogly
Thomas E. Ellingson

Table of Contents

Page

List of Figures

List of Tables

Abstract

Cleaning up hazardous and toxic wastes left from past activities has become one of the major goals of the Department of Defense. Within the Air Force, individual major commands (MAJCOMs) annually review numerous projects submitted under the Defense Environmental Restoration Program (DERP) and forward these projects to HQ USAF/CEVR for funding. Until recently, adequate resources have been available to fully fund all projects. However, within the last two years, funding shortfalls have been experienced, and projects have received only partial funding. The Air Force needs a decision support system that will assist in determining funding priorities for these projects.

This thesis presents two possible methodologies and resulting multicriteria decision models for determining funding priorities within the constraints of a limited budget. The first method utilizes a Delphi procedure to elicit pertinent criteria, weights, and utilities from DERP experts. The second method utilizes multiattribute utility theory to determine the preference structure of a single decision maker. Each method results in a working model which can be used to prioritize DERP projects. Both models resulted in risk being the primary decision criterion. Additionally, the Delphi model also utilized cost, community

acceptance, technical feasibility, mission impact, and socioeconomic impact.

DEVELOPMENT OF A DECISION SUPPORT SYSTEM

FOR PRIORITIZING AIR FORCE

ENVIRONMENTAL RESTORATION PROGRAM PROJECTS

I. Introduction

The toxic wastes of New York's Love Canal, Kentucky's Valley of the Drums, and Missouri's Times Beach brought to light serious threats to the public's health from past hazardous waste disposal practices and spills (EPA, 1990c:1). In 1975, five years before the passage of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), the Department of Defense (DoD) took note of the public furor caused by these events and began the Defense Environmental Restoration Program (DERP) (Air Force, 1992:23). Given the heightened interest in the environment and the number of base closures as a result of defense drawdowns, DERP has become one of the Armed Service's top priorities (Baca, 1992:18).

From its inception, DERP has evolved to keep pace with legislative developments, public pressures, and new technologies. CERCLA and its amendments, similar state laws, and several DoD and Environmental Protection Agency (EPA) regulations set forth the overall objectives, procedures, and cleanup standards for the program. While these laws and regulations establish the actions that will be required, funding determines the rate at which the cleanups progress.

DERP funds are distributed from a special Congressional appropriation whose growth has paralleled the popular environmental movement. Until recently, these funds have been adequate; however, new sites are continually uncovered, the number of studies and remediation projects under DERP continue to grow, and the program has evolved from the investigative stages to the more costly remediation stages.

With the heightened awareness and effort has come an increased competition for available funds. Last year, the Air Force was able to fund only 45 percent of its program (Owendoff, 1993a). While various means to allocate these funds have been proposed, none of the schemes adequately account for the multiple program objectives and the regulatory commitments made at the various administrative levels. Instead, funds are allocated to the Major Commands (MAJCOMs) based on each MAJCOM's percentage of total costs for all projects meeting basic screening parameters (Owendoff, 1993a). This decision rule forces DERP managers to delay critical work at some bases while less important work proceeds at another base under a different MAJCOM. The situation is exacerbated as competition increases.

Research Problem

Given the funding dilemma, Mr. Gary Vest, the Deputy Assistant Secretary of the Air Force for Environment, Safety, and Occupational Health, requested development of a new decision support system (DSS) (Vest, 1992). A multicriteria decision model (MCDM) in support of the DSS will help establish a distinct funding hierarchy among DERP project alternatives at every stage in the cleanup process. The resulting priorities must be consistent with CERCLA, state laws, and the governing regulatory objectives. Furthermore, the funding priorities should be acceptable to the MAJCOMs who have been delegated responsibility for the program. Finally, the model must satisfy Congress, the EPA and state regulatory agencies, and the affected public who decide how large the total DERP budget will be, who help decide what the installation priorities are, and who judge the results of Air Force efforts.

Research Objectives

The purpose of this research is to support development of a new DSS for determining DERP priorities. In order to do this, the research will be designed to accomplish two objectives. First, the goals of the DERP, their relative importance, and their relationships with one another will be determined. Second, these findings will be used to develop an MCDM to support Air Force decision makers.

The first objective will be accomplished by means of a literature review and surveys of key DERP and regulatory personnel. The following questions should be answered to fully support this objective:

1) What are the objectives of CERCLA, similar state laws, and DoD and EPA regulations with regard to the DERP?

2) Which DERP project criteria are most important to meeting these objectives and how are they measured?

3) How should inherent project uncertainties be addressed?

4) How can a comparison be made among multi-phase, multi-year projects with different cost and benefit streams?

The answers generated from the literature review and survey will be incorporated into a suitable MCDM to satisfy the second objective. As a result, the MCDM should assist in making decisions which are less arbitrary, make use of the full power of discriminating criteria, and most importantly, allocate funding to deserving projects more equitably.

Scope/Limitation

Since future requirements are expected to grow much faster than DERP appropriations, a new means of prioritizing projects is urgently needed. As such, the research will not devote time to developing new means to measure progress with DERP objectives. Rather, an attempt will be made to reach a consensus among experts on the most suitable existing measures to use in the model (a partial response to question 2 above). Additionally, the MCDM will not be developed to help choose among alternative methods for site remediation. At this stage in the research, existing systems and expert judgment must be relied on to make site-specific remediation technology decisions and to weigh the uncertainties involved in the choices. Finally, validating the MCDM with an existing ranking of actual projects will not be attempted. Key parameter measures may not be available in existing programming documents, and the time to research or develop them will not be available.

While these limiting features will likely raise suspicions as to the validity of the resulting MCDM, the overall research objective will be met. The MCDM will provide an immediate, equitable means to allocate funds and will give DoD a starting point upon which to build support for their prioritization system, solicit improvements, and respond fully to the four questions posed previously.

Organization of the Research Report

The first step in developing an appropriate MCDM for prioritizing DERP projects is to establish an understanding of the program, its written objectives, and previous research into similar problems. The literature review accomplishes this purpose. Following the literature review, a description of the methodologies used to gather relevant criteria for the prioritization problem and the preference structures used to analyze and compare the criteria are discussed. Additionally, the procedures employed to develop appropriate MCDMs for the decision support systems are addressed. The research findings and analysis are reported in Chapter Four, followed by the conclusions and recommendations for further study in Chapter Five.

II. Literature Review

Cleaning up hazardous and toxic wastes left from past Department of Defense (DoD) activities is receiving national attention. Funding for cleanups has grown from just $150 million in fiscal year 1984 to more than a billion dollars in recent years (DoD, 1992:1; West, 1991:8). More and more contaminated sites are being identified, and the number of studies and remediation projects in the Defense Environmental Restoration Program (DERP) continues to grow. With the heightened awareness and efforts has come an increased competition for available funds. This research is aimed at developing a multicriteria decision model (MCDM) for use in a new decision support system (DSS) for determining DERP funding priorities among the competing projects.

Introduction

Two objectives must be met in order to develop the DSS. First, the goals of DERP, their relative importance, and the relationships between them must be determined. Second, these findings must be used to develop an MCDM to support Air Force decision makers.

A thorough understanding of the program is required before the first objective can be met; therefore, the program's background was researched. The applicable legislation, a brief history of the events that led up to their passage, and the EPA's interpretations of the legislative mandates were each researched to determine the goals and objectives of the program. Next, DoD and Air Force programs were studied to provide insight into the scope of the problem. They were also analyzed to determine if the stated objectives for their programs were consistent with the legislation, and if the current project approval and prioritization system would fulfill those objectives. After establishing program objectives, common restoration methods were discussed to provide a better understanding of the current state of technology, aid in developing criteria and measures to distinguish among project alternatives, and understand project uncertainties better.

To satisfy objective two, the answers generated from this literature review and surveys of experts will be incorporated into a suitable MCDM. A brief review of decision models and decision making theory was conducted to gain an appreciation of this task. A more thorough review of MCDMs will be presented in the methodology section. Likely parameters for the model were also reviewed. Since it appeared that reducing risk was of paramount importance, risk as a decision parameter was researched in detail. Other seemingly important factors such as cost-effectiveness, feasibility, and the value of innovative technologies were also analyzed to aid in determining their relative importance to the proposed model.

Finally, to complete the literature review, similar research done by others was examined. Several studies related to prioritizing work based on involving the public, reducing risk, funding the worst sites first, and focusing on incremental improvements were found to be relevant to this MCDM.

Background

DERP has not existed very long, but it has received much attention in this decade of environmental awareness. Both Congress and the public expect progress for the money they are investing in the program, and the Air Force's prioritization methods and subsequent allocation of funds need to address their concerns. Therefore, a review of the program's inception and an understanding of where it stands today are discussed below:

Legislation. The first significant attempt at regulating threats to the public's health and the environment from past hazardous waste disposal sites was the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 [Public Law 96-510, 42 United States Code (USC) 9601-9657]. This law, commonly referred to as Superfund, authorized the government to respond to releases or threatened releases of hazardous substances that could endanger the public or the environment. It also established a means to force responsible parties to pay for cleanups and provided a $1.6 billion fund to clean up the Nation's highest priority sites. (EPA, 1990c:1)

According to Don Clay, Assistant Administrator for the Solid Waste and Emergency Response (OSWER) office of the EPA, Superfund had six goals:

1) Make the sites safer. Control immediate threats and cleanup the worst sites first.

2) Make sites cleaner. Quickly implement and improve long-term cleanups.

3) Strengthen enforcement and maximize actions by responsible parties.

4) Encourage innovative restoration technologies.

5) Involve the community.

6) Communicate results to the public. (EPA, 1990c:V)

The Superfund Amendments and Reauthorization Act (SARA) of 1986 was passed when it became apparent that CERCLA was not going to accomplish its objectives. SARA broadened CERCLA, extended the authorization for five years, and added $8.5 billion to the cleanup fund. It also emphasized the use of alternative or resource recovery techniques and the need for permanent solutions. (EPA, 1990c:2)

Sovereign immunity is often waived in federal statutes to require federal agencies to comply with the procedural and substantive requirements of state and local regulations (Spectrum, 1990:6). CERCLA Section 107(g) waives sovereign immunity for federal facilities. This section was later reinforced by SARA Section 120 (EPA, 1988:II-6). Executive Order 12088 also dictates that agencies comply with applicable pollution control standards and that they cooperate with state and local agencies to control and abate pollution (EPA, 1988:II-1). DoD has taken these mandates seriously, and former Defense Secretary Cheney committed DoD to an environmental leadership role (Spectrum, 1990:1).

Air Force and DoD cleanup activities fall under the auspices of DERP, which was established by Congress as Section 211 of SARA (EPA, 1988:II-7) under Title 10, USC 2701-2707 and 2810 (Air Force, 1992:1). DERP consists of three basic elements. The first element, the Installation Restoration Program (IRP) was established to identify, investigate, and clean up contamination at federal installations. Its primary purpose is to reduce public health risks by cleaning up hazardous wastes associated with past practices and to restore affected natural resources for future use. Approximately 94% of the $1.165 billion in fiscal year 1991 was used for the IRP (DoD, 1992:i) The second element consists of other hazardous waste operations. This program funds hazardous waste reduction initiatives to include equipment, costs for procedural changes, and research and development costs. It also may fund unexploded ordnance detection and range clearance operations. The third and final element is the building demolition and debris removal program. Under this program, unsafe buildings and structures can be torn down and removed. (Air Force, 1992:2)

CERCLA, as amended by SARA, and the Clean Water Act (CWA) both gave rise to the National Contingency Plan (NCP). The NCP was rewritten by the EPA under the authority of Executive Order 12580. The NCP provides implementing guidance and procedures the Air Force must follow to comply with CERCLA, SARA, and the CWA (EPA, 1990a:8813-14). Of particular interest, the NCP sets forth nine criteria for the selection of remedial alternatives:

1) Will the proposed alternatives adequately protect human health and the environment?

2) How well do the alternatives meet federal and state Applicable or Relevant and Appropriate Requirements (ARARs)?

3) What is the residual risk at the site after completion of the proposed remedial actions? This criterion assesses long-term effectiveness of the remedy.

4) Do the proposed alternatives permanently and significantly reduce the toxicity, mobility, or volume of the hazardous wastes?

5) How well do the actions address human health and environmental effects during implementation and until the cleanup objectives are met? This criterion addresses short-term effectiveness which compliments the long-term effectiveness assessed in the third criterion.

6) Can the alternatives be readily implemented? Are they technically feasible, administratively feasible, and will the necessary personnel and materials be available when required?

7) Are the alternatives cost-effective in relation to the other criteria?

8) Are the alternatives acceptable to the affected state?

9) Are the alternatives acceptable to the affected community, including the public, other groups, and other potentially responsible parties (PRPs)?

The NCP states that the lead agency (the Air Force on its installations) must balance the tradeoffs among the alternatives with respect to these nine criteria. The alternative that protects human health and the environment, complies with the ARARs, and best meets the other criteria is selected as the preferred alternative. (EPA, 1990a:8719-8724)

Aside from explicit legislation and regulations, EPA policy directives also provide insight on where cleanup priorities should be set. In a recent directive, OSWER noted that the top priority for Superfund is to reduce imminent risks, and that the site closure and deletion from the National Priorities List (NPL) is secondary to risk. Efficiency, effectiveness, and equitability were espoused by OSWER as its key principles. In the same directive, OSWER noted that federal facility enforcement was extremely important because of their program's high visibility, the interest shown by the public, the significant threats posed, the impact of base closings, and the magnitude of the resources needed to oversee their operations. Their goals with regard to federal sites are to improve efficiency through accelerated response, integrate the Resource Conservation and Recovery Act (RCRA) and CERCLA through federal facility agreements (FFAs), use innovative technologies and pollution prevention principles, comply with mandated time frames, and enhance oversight of base closure actions. (Office of Emergency and Remedial Response, 1992:I-1-2, 17-18)

In addition to the watchful eyes of the EPA and state agencies, SARA Section 120 includes a provision enabling private citizens to sue the government (EPA, 1988:II-6). SARA Section 310 states that these suits may be brought against a party or the responsible officials who violate a requirement or an order under Superfund. Furthermore, RCRA Section 7002 authorizes citizen suits to force appropriate actions addressing hazardous wastes when they pose a danger to human health or the environment (Lucero, 1989:81).

<u>Air Force Installation Restoration Program</u>. According to Mr. Gary Vest, the Air Force has approximately 4,000 contaminated sites in their program. To meet the Air Force Chief of Staff's goal of cleaning up those sites by the year 2000, the Air Force will need to spend between $650 million and $700 million a year. The sites that pose the greatest hazard to human health or the environment will be given first priority. (West, 1991:8)

To achieve these ambitious goals, the Air Force will need to carefully rank their projects to ensure the ones sent forward meet DoD objectives and can compete successfully with other services for cleanup funds. The competition will be fierce. DoD has approximately 18,741 sites that are expected to cost $25 billion to clean up (Hushon, 1993).

In addition to the year 2000 goal, the Air Force has established several other goals aimed at improving the program. First, the Air Force would like each installation to have a single contractor or service center managing their program. That contractor/center should then be challenged to reduce documentation and streamline procedures. Additionally, interim remedial actions should be used to the fullest extent possible, and cleanups should be performed in phases, when appropriate, to match the strengths of different remedial technologies to the various stages of contaminant removal. Finally, incentive-based contracting methods that are sensitive to schedules should be emphasized. (Air Force, 1992:8)

DoD's policies affecting the Air Force are similar to those found in the NCP. Specifically, DoD agencies are directed to:

1) Protect the health and welfare of installation personnel and the public by dealing with the contamination in a timely manner.

2) Comply with all applicable requirements for the program.

3) Keep regulatory agencies apprised of their activities and solicit appropriate comments on their plans. DoD will also negotiate FFAs with EPA and will follow the model FFA language where possible.

4) Encourage Defense and State Memoranda of Agreement (DSMOA) to expedite cleanup and reimburse states for their technical support at our sites.

5) Involve the public in DERP activities.

6) Take immediate actions to address imminent threats.

7) Have a bias towards remediation activities instead of studies.

8) Be required to clean up DoD property before transfer or sale.

9) Initiate waste minimization measures to prevent future restoration problems (although DERP funding is not likely to be available for these initiatives).

10) Comply with the memorandum of agreement with the Agency for Toxic Substances and Disease Registry (ATSDR).

11) Conduct research and development for innovative technologies. (Air Force, 1992:3-4)

These priorities are stated more succinctly in DoD's 1991 report to Congress. In this report, DoD states that it gives highest priority to sites that represent the greatest risk. Removal of imminent threats, interim and stabilization measures that prevent further deterioration and achieve life-cycle cost savings, and actions necessary to comply with SARA are also listed as priorities. (DoD, 1992:3)

The Deputy Assistant Secretary of Defense for the Environment has overall responsibility for managing DERP. His or her responsibilities include developing and defending the budget, providing policy and guidance, determining eligibility criteria and priorities, overseeing the program, and acting as liaison to outside agencies (Air Force, 1992:5). While new guidance may be forthcoming, the former Secretary, Mr. Baca, stressed the need for cleaning up sites quickly, streamlining the cleanup process to the extent the law allows, and developing standard procedures to deal with similar types of contamination. (Over 80% of DoD's wastes are petroleum and solvent products.) (Baca, 1992:51,52).

Many projects are eligible for the IRP, but only about 50% of those submitted are projected to be funded over the next several years (Myers, 1991). This percentage gets smaller as more projects are identified. Funding for the IRP is divided into three categories. Priority 1 projects are likely to be at least partially funded and include those projects which:

1) Eliminate or reduce human exposure to contamination. Two examples of this type project are providing alternate water supplies and removal actions.

2) Are time-critical. Projects which are needed to meet time-sensitive regulatory mandates and court orders would fall into this category.

3) Maintain compliance with legal obligations or official agreements. A project agreed to under an FFA would meet this criterion.

4) Maintain progress at proposed or listed National Priority List (NPL) sites. Operational support of a remediation system at an NPL site would qualify as a Priority 1 project.

Priority 1 projects requiring current year funds are further categorized as 1A projects, and those that could be funded in a subsequent fiscal year are denoted as priority 1B projects.

The second category for funding is designated Priority 2. Projects which help ensure adequate health protection and those which maintain IRP progress (as opposed to NPL progress) would be put into this category.

The last category, Priority 3 funded projects, are those that support generalized, high-potential research and development, improve environmental quality, or demonstrate environmental leadership. Under current funding projections, these projects are unlikely to receive any support. (Air Force, 1992:8-11)

The final criterion documented in the programming guidance to be used for ranking DERP project alternatives is the Defense Priority Model (DPM) score. DPM was developed as a prioritization tool, and a DPM score is required for most sites that are ready for remedial action. The score reflects the potential risk at a site and is a compilation of risks for all likely contaminant transport pathways and receptors (The Earth Technology Corporation, 1992:1). Sites that score high on the DPM are considered to be a greater threat to human health or the environment and are given funding priority. However, mission impact, community concerns, regulatory considerations, and other issues can cause the DPM to be overruled. (Air Force, 1992:16-17)

Restoration Methods. The selection of an appropriate remediation alternative is accomplished at the end of the feasibility study stage of the restoration process. The decision depends on the cleanup goals of the site, which, in turn, are based on the ARARs for the contaminants found at the site (Preslo, 1989:2-4). The geology of the site, the fate and transport of the contaminants, background contaminant levels, and the regulatory issues and concerns also influence the final decision (Long, 1992:9; Splitstone, 1991:90). A thorough knowledge of remediation alternatives and their relative feasibility and costs are essential to the selection of the appropriate technique (Preslo, 1989:2-4).

While a complete description of the wide range of remedial actions available to clean up a site is beyond the scope of this research, it is important to highlight several key characteristics which could influence the allocation of funds among the various alternatives. The characteristics of interest include relative costs, uncertainty, permanence, acceptability, and similar criteria.

To begin the discussion of potential means of remediating a site, it should be noted that the objective of the treatment can include: removing the hazard, blocking the pathway between the hazard and the potential receivers, relocating or isolating the receiver from the hazard, and/or otherwise blocking the potential for exposure to the hazard. Any or all of these objectives can be targeted in a treatment methodology.

Cleanup techniques are initially classified on the basis of the location of the treatment. In situ alternatives treat the contaminant in place, which can be either in the soil, the groundwater, or both (Preslo, 1989:1). Non-in situ treatments require excavation, extraction, or some physical process to remove the contaminant and the medium for further processing. The advantages to leaving the contaminant in place are the elimination of costs for moving the contaminant and the surrounding soil or water, reduced worker exposure to the contaminant, and the potential for more complete removal of the contaminant (Masters, 1991:260) Non-in situ methods have the potential of reducing the uncertainty of the process and can lead to faster cleanups.

Treatment technologies are also commonly categorized as being physical, chemical, biological, or thermal in nature. A fifth category, fixation/stabilization, is also sometimes recognized. Physical methods include gravity or mechanical separation, adsorption, phase change systems, or filtering. Chemical treatment changes the contaminant into a less hazardous substance through neutralization, oxidation, reduction, or precipitation. Biological methods are receiving a great deal of attention recently. They all have in common the use of microorganisms to degrade the contaminant. Thermal destruction is one of the preferred methods for treating hazardous wastes because of its permanence and speed. Finally, some wastes are immobilized through the fixation/stabilization process. (Masters, 1991:252-253)

Biological, chemical, and thermal processes all have the potential to destroy the toxicity of the contaminant. Bioreactors, bioremediation, composting, and land farming all can transform hazardous organic compounds into harmless cell matter, carbon dioxide, water, and various inert materials given the right environmental conditions (Long, 1992:24). These processes can also be combined with other physical or chemical processes to enhance the reliability or effectiveness of the overall treatment (Long, 1992:24). However, this technology has only been found to be effective for a limited number of contaminants in limited field applications (Fox, 1991:293-303).

Chemical treatment technologies are seldom used for Air Force remediation work. The costs can be high compared to other methods, and a high degree of control is required (Long, 1992:36-37).

Physical methods must be combined with other treatment technologies to achieve contaminant destruction. Air stripping, carbon adsorption, oil-water separation, soil vapor extraction, and soil washing are typical of the physical processes. Each of these methods frees or concentrates the waste of interest for further processing. (Long, 1992:18-23)

Given the legislative bias towards permanence and toxicity reduction, thermal treatment is the technology of choice for many contaminants. Incineration can completely detoxify a waste and is useful for concentrating those that it can't (Masters, 1991:261). Thermal desorption is typically employed in combination with a carbon adsorption exhaust filter to volatilize and capture hydrocarbon contaminants. It tends to be less expensive than incineration and easier to permit (Long, 1992:35-36).

Fixation and stabilization techniques may combine chemical and physical processes to eliminate the transport mechanism and thereby negate risk. Asphalt and concrete incorporation methods have been tried, but regulators are not convinced of the permanency of these treatment methods. Vitrification is also sometimes used to treat contaminants, but it is generally too expensive for most large scale applications.

While it is difficult to sort through the myriad of remediation alternatives, decision support systems are emerging to make the task easier. One such tool, the Remedial Action Cost Engineering and Requirements (RACER) system under development at the Air Force Civil Engineering Support Agency, will help ensure the best technologies are chosen and that they are accurately priced. The expert system component of RACER, the Remedial Action Assessment System (RAAS), is being designed to select among available remediation methods and combinations of methods given available site data. ARARs are built into the system database, and the outcome will be fully documented with the site data, the calculations used to determine the effectiveness of the alternatives, and a sensitivity analysis of the failure potentials. The parametric cost estimates provided by the system will help with budgets for all aspects of the remedial process, are used by the system for a life-cycle cost analysis of each alternative, and will provide a means to record historic costs. (Gregory, 1992:32-33) Another decision aid is the Air Force Center for Environmental Excellence (AFCEE) Remediation Matrix-Hierarchy of Preferred Alternatives. This matrix (Appendix B) ranks technologies in order of preference and is used to screen technologies for use at Air Force sites (Owendoff, 1993a).

Prioritization Modeling

According to Janssen, Nijkamp, and Voogd, a multicriteria environmental analysis should start with the problem definition. From there, it should proceed to identifying pertinent objectives or characteristics within the broad range of environmental criteria. Discriminating characteristics can then be established based on these objectives. Only after this prior step should an appropriate evaluation method or model for the DSS be chosen. Once the model is selected, one can evaluate the problem and test the model. (Janssen, 1985:1,2)

Decision Criteria and Models. Because of the multitude and complexities of discriminating criteria for this resource allocation problem, some means of achieving a weighted hierarchy of these criteria will be established in the research. The outcome should be supported by key DERP managers to instill confidence in the resulting model. The Delphi technique is one possible method for achieving these results.

The Delphi technique takes advantage of the benefits of group thinking while eliminating many of the disadvantages. The first step involves mailing questionnaires to key decision makers. Their responses are summarized, and the summaries are sent back with a request to reevaluate and comment on the summary. Several iterations of this process may be accomplished before the surveycr is satisfied that a consensus is reached. (Oxenfeldt, 1979:146)

It is important to distinguish between first-order and second-order selection criteria before finishing the Delphi survey. First-order criteria are those conditions that must be met. Second-order criteria should be met but aren't as critical. (Janssen, 1985:352-353) Oxenfeldt calls these ultimate and instrumental criteria. and he states that the criteria in each class can be either compatible or conflicting. When the criteria will be used to determine an allocation of limited resources (as in this research problem), Oxenfeldt notes the importance of establishing a ranking among the criteria. He cautions, however, that the ranking will vary depending on the circumstances and external influences prevailing at the time the priorities are set. (Oxenfeldt, 1979:185)

It is important to note that one of the primary reasons for developing a decision model is to force managers to be objective and obtain information that protects them from making decisions by impulse and emotion (Oxenfeldt, 1979:139). The success of the model will be measured by how well the Air Force achieves the stated objectives (Chankong and Haimes, 1983:8).

The Delphi technique, the surveys of experts, and MCDMs will be discussed in further detail in the methodology section (Chapter Three).

Risk as a Decision Parameter. The use of risk as a decision parameter is critical to meeting legislative mandates. As stated earlier, the main goals of CERCLA and DERP are to make sites cleaner and safer. Risk is the primary method used to measure the relative safety of a site. As the Science Advisory Board (SAB) notes:

> One tool that can help foster the evolution of an integrated and targeted national environmental policy is the concept of environmental risk. ... The concept of environmental risk, together with its related terminology and analytical methodologies, helps people discuss disparate environmental problems with a common language. It allows many environmental problems to be measured and compared in common terms, and it allows different risk reduction options to be evaluated from a common basis. Thus the concept of environmental risk

> can help the nation develop environmental policies in a consistent and systematic way. (EPA, 1990b:2)

In the same report, the SAB also recommended the EPA use risk reduction in setting priorities for environmental protection. (EPA, 1990b:16).

Risk, however, can have many interpretations depending upon its use and context. Additionally, the measurement of risk for use in remedial actions is fraught with uncertainty and controversy. (Chiras, 1991:327-328)

The technical definition of environmental risk is the probability of an adverse response to a specific dose over a specific period of time (Barill, 1991). This definition is based upon the knowledge that any substance has the potential to cause an adverse response, given that it is received in a large enough dose, or over a long enough period of time. A second definition used is the legal or regulatory definition. It states that risk is the potential to experience harm from a hazard, or the possibility of human exposure to a hazard (Barill, 1991).

We measure risk in terms of the probability of harm or exposure. Several factors give rise to this probabilistic nature of risk:

1) Variables are not known and cannot be predicted with certainty.

2) The science of risk is not fully understood.

3) The processes involved are probabilistic and their relationships are complex.

4) The uncertainty often depends on the perspective of the individual at risk. (Morgan, 1981:61)

In the following sections, the process for determining risk and specific factors that give rise to uncertainty are examined.

Risk Assessment. Environmental protection based on the concept of risk begins with the risk assessment. Risk assessment is the process by which the sources of hazards, the exposure routes, and the dose-response relationships are assessed and the risks are characterized (Cohrssen, 1989:7-8). This process is paramount to decision making and provides the information needed for assessing specific control options, setting priorities, allocating resources, and assessing damages for compensation purposes (Hattis and Smith, 1987:60).

The first step in a risk assessment is to determine the sources, amounts, and duration of exposures to toxic agents. For DERP work, the sources are a result of past hazardous waste disposal and spills. Several distinct sites may contribute to the overall risk, and each source may contain numerous hazardous chemicals. Depending on site specifics such as the geology of the site and the nature of the contaminant, the amount and duration of the exposure will vary.

Exposure, as used above, is the term for plant, animal, and human contact with harmful chemicals. For humans, the most common routes of exposure are ingestion and inhalation.

The primary media through which chemical exposures occur are air, water, soil, and dust. Pathways describe the means and media by which the exposures occur, and several pathways may be involved for each exposure. For instance, a chemical may be transmitted through air, deposited in soil, dissolved in water, absorbed by other plants or animals, etc. before a human is ever exposed.

Both the source and the exposure assessments introduce uncertainty in the overall risk assessment. The choices made regarding sampling locations and contaminants to sample, the randomness of climatic conditions, assumptions about the exposure pathways, and the heterogeneity of the site all can introduce uncertainty into the calculation of risk.

Another critical step in a risk assessment is the dose-response assessment to determine the relationship between the chemical exposure and the resulting response by the recipient of that chemical. The toxic agents at a site generally fall into one of three categories, each with a unique dose-response relationship. First are the fast poisons. These are chemicals which cause acute symptoms but do not persist. That is, if the toxin is ingested or otherwise taken into the body, it does not linger. Ingestion of fast poisons generally does not occur on a regular or ongoing basis. (Rodricks, 1992:49)

The second category is the slow poisons. Slow poisons are chemicals which are normally ingested over longer periods of time. They may either accumulate in the body, causing damage only after reaching a certain concentration, or they may be ingested on a regular basis, causing a small amount of damage with each event. In the latter case, the damage is not usually noticed until the process has gone on for quite some time. (Rodricks, 1992:66)

The third group of toxic agents is the mutagens, which include carcinogens and teratogens. Mutagens include the general class of chemicals which alter the genetic structure of affected cells in the subject. Carcinogens are chemicals which specifically cause cancer, and teratogens are chemicals which specifically cause birth defects (Masters, 1991:196). For substances that induce a carcinogenic response, it is generally (and conservatively) assumed that there is no 'no-effect' dose, meaning that any dose of the carcinogen will create some likelihood of cancer (Masters, 1991:201).

Using the dose-response data, it is possible to determine if there exists a threshold of toxicity for that chemical. In his book, Calculated Risks, J.V. Rodricks notes:

> If for every chemical in the environment we knew the range of 'no-effect' doses and the point at which toxicity begins to appear - the point at which the threshold of toxicity is passed - we could then act to

> prevent exposures from ever reaching the levels at which harmful doses are created. (Rodricks, 1992:158)

The uncertainty of the effects of the toxic agent in the dose-response relationship is often related to the length of the exposure period and the complexity of the damage mechanisms. The dose-response relationships of carcinogens involve the most uncertainty. Dose-response information is generally gathered through animal testing. Test animals are given extremely high doses of chemicals for extended periods of time in an attempt to accelerate the effects of exposure. These doses and exposure durations are then extrapolated back to obtain theoretical responses for lower levels of dosages and exposures in humans. The generalizability of these tests are the source of much controversy. There is no way to be certain that extrapolation back to the levels to which humans are likely to be exposed is valid. Even with extremely large numbers of animals in a bioassay, the lowest risks that can be calculated exceed the acceptable risk ranges mandated for humans by several orders of magnitude. (Masters, 1991:202)

Knowledge of the sources, the many exposure pathways, and the dose-response relationships are critical to risk characterization. Risk characterization is the analysis phase whereby an overall numerical estimate or probability of an individual being affected by some hazard is calculated, the uncertainty involved is characterized, and ways to reduce the risk are determined. (Cohrssen, 1989:84)

Risk characterization has also been described as assessing the worst-case impacts via a variety of conservative input assumptions and/or analytical techniques (Tusa, 1992:46). As a result, these assumptions frequently overstate the risks of hazards by a factor of 50 or more (Lave and Grunspecht, 1991:685). Given this uncertainty and the limitations inherent in the process, the risk estimates should be qualified with a description and discussion of the uncertainties and analytic assumptions (Cohrssen, 1989:84).

Risk Management. Risk management uses the information from a risk assessment in an attempt to reduce that risk. It describes the process whereby decisions are made about whether an assessed risk needs to be reduced and on the means that should be used to achieve the desired reduction (Rodricks, 1992:182). In addition to protecting human health, the risk management actions should be protective of the environment, be consistent with relevant laws and regulations, and consider social, economic, and political values (Ruckelshaus, 1985:25).

Risk reduction in the context of DERP refers to removal actions or remedial actions taken to 'clean up' a site, thereby lowering the potential for harm to the likely recipients. Completely eliminating a hazard is never cost feasible and is rarely technically feasible. The decision to be made is where to establish the trade-off between risk reduction, remediation cost, and other criteria. Current remediation decisions appear to be driven largely by cost, policy, ARARs, and subjective judgment rather than current or future risk levels. (Travis and Doty, 1989:1333)

Figure 1 shows a summary of the risk management process, given the information from the risk assessment procedures referred to previously.

Secondary Decision Criteria. In their report on risk assessment, Doty and Travis note that:

> Reducing public health risk involves not only defining risk, but also involves using risk assessment as a priority setting tool and defining risk reduction within the confines of the current state of technology and the resources available with which to address risk.

Here, Doty and Travis indicate that the risk assessment should be used in combination with several other criteria in setting priorities for risk reduction (Doty and Travis, 1990:2). Among those mentioned in the literature, cost-effectiveness, technical and contractual feasibility, innovation value, and community input appear to be the most important. The results of this research will determine how much weight each of these criteria is to be given in the resulting MCDM and if additional factors should be considered in the final decision model.

Cost. Cost-effectiveness was mentioned consistently in the legislation, implementing guidance, and DoD policy along with risk reduction as an important criterion for establishing priorities. The Superfund Handbook defines a cost-effective alternative as the method

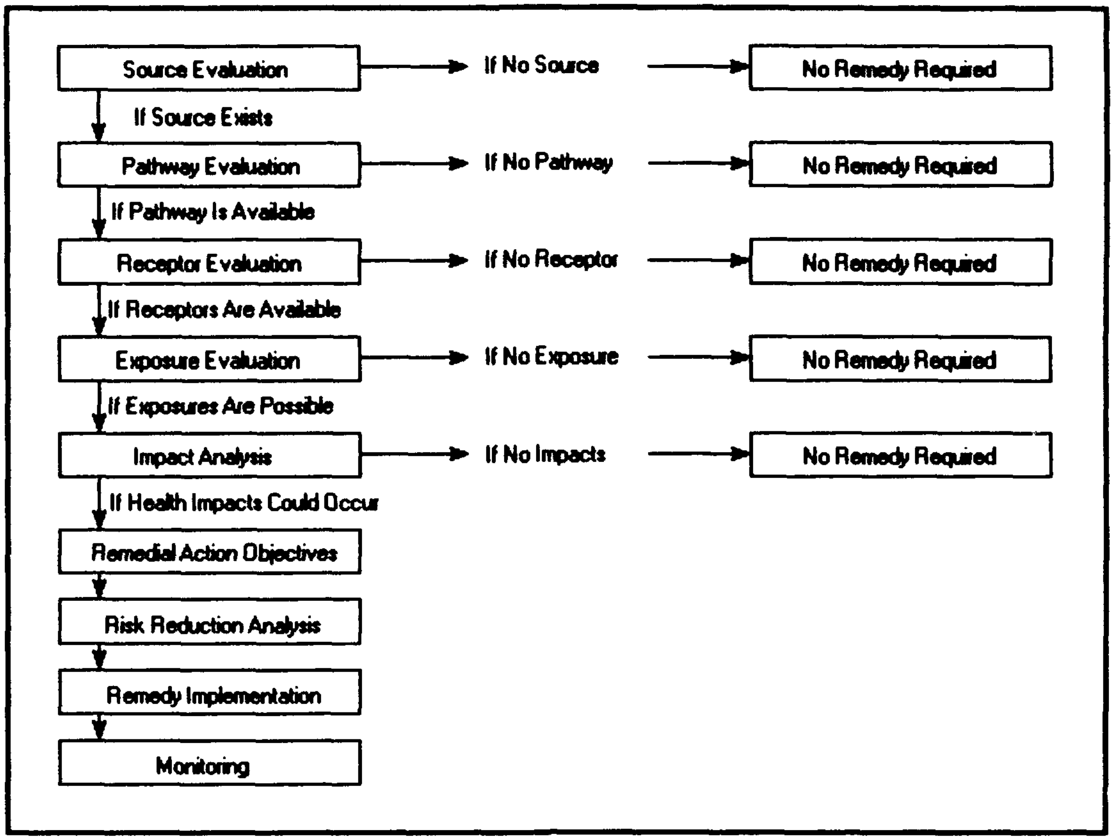

Figure 1. Risk Management Summary (Tusa, 1992:48).

identified as the best available in terms of reliability, permanence, and economics. It notes that the least expensive method is not necessarily the best alternative. (Lucero, 1989:5)

While selecting an alternative that meets the above definition would seem intuitive, an economic analysis should be accomplished to focus the manager's thinking, surface assumptions, and to document the methodology and evidence. Three basic principles should be followed in the analysis. First, all reasonable means of fulfilling the program objectives should be evaluated. Second, the alternatives should be analyzed in terms of their life-cycle funding implications and their life-cycle costs/benefits. Last, the time value of money must be considered. (Research and Education Association, 1982:3)

The steps to an economic analysis follow the standard problem-solving format. First, the objectives must be defined. Next, alternatives are generated and assumptions are listed. The costs and benefits of each alternative are then determined and compared so that a hierarchy can be established. Finally, because uncertainties exist, sensitivity analysis should be performed. (Research and Education Association, 1982:4-7)

The difficult step in this process is quantifying the costs and benefits. Since many of the costs and benefits in environmental problems are externalities and are not valued in the marketplace, little relevant data is available, and both are highly uncertain. Additionally, previous attempts at placing a value on public health and environmental improvements have been highly controversial. (Lave, 1991:682-683)

Feasibility. Preslo and his associates argue that both relative cost and feasibility influence the choice in an environmental problem. They further break the category of feasibility into core areas, which include both technical and implementational feasibility. (Preslo, 1989:2-4)

Technical feasibility addresses the effectiveness of the alternative given a wide range of variables. For example, soil chemistry, porosity, permeability, adsorption characteristics, and moisture content all can affect the suitability of the treatment methods for various contaminants. Site-specific climate conditions such as temperature, wind, humidity, and average precipitation also influence the effectiveness of the alternatives. (Preslo, 1989:20-23) Therefore, any decision model will have to consider the inherent uncertainties and site-specific needs of each alternative.

Implementation feasibility addresses the ability to design the alternative, to obtain the necessary equipment to install or operate the system, to treat and dispose of the wastes, and to monitor and obtain a regulatory permit for the system (Preslo, 1989:2-4). The Air Force also has to examine the procurement feasibility for first obtaining a flexible enough contract for environmental work and then retaining options on that contract.

Innovative Value. With the staggering cleanup costs facing the Nation today, and with the relative inexperience of the remediation industry, a great deal of emphasis is being placed on developing innovative technologies. These new technologies hold the promise of quicker, less expensive, more permanent treatment of the toxic waste problem, but at the same time introduce a great deal of uncertainty. While the potential for improvement is great, the value that should be placed on developing innovative technologies is difficult to quantify. In turn, the value that should be placed on this criterion in a prioritization model will also be difficult to determine.

Other Criteria. As noted in the previous discussions of objectives, several other criteria should be considered in the final MCDM. Possibilities include:

1) Public involvement in deciding the overall priority of a site. The public ultimately pays for the cleanup and are the ones exposed to the risk, therefore, their concerns should be represented in the MCDM.

2) Compliance with existing regulatory agreements and schedules. Base-level commitments were made to both the regulators and the affected public that should enter the decision. At the same time, the schedules agreed to were based more on technical feasibility than current economic realities.

3) Past execution history. In some cases, a large percentage of prior year funds have been obligated, but have not been spent (Owendoff, 1993a). Should more money be allocated to those projects before the prior year funds are expended?

4) The effectiveness in allocating past funds. This might be an important predictor of future performance. In a recent article, it was estimated that as much as 70-75 percent of the cost of cleaning up Department of Energy (DOE) sites is wasted. The average efficiency was thought to be in the range of 60-65 percent. Additionally, huge disparities existed in the price of services among various agencies that could not be accounted for by geographic or technological differences. Prioritizing projects based on past effectiveness could be an incentive to improve performance. (Pasternak, 1992:34-36)

Measuring these criteria for use in the MCDM and establishing a relative weight may prove difficult. One possibility would be to lump these kinds of criteria into a single metric and let the MAJCOMs determine their relative importance. MAJCOMs already rank their projects and submit to the Air Force only those that meet Air Staff standards, can successfully compete for funding, and are known to be important to the various Installation Commanders or the affected public. They also provide an important check on the validity of the installation's submission.

The benefits and shortcomings of using MAJCOM priorities is comparable to that placed on any group decision making. Some of the benefits of this type decision making might include a better consideration of the problem as a whole. Groups tend to consider more facets, have more background knowledge, and can reduce the probability of missing a key aspect of the problem. Additionally, allowing this input might instill a commitment on behalf of the participants in the program and the resulting decisions. Finally, the process could better facilitate the communication of both the decisions and the rationale for the decisions to impacted parties. (Kroenke, 1992:160-161)

Findings From Related Analyses

A number of other reports have been produced for the DoD, individual DoD services, and the EPA in the last three years which have addressed the issues involved in priority-setting with limited funding capability. The following sections give a brief overview of these publications.

The Keystone Report. The most recent report on priority-setting in the IRP, produced by The Keystone

Center, promulgates a set of recommendations for improving the federal priority-setting process. These recommendations include:

1) Improving the dissemination of Federal Facilities Environmental Restoration (FFER) related information,

2) Improving stakeholder involvement in key FFER decisions, with special emphasis on the use of site-specific advisory boards (SSABs), and

3) Improving consultation on FFER funding decisions and setting priorities in the event of funding shortfalls. (Keystone, 1993:v)

The Keystone report emphasizes improving the role of, and increasing the involvement of the affected public in the decision making process. The report delineates procedures for stakeholder involvement through SSABs, including determining when an SSAB is required, determining SSAB membership, and appropriate operating procedures for the SSAB. The report also proposes a list of the major functions of the SSAB, and the decision milestones in which the SSAB should be actively involved.

The basic recommendation of the Keystone Report is that a policy of 'fair share allocation' be adopted. This implies that if Congress appropriates only a fraction of the funding requirement of the FFER program, then all sites would share equally in the amount of the funding shortfall, thus receiving only a fraction of the requested funding. (Keystone, 1993:45) This policy would force prioritization of sites down to lower agencies who submit the funding requirements. However, the system could easily be 'gamed' by increasing the amount of funding requested for each site, thus defeating the intent and practicality of fair share allocation.

The recommendation of the Keystone report follows from their opinion of the insurmountable obstacles in developing a prioritization system. In their words:

> The Committee believes that: 1)existing data and science are currently inadequate to determine objective consensus clean-up priorities; 2)factors other than environmental and human health risk deserve consideration in allocating clean-up resources; 3)broadly acceptable and objective methods for evaluating some of the criteria relevant to the allocation of clean-up priorities do not currently exist, and, in some cases, may never exist and may even be inappropriate; and 4)regardless of any party's opinion about the quality of available data and science, it is appropriate in a democracy to allow a variety of affected interests to provide input on decisions that affect them. (Keystone, 1993:44)

The Coalition on Superfund Reports. In early 1992, two separate reports were presented to the Coalition on Superfund which address the emerging issue of Superfund priorities. The following sections briefly outline the details of these reports.

The Arthur D. Little Report. This report was subcontracted to the Center for Technology, Policy and Industrial Development at the Massachusetts Institute of Technology, and was presented in February 1992. It maintains that Superfund sites should be prioritized based upon two main criteria: the urgency of the clean-up and the availability of resources to address the problem. (Center for Tech..., 1992:6) These criteria are further broken down into the following eight specific system requirements:

1) The system must sort sites as they are encountered.

2) The system should not be wasteful.

3) The system should be able to differentiate technical feasibility among alternatives and sites.

4) The process should address sites in a timely manner to avoid significant worsening of site contamination.

5) The process should be flexible, to allow for re-ordering of priorities.

6) The system should have a means of deferring sites with low urgency.

7) The system should have a means of deferring sites where the effectiveness of remedial technologies is uncertain.

8) The system should include the option to stabilize a site to defer allocation of resources. (Center for Tech..., 1992:7)

The report presents six recommendations for the improvement of the existing Superfund site prioritization procedures:

1) Site Categorization. Analogous to operable units, sites with similar characteristics should be grouped together for prioritization.

2) Creation of a No Action, Monitor Pathway. Deferral of action until action is urgent.

3) Immediate Action/No Action, Monitor Pathway. Similar to recommendation 2, except the decision to monitor should follow an interim risk-reducing action.

4) Integration of Formal HRS Re-scoring into Recommendations 2 and 3. Sites are re-scored after the assessment and interim actions. Sites below the trigger level can be removed from NPL.

5) Creation of Recontrol and Monitor Pathway. Sites where remediation technologies are uncertain are stabilized and deferred until action is urgent.

6) Broadening of Removal Authority. An expanded set of removal actions should be allowed and should be reflected in formal HRS scoring, thereby avoiding the need for inclusion on the NPL. (Center for Tech..., 1992:2)

While the emphasis of this report is clearly on prioritizing sites, it does not present a working decision support system. The six recommendations for modification of the Superfund regulatory framework will allow greater flexibility for allocation of resources to sites with greater urgency, but they do not offer much guidance in selection of those sites whose urgency has been established.

The Putnam, Hayes, and Bartlett Report. This report was presented to the Coalition on Superfund in March 1992. It emphasizes the prioritization of individual actions within sites but does not necessarily emphasize prioritizing the sites themselves. (Putnam, et al, 1992:2) The report approached the problem from the perspective that certain actions at a site will achieve greater risk reduction at lower cost than other actions. Therefore, the individual actions within the site should be prioritized to achieve the greatest cost/benefit efficiency.

The report suggests three separate components be incorporated into the Superfund prioritization approach:

1) Identification of early actions which may be taken at sites that are quick and could significantly reduce risk at a relatively low cost.

2) Identification of possible alternative site 'destinations', such as innovative remedial technologies or special 'categorical' studies.

3) Use of a prioritization scheme after the signing of the ROD which will identify and prioritize actions similar to the early actions of the first suggestion. (Putnam, et al, 1992:2-4)

The emphasis of this report is on identifying those actions within a Superfund site which can most efficiently reduce risk at the lowest cost. The report does not clearly identify whether, or how, these actions should be prioritized across sites. Therefore, it does not contribute to the problem of first deciding which sites to address under the constraint of a limited budget.

The Applied Decision Analysis (ADA) Report. The ADA report was presented to the DoD in 1990, and outlines three conceptual priority systems. These systems are:

1) A site ranking system which ranks DoD sites according to urgency of remediation,

2) A project prioritization system which ranks projects according to the estimated benefit they would produce per dollar spent, and

3) A 'marginal analysis' funding allocation system which distributes funds among Services and installations in the order of greatest marginal benefits. (ADA, 1990:2-6)

To date, none of these suggestions have been explored further or implemented. The approach taken by ADA does not lend itself to widespread use across organizations, mainly because there has been no consensus on what the system objectives should be. Disagreements precluding the use of these systems have arisen over 1) the basic unit of prioritization (e.g., ranking sites vs. projects vs. actions vs. requirements), 2) the inclusion of all program activities vs. some subset of program activities, and 3) the basis for decisions (e.g., risk-based decisions) (Reed, 1993:1). Also, "[the various] Services do not want to be locked into a decision support system - they want to retain ultimate flexibility in allocating resources" (Reed, 1993:1).

Clearly, the interest in this issue indicates that it has widespread impacts and applications for a variety of organizations. However, to date, no particular approach to resource allocation or site prioritization has had wide acceptance either within its target organization, or across organizations.

Conclusion

The Air Force and other branches of the Department of Defense are required by legislation such as CERCLA and SARA to accomplish the remediation of hazardous waste sites. Prioritizing the remedial investigations, designs, and actions for the 4,000 Air Force hazardous waste sites currently listed in the DERP program is a monumental task.

Among the issues which must be considered while ranking the projects are the legislative and regulatory objectives, DoD program objectives, the remediation methods chosen, and the risk at each site. Possible decision variables include risk reduction, cost, feasibility, innovative value, and a host of other criteria. The decision on which of these criteria to include in the final MCDM and their relative weights will depend on the outcome of the surveys.

A valid decision model will account for all those factors that are judged to be pertinent. Additionally, it will enable the Air Force to demonstrate its objectivity, consistency, and stewardship in complying with this important program to protect human health and the environment.

III. Methodology

This chapter outlines the procedures used in developing a multicriteria decision model (MCDM) for use in an Air Force decision support system (DSS) to establish a funding hierarchy among Defense Environmental Restoration Program (DERP) projects. Given the nature of the problem and the time constraints for the research, two procedures were simultaneously employed. Each procedure was based on different assumptions and designed to accomplish a specific objective.

Background

As the literature review suggests, there are numerous conflicting opinions on the criteria to be used for deciding Installation Restoration Program (IRP) priorities and on which criterion is most important. The various authors have either voiced their opinions, often with excellent arguments, without establishing a specific prioritization method or metrics for their criteria, or have stopped short of completing their models because of a lack of consensus among the stakeholders.

In contrast to the earlier work, the motivation for this research fits the category Morgan termed 'substance-focused' motivation. It is intended to not only develop further insight and understanding into the problem for both the decision maker and other interested stakeholders, but more importantly, its focus is on answering a formulated policy question. (Morgan, 1990:34)

The resulting decision model is intended to be a 'first step', or as Clark puts it, an 'adaptive design'. The problem is complex and varies from one context to the next; therefore, it will be extremely difficult to solve it precisely. Instead, the goal will be to seek an adaptive solution that can be improved as more information is obtained. (Morgan, 1990:28)

Rationale For Two Models

The process of choosing the best research method to develop this 'adaptive design' presented a difficult challenge. Several studies have shown, and the literature review confirmed, that the stakeholders often can't agree on the problem to be solved (e.g., prioritizing sites according to risk or projects according to cost-benefit), the objectives for the research (e.g., difficulty in establishing a consensus on the goals of Superfund and choosing metrics that will be useful for a DSS), the past and future states of the environment (e.g., how clean is clean), or even the consequences of alternative courses of actions (e.g., does a particular technology even work). This leads to different stakeholders solving different problems, and in particular, a difficulty in analyzing data generated at different levels of management. (Vari, 1986:317)

These same difficulties led Goldstein to conclude, as paraphrased by Morgan:

> The process of choosing decision criteria and policy strategies may not involve a single decision and may not precede all analysis. Until a problem has been subjected to some analysis, one may not understand it well enough to make reasonable choices. Indeed, even while different parties are arguing that a problem should be framed in terms of different decision criteria and policy strategies, it is sometimes possible to perform an analysis that can accommodate and allow a comparison among these alternatives. (Morgan, 1990:29)

Given these insightful comments, it was decided the research should not look for an 'ideal' methodology but instead should utilize the strengths of two common strategies and compare the results. Both are briefly described below and are discussed in detail in the following sections.

The first procedure chosen, the Delphi procedure, was chosen to overcome the stakeholder agreement dilemma. It was used to solicit the opinions of several DERP and CERCLA experts at an operational decision making level to determine what criteria should be employed in the DSS and the relative importance to be assigned to each of those criteria. While the Delphi method is very useful for gathering the decision criteria, and by increasing the number of people in the procedure the range of ideas generated increases, the analysis can become unwieldy (Saaty, 1982:234). In fact, designing a methodology for analytically determining the group utility function for many experts often cannot be done (Chan, 1993:65). Therefore, a simple additive weighting (SAW) multicriteria decision model (MCDM) was pre-selected for the resulting DSS, and the experts were asked to subjectively determine the weights to be assigned to each criterion. As Hwang notes,

> ...theory, simulation computations, and experience all suggest that simple additive weighting yields extremely close approximations to very much more complicated nonlinear forms, while remaining far easier to use and understand. (Hwang, 1981:103)

More will be said about the implications of this design in Chapter 4.

The objective of the second procedure was to use the strengths of multiattribute utility theory (MAUT) in a questionnaire format to determine an MCDM. To simplify this procedure, the utility function of one decision maker, the head of the Air Force Environmental Restoration Division, Colonel James Owendoff, was examined. (It should be noted that Col. Owendoff worked very closely with his DPM expert, Mr. Scott Edwards, in responding to the questionnaire. Additionally, Mr. Edwards provided responses to some of the follow-on interview questions.) Unlike the Delphi technique, pre-selected decision criteria were used in the questionnaire. The criteria were chosen on the basis of the literature review and a pre-questionnaire interview with Col. Owendoff. While this method does not inherently build stakeholder support for the findings or take advantage of the power of group decision making for criterion selection as in the Delphi technique, it also doesn't suffer from having to assume a form of MCDM. Instead, the results of the questionnaire were used to determine the form of model for the resulting DSS.

Delphi Procedure

This section outlines the methodology to be used in association with the Delphi method for eliciting the opinions of experts. Creating a DSS using this approach requires the completion of two phases. The first phase is the determination of the criteria relevant to the prioritization of IRP sites. The second phase is the development of a model which incorporates the preference structure of the group, and which will bring each of the criteria into a common scale, called utility.

Phase One - Determining Criteria. The determination of discriminating criteria comprises the bulk of the data collection of this portion of the research and consists of several steps:

1) Defining the population of interest,

2) Selecting a manageable-sized sample from this population which represents the interests of the entire population,

3) Developing an appropriate data gathering instrument,

4) Testing the data gathering instrument, and

5) Collecting data using the data gathering instrument. These steps are specifically addressed in the following sections.

Population of Interest. The population of interest for this research consists of all stakeholders involved in the restoration of contaminated military sites, including the Department of Defense (DoD), Congress, the Environmental Protection Agency (EPA), individual state regulators, and the affected public. This population determines the size of the DoD budget, sets priorities, and ultimately judges DoD's efforts in meeting their objectives.

Sample Selection. Since a survey of the entire population is not feasible, a sample of the population must be taken. Initially, a judgment (non-probability, purposive) sample composed of approximately eight to ten DoD Installation Restoration Program (IRP) experts will be selected. Other experts in IRP and CERCLA management, including experts from the EPA and civilian universities, will be identified using a 'snowball' selection method, and will be encouraged to participate. This research will include the opinions of other stakeholders because these individuals and organizations are heavily involved in, and have significant influence over, the IRP prioritization process.

Due to this relatively small sample size, each selected individual has the potential of greatly affecting the results of the data collection process, and thus the confidence in the resulting MCDM. Therefore, respondents will be selected on the basis of their position and experience as IRP or CERCLA managers, researchers, or regulators. While a judgment sample has the potential of being biased, other segments of the population generally do not have the background knowledge required to provide the type of input requested in this process. Instead, the general population frequently looks to regulatory agencies to decipher the technical issues associated with the IRP. Additionally, state regulators and Congressional members have more localized interests which may bias the survey with factors representative of the sites within their jurisdiction. For these reasons, the selected body of experts will be relied upon to represent the current paradigm for environmental restoration within the DoD.

Development of the Data Gathering Instrument. For this phase of the research, the objective of the data collection process is to gather data which is amenable for use as input data in a simple additive weighting (SAW) MCDM. The process of resolving the investigative questions (presented in Chapter One) will produce the necessary data to construct this model.

The Delphi procedure was chosen as the best means to answer the investigative questions. The Delphi is a heuristic for the gathering of group opinions and is particularly well suited for eliciting the opinions of experts (Brown, 1968:3). The iterative nature of the Delphi technique has several advantages for data collection over other standard questionnaire surveys. The Delphi technique takes advantage of the benefits of group thinking, such as brainstorming and idea construction, as well as providing capacity to clarify both questions and responses in order to reach a consensus among participants. Simultaneously, by avoiding face-to-face discussion, the technique eliminates the drawbacks of group thinking, such as domination by a particular individual, extraneous noise, reluctance to change a publicly stated opinion, compromise, and the desire to conform to majority opinion. (Brown, 1968:2; Dalkey, 1967:3; Dalkey, 1969:14)

The Delphi technique consists of three basic features which are intended to increase validity and reliability.

> In general, Delphi procedures have three features: (1) anonymity, (2) controlled feedback, and (3) statistical group response. Anonymity, effected by the use of questionnaires or other formal communication channels, such as on-line computer communication, is a way of reducing the effect of dominant individuals. Controlled feedback - conducting the exercise in a sequence of rounds between which a summary of the results of the previous round are communicated to the participants - is a device for reducing noise. Use of statistical definition of the response is a way of reducing group pressure for conformity...(Dalkey, 1969:16)

Use of the Delphi technique with groups of experts has been shown to provide reliable results to the extent that results tend to be reproducible (Dalkey, 1969:12). This is especially true when the goal of the process is to determine a numerical estimate of the median value of individual estimates, even though individual estimates may exhibit considerable variance (Dalkey, 1967:3; Dalkey, 1969:10).

Testing the Data Gathering Instrument. While a Delphi questionnaire primarily consists of open-ended questions, some criteria discovered in the background research will be included in the questionnaire to help clarify its intent. This should also reduce the number of iterations required to identify and give weight to all the discriminating criteria and allow more time for reaching a consensus. Any biases introduced by providing potential responses will be minimized by allowing respondents to strike out any suggested criteria they feel are inappropriate. Prior to sending the questionnaires, each iteration of the Delphi will be presented to members of the faculty to ensure that the intent of each question is understandable and elicits the appropriate type of response.

Collection of Data. The Delphi technique will be performed by sending questionnaires to the selected experts, gathering and summarizing responses, providing feedback to participants, and performing subsequent iterations consisting of either refined questions or new questions which may evolve as a result of observations from previous iterations, or a combination of both. A maximum of three iterations will be used to accomplish the objectives of this portion of the research. If further information is required, in the interests of time, a face-to-face group discussion may be held at The Air Force Institute of Technology (AFIT) to finalize the results.

In performing the multiple iterations of the Delphi technique, some data analysis is inherently performed. This occurs as a result of compiling responses and revising questions for the subsequent round of questioning. Therefore, upon completion of the Delphi, very little manipulation of the data will be required to construct the simple additive weighting decision support model.

Phase Two - Model Development. This phase of the research is concerned with the development of a decision support model commensurate with the level of data elicited from the experts. This will be accomplished by first determining the preference structure of the experts involved in Phase One which will indicate a utility function for each criterion. Combining the utility functions of the criteria with the weighting factors also determined in Phase One will produce the decision support model. These topics are described more fully in the following sections. Also, a discussion of how this model will be evaluated will be presented following the MAUT methodology.

Determination of Preference Structure and Utility Functions. Preference structure refers to the set of rules which govern the processing of discriminating criteria within a model. The preference structure brings each of the criteria into a common scale called utility. For this portion of the research, the determination of the group preference structure will consist of sending out a round of questions in a final iteration of the Delphi technique. This iteration will have the experts specifically identify how they value each criterion within the range of possible values. The responses to these questions will be used to arrive at a median utility function for each criterion. The utility function can be depicted as a graph showing how the experts' utility decreases as conditions favoring prioritization decrease.

Development of a Decision Support Model. As mentioned previously, this portion of the research assumed preferential independence of the criteria Therefore, a simple additive weighting model is applicable as a means of analyzing and comparing the criteria and prioritizing the projects (Chan, 1993:33). The IRP projects will be scored with a value function that is in the form:

$$\text{Project Score} = \sum w_i v_i(y_i) \qquad (1)$$

Where w_i represents the weighting factor for criterion i, and $v_i(y_i)$ represents the criterion-specific utility for the value y_i (Chan, 1993:33). The utility term can be simplified to u_i yielding the form:

$$\text{Project Score} = \sum w_i u_i \tag{2}$$

The weighting factor will be transformed to a scale of 0 to 1, where the sum of the weighting factors equals 1. The utility factors will remain essentially unchanged from the form which is returned by the Delphi participants, and will be on a scale of 0 to 100. Therefore, the final score for any project to be evaluated will be on the scale of 0 to 100. This should facilitate ease of use and understanding for this model because it brings the values of several criteria into a common scale, it relates the project score on a scale which is familiar, and it promotes the ability to distinguish trends in the data.

While this method of obtaining weights is straightforward and simplifies the computations, it forces the experts to simultaneously analyze the relationships of many variables This weakness is analogous to rank ordering a group of items from heaviest to lightest without a scale. It is very difficult to correctly order them by picking up each item and assigning them a weight. It is much easier to pick up two items and do a pairwise comparison, continuing this process until all pairs have been assessed. The MAUT procedure overcomes this weakness. (Saaty, 1980:6, 33)

MAUT Procedure

MAUT has recently found favor among researchers for its ability to enhance decision making. As Saaty notes, the process helps decision makers organize their thought patterns and reach conclusions. It allows us to simplify and structure a system into its interacting components, and to synthesize the components by measuring and ranking their impact on the decision at hand. Furthermore, MAUT is capable of converting qualitative data into a quantitative measures that permit comparisons and evaluations. (Saaty, 1982:2-6, 202)

There are four basic steps to any decision analysis problem. The first step involves structuring the problem, or the identification of goals and criteria. Next is the model formulation step. The third step is eliciting the relationships and values of the criteria from the decision makers or experts, and last is the evaluation of the resulting model. (Barron and Kleinmuntz, 1986:291)

Problem Structure. The first task in MAUT policy analysis is to identify the goals/objectives and criteria to use. Morgan identifies three distinct types of objectives for use in risk management policy analysis. They are:

1) Utility-based objectives which all involve decisions based on the valuation of outcomes. This category includes cost-benefit, cost-effectiveness, maximum utility, and the like.

2) Rights-based objectives which are less concerned with the outcome as they are with the process or allowed

activities. Zero risk, compensation for risk, and constrained risk are examples of rights-based objectives.

3) Technology-based objectives which are frequently used in environmental regulations. An example of this objective is reducing risk to the extent the best available technology allows. (Morgan, 1990:25-28)

A utility-based objective best fits this research problem. Briefly restated, the objective is to maximize the utility associated with important project attributes given the fiscal constraints imposed by the Defense Environmental Restoration Account (DERA) budget.

The decision one makes as to what criteria to include in the problem and which to leave out is among the most important and difficult decisions to be made in quantitative policy analysis (Morgan and Henrion, 1990:31). As the literature review demonstrated, there are a host of relevant criteria and little agreement on which to employ in a model. There are, however, several good reasons for limiting the number of criteria in the model. First of all, for every criterion used, a metric has to be developed which will apply to the wide spectrum of projects that make up the IRP (studies, management, design, construction, monitoring, research and development, etc.) The choice of the metric itself can be controversial and may detract from the model's credibility or the utility associated with a given criterion. Secondly, the difficulty of maintaining independence among the criteria is proportionate to the number of criteria. The lack of independence leads to a highly complex modeling task (Chan, 1993:40). The decision maker will have difficulty assessing his or her utility for a variable in the presence of many possible compensatory or noncompensatory variables, and the analyst will have more difficulty designing the questionnaire and computing the results to elicit the factors and weights associated with that utility. Finally, the documentation that will have to be submitted with each project and analyzed by the decision maker will also increase proportionately with the number of criteria chosen. Since the Air Force has over 4,000 sites, this could be a significant factor in the usefulness of the resulting DSS.

With these difficulties in mind, it was decided that the possible criteria identified earlier should be collapsed into three or four criteria that would be used in the final MCDM. The final criteria should be widely mentioned in the literature. Additionally, similar criteria should be combined so as to maintain independence among the criteria. Finally, a semi-structured interview with Col. Owendoff was employed to elicit the decision maker's preferences for variables and metrics before the design of the questionnaire. A copy of the interview guide and responses can be found at Appendix C. The description of the final criteria selected and the metrics chosen to represent them follow.

Site risk. This criterion was identified by Col. Owendoff as an important consideration, was mentioned in most of the previous studies, is a statutory consideration, and is also emphasized in Air Force regulations and guidance. A project associated with a high risk site is assumed to be strongly correlated with protection of human health and the environment, risk reduction, and reduced future liability.

Site risk will be measured using a DPM score. The DPM was developed to assist DoD in prioritizing sites and is a reflection of the overall risk at the site. While a reduction in risk, as examined by Edwards in 1992, is perhaps a better metric for projects like removal actions and remedial actions, other categories of projects have no potential to reduce risk. Therefore, the site risk represented by the DPM score will be used for all projects.

Major Command (MAJCOM) priority. This measure is an attempt to combine several subjective criteria mentioned in the literature while recognizing the difficulty of establishing a meaningful, quantitative measure to those criteria. Furthermore, Col. Owendoff indicated that the MAJCOMs are frequently the true decision makers in that they must allocate the funds provided by higher headquarters to the projects under their jurisdiction they feel are most deserving. He also noted that the MAJCOMs are closer to the operating level and have a better grasp of the site demands.

To implement this criterion, MAJCOMs with 50 or more sites would be asked to rank the projects submitted each fiscal year on the basis of the urgency of the requirement (whether or not it is required in the current fiscal year by statute, agreement, or as a result of other pending actions like new construction on the site), the feasibility of the technology to be employed, the political sensitivity of the site, compliance with established planning documents and concurrence of the technical review committee and affected public, environmental equity (site goals are commensurate with other sites), and overall compliance with Air Force goals (10% of the sites closed each year, 60% of the funds spent on remedial actions, and complete all sites by the year 2000).

The MAJCOM priority will be converted into a value ranging from zero to one with the following equation:

$$\text{Value} = 1 - [\text{priority} \,/\, \text{total number of projects}] \quad (3)$$

A MAJCOM's highest priority project will have a value almost equal to one. The lowest priority project will have a value of zero. Smaller MAJCOMs and other activities with fewer than 50 sites could have their projects evaluated and prioritized by a committee from the Air Force Center for Environmental Excellence (AFCEE) to make the overall ratios commensurate with the larger MAJCOMs. AFCEE has a good understanding of overall Air Force requirements and provides technical support to many of the smaller commands. Since this process establishes a zero to one scale and establishes mid-management's utility for the projects, the questionnaire will only be used to determine the decision maker's preference for the weight to given to this criterion in the overall utility function.

Cost. The need for a prioritization model is predicated on an overall funding shortfall. The literature consistently cited cost effectiveness as an important factor to the resulting decision, and several studies used cost-benefit ratios to prioritize the alternatives. This model will not seek to optimize the ranking of projects by using costs in this manner since cost-benefit ratios implicitly assume linear utility functions with ratio-level data. One possible problem with this assumption concerns the magnitude of the potential disparity between the highest cost project and the lowest. This difference could reduce the discriminatory power for low and moderate cost projects (e.g., if the most expensive project cost $10 million and the scale was based on total cost divided by the most expensive project, all projects under $1 million would be scaled between 0.9 and 1.0). Another problem would be created if the measurement of benefits were not represented on an interval scale. Without an interval scale, division by a scalar such as cost changes the ratio of two measurements (Chankong, 1983:30) and renders utility functions meaningless. Furthermore, cost-benefit ratios overlook other possible covariance relationships among the criteria. Therefore, a cost-benefit ratio will not be assumed. Instead, the relationship to other criteria in the overall value function, its relative weight in that relationship, and the univariate utility function for project costs will be determined from the decision maker's responses to the questionnaire.

Model Formulation. There are many types of decision models which can be used to solve problems composed of multiple criteria or attributes. The class of model chosen depends mainly upon the type and structure of data available for use, as shown in Figure 2. The choices of models may generally be separated into the two categories of noncompensatory models and compensatory models.

Noncompensatory models are MCDMs which do not allow for trade-offs between criteria. This means that a deficient value in one attribute cannot be compensated by an abundance in another attribute. Scores are calculated on an attribute-by-attribute basis. Models in this category are dominance, maximin, maximax, conjunctive constraint method, disjunctive constraint method, and lexicographic ordering. (Schooff, 1990:22) The questionnaire results will determine if a noncompensatory model is appropriate; however, given the nature of the criteria, this result is unlikely.

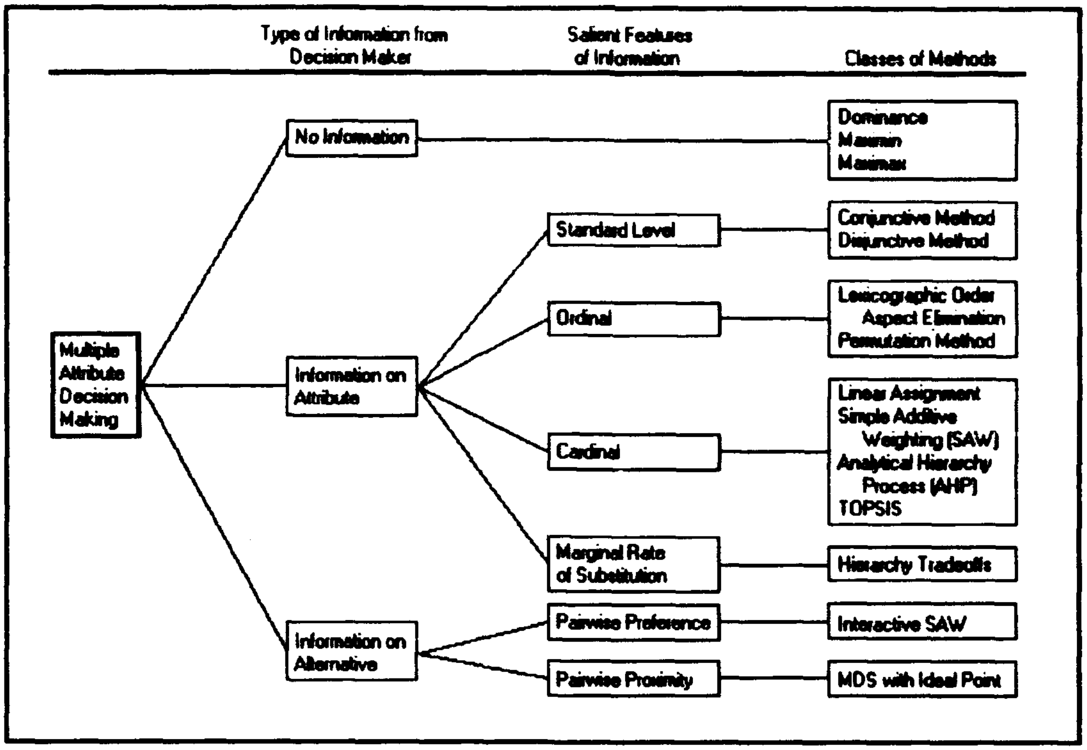

Figure 2. A Taxonomy of Multi-Attribute Decision Making Methods (Hwang, 1981:6).

Compensatory models are MCDMs which permit trade-offs between criteria, or stated differently, changes in one attribute can be offset by changes in other attributes (Hwang, 1981:25). This type of decision model requires that a preference structure be determined by the decision maker. Typically, this is done by assigning a set of weights to criteria through pairwise comparisons.

Compensatory models are further divided into three sub-categories:

1) Scoring models. These models select alternatives on the basis of highest score. This requires a well defined preference structure which assigns values to each criterion and tallies them for a final score. Models in this sub-

category include simple additive weighting (SAW), analytical hierarchy process (AHP), and interactive simple additive weighting.

2) Compromising models. These models select alternatives based upon their distance from some ideal score. This approach is referred to as goal setting (Chan, 1991:13). This sub-category includes the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) model.

3) Concordance models. These models arrange a set of preferences which best satisfy a given concordance measure (Schooff, 1990:23). Models in this sub-category include permutation method and linear assignment method.

The outcome of the questionnaire will determine the exact model used; however, based on the objectives of the research and the criteria chosen for inclusion in the model, it is anticipated that the class of MCDM selected will be in the compensatory category, and further, that the model will be a scoring model such as SAW or AHP.

Eliciting Relationships and Values. Once the criteria of interest have been determined, the research task focuses on the value-function measurement task. This five step process has been described by Zelany as follows:

1) Familiarize the decision maker with the concepts and techniques of the process.

2) Identify the form of the utility function. This step involves determining preferential independence (the trade-off between two variables is not affected by a third variable) and mutual utility independence (the relative utility of a variable remains the same regardless of other variables) of the criteria. An additive value function requires preferential independence, whereas both types of independence are required for multiplicative models.

3) Measure the component value functions. This step requires utility calculations on each criteria independent of the other criteria.

4) Determine the scaling factors and relative weights to be applied to the criteria. The scaling factors allows all the criteria to be represented on a scale of zero to one so that one criterion does not dominate another simply on the basis of the representative metric. The relative weights are indicative of the importance of each criterion on the overall score.

5) Validate the model against observed rankings. This step will be described in the next section as part of the evaluation of results. (Chan, 1993:32,40-44)

The pre-questionnaire administered to Col. Owendoff accomplished step one of this five-step process. The data for the remaining analysis was collected via the research questionnaire (shown with responses) found at Appendix D. Section A, questions 1-6 of the questionnaire were designed to test for both preferential independence and the weights associated with each of the criteria. Section B, questions 7-9 tested for mutual utility independence. The next three questions, Section C, were designed to elicit the certainty equivalents for several ranges of DPM scores and costs so that a utility function could be determined for each. Section D provided a check on the responses to Section A by gathering additional data required for determination of the consistency of the weights associated with each of the three criteria. Finally, Section E was added as a check on the questionnaire. The results of the analysis can be compared to the answers provided for question 15 to determine if they make sense. Question 16 is a check on the validity of the criteria used for the model, and question 17 was an attempt to verify the assumption that the projects being ranked by the model should be treated as discrete units rather than continuous variables. If the decision maker believes project managers have great flexibility in scaling back their projects, then the assumption that the projects should be treated as discrete units (all or none) may not hold. Continuous variables can be subjected to much more rigorous analytical methods involving marginal analysis, optimization, and the like.

Evaluation of Delphi and MAUT Results

As Morgan and Henrion appropriately noted, policy analysis models often are difficult or impossible to empirically validate (1990:18). The prioritization problem which this research is trying to overcome is a recent phenomenon and existing models are not available for comparison of results. Also, because current decisions are made on the basis of a 'fair share allocation', a prioritized listing of actual projects is not available. Furthermore, many of the criteria used in the DSS are not submitted with the project documentation currently needed for validation and approval.

These problems were not unexpected, and part of the justification for two research methodologies lay in providing a means of comparison of results. As a method of evaluation, the output of the two models will be compared. For the purposes of this research, a set of actual IRP projects will be used to compare model rankings. Where data gaps exist, information will be assumed from the information available, and possibly gathered from IRP managers familiar with the individual projects. A comparison of the resultant rankings will give an indication of the validity of the two prioritization methods.

Summary

This chapter has presented the proposed methodologies for this research. The processes of determination of the discriminating criteria and development of appropriate MCDMs are anticipated to result in a much needed decision support system. Data collection results and analyses performed under this research, as well as concluding statements will be presented in the subsequent chapters.

IV. Results and Analysis

The results of the methodology employed in Chapter 3 are documented in this chapter of the research. The Delphi results are presented separately from the multiattribute utility theory (MAUT) results. This chapter is concluded with a comparison of the two procedures.

Analysis of Data from the Delphi Procedure

The research performed in association with the Delphi procedure consisted of three rounds of questionnaires. Each round was sent to a group of experts with experience in prioritizing DERP projects or CERCLA management. The first two rounds established the criteria the experts felt to be pertinent to the prioritization of DERP projects and the weights associated with those criteria. The third round of the Delphi established a preference structure for values within each of the criteria. Using these criteria, weighting factors, and preference structures, a decision support model will be used to assign scores to DERP projects for comparison and prioritization. The results and analysis of data from each round of the Delphi procedure, the subsequent construction of the decision support model, and the results of testing the model will be discussed more fully in the following sections.

Delphi Round One. This portion of the Delphi procedure consisted of identifying a group of experts to be used as a sample of the population of interest and familiarizing these experts with the goals of the research, collecting first-round data identifying the criteria which these experts felt were important in prioritizing IRP projects, and summarizing the individual data collected from the first questionnaire for use in the second round.

Identifying Experts for Use in the Delphi Analysis. As indicated previously, the population from which a sample will be selected for this research consists of DERP and CERCLA experts familiar with the problems of prioritizing DERP projects. A list of Air Force MAJCOM-level DERP experts, and others with knowledge in the DERP process, was provided by Captain Rob Wilson, an instructor at AFIT/DE, who has had the opportunity to work with these individuals for the purposes of education and dissemination of information on recent DERP issues. Prior to sending out the first questionnaire, each expert was contacted and given a general background of the research, and the objectives of the Delphi procedure. Attempts were made to contact each of the MAJCOM-level experts identified by Captain Wilson.

From the list, eight experts agreed to participate in the study. The list of names provided by Captain Wilson is included at Appendix E. Two additional respondents from non-Air Force institutions were also identified and included in this round of the Delphi procedure. These individuals have expertise in other aspects of DERP and CERCLA, and do not necessarily have the same priorities as the Air Force or DoD. They were included in an attempt to incorporate a wider perspective on the DERP prioritization process and to represent the many non-Air Force and non-DoD factions which have influence in this process.

Collecting First Round Data. In order to minimize the number of iterations required to elicit usable data from the experts, and to further clarify the intent of the questionnaire, the first round of the Delphi included nine potential criteria taken from the National Contingency Plan (NCP), 40 CFR 300.430(e)(9). These criteria are meant to be used to compare remediation alternatives and to evaluate the appropriateness of response actions in the IRP process. However, the criteria are also applicable to other stages of the clean-up process (e.g., studies and investigations).

The experts were asked to examine these criteria for their appropriateness in prioritizing DERP projects, with the option of adding any criteria they felt were important, or deleting any criteria they felt were not important. The experts were also asked to give a brief justification for each addition or deletion, and give a means of measurement for each criterion included. Finally, the experts were asked to assign a weight to each criterion which reflected its importance relative to each of the other criteria.

The cover letter, distribution list, and questionnaire from the first round of the Delphi are included at Appendix F.

Summarizing the Data from Round One. Of the ten experts included in the first round, eight responses were gathered. Table 1 shows the criteria which were identified by the experts and the weight assigned to each criterion. In summarizing this round of results, the mean was used to rank the relative importance of each criterion. In the subsequent rounds of the Delphi, the median response was used to arrive at the final weight.

Table 1
Round One Summary: Criteria and Weights

		Expert Number								
Criteria:		1	2	3	4	5	6	7	8	Average Weight
1	Protection of HH & E	90	100	97		100		100	100	73
2	Implementability	95	85	95		70	70	49	71	67
3	Cost	40	95	87	50	60	50	60	80	65
4	Long Term Effectiveness	50	90	94		40	80	65	89	64
5	Community Acceptance		90	98	65	90	20	25	73	58
6	Reduction in T, M & V		95	65		75	70	70	70	56
7	Short Term Effectiveness	100	50	70		30	70	50	50	53
8	State Acceptance		65	90		95	30	30	75	48
9	Compliance with ARARs		70	80		40	80	20	90	48
10	Risk to HH & E				100		100			25
11	Future Land Use			99		50				19
12	Risk Assessment			100						13
13	Federal Facility Agreement				85		10			12
14	Protection of Resources					80				10
15	Pollution Prevention					70				9
16	Institutional Control of Risk					50				6
17	EPA Acceptance	35								4
18	Completion of Work in Prog.					25				3
19	Political Factors						20			3
20	Socioeconomic Impacts						10			1
21	Mission Impact						10			1

Delphi Round Two. This portion of the Delphi procedure consisted of developing and sending out a second questionnaire which served two purposes: 1) reporting the summarized results of the first round of the Delphi, and 2) collecting refined second-round data for the criteria important in prioritizing IRP projects. This round was concluded by summarizing the new data collected from the second questionnaire.

Developing the Second Questionnaire. In order to focus on the issues involved in the prioritization process and bring the experts toward consensus on a limited number of criteria, the data gathered in the first round were collapsed into eight new criteria. These new criteria were deduced by the researchers through inspection of the individual criteria returned in the first round of the Delphi. The basis for grouping several criteria into a single criterion was taken mainly from similarities in the experts' recommended method of measurement for the criteria.

Collecting Second Round Data. The second Delphi questionnaire permitted the experts to examine the collective results of the entire group, to examine the restructured criteria, and to re-weight the new criteria in light of this feedback. Included in the second questionnaire was a brief definition of each criterion and a proposed method of measurement based upon the suggestions from the first round. The experts were asked to examine these definitions and give any comments they may have regarding potential problems. Prior to this round, two additional non-Air Force experts were added to the original ten experts participating in the Delphi procedure.

The cover letter, distribution list, and questionnaire from the second round of the Delphi are included at Appendix G.

Summarizing the Data from Round Two. Responses to the second Delphi questionnaire were received from seven of the twelve experts. Table 2 shows how the experts assigned weights to each of the new criteria. Based upon the fact that no other criteria were introduced (or re-introduced), no additional iterations were performed to attempt to further refine the criteria or their associated weights.

Table 2
Round Two Summary: Criteria and Weights

		Expert Number						
Criteria:		1	2	3	4	5	6	7
1	Threat to HH & E	100	100	100	100	100	99	100
2	Expected Reduction of Risk	90	0	90	95	90	95	80
3	Technical Feasibility	85	70	90	95	70	98	70
4	Cost	80	60	80	95	80	97	50
5	Federal Facility Agreement	30	85	10	90	70	93	50
6	Community Acceptance	50	65	50	85	30	96	40
6	Mission Impact	20	0	80	75	50	100	20
8	Socioeconomic Impacts	10	0	10	80	30	94	20

Delphi Round Three. This portion of the Delphi procedure consisted of developing and sending out the third Delphi questionnaire to collect data pertinent to the experts' preference structure for data points within each of the criteria identified during the previous rounds of the Delphi. All analysis of the results of the third questionnaire, and further analysis of the data received in the second questionnaire will be discussed later in the section on development of the decision support model.

Developing the Third Questionnaire. Having gathered data for the criteria and weights associated with the project prioritization problem, a preference structure was needed in order to bring various data points within each criterion into a common scale. The Round Three questionnaire was designed for this purpose. The third questionnaire also reported the compiled results of the previous round, however, no further changes were requested for the criteria or weights.

In the third questionnaire, the experts were given a number of data points within each criterion, and were asked to assign their utility for each data point. The scale used for utility was from 0 to 100, where a utility of 100 was to be assigned to a value within a criterion which would most strongly qualify a project for funding (and hence, increase its priority). Conversely, a utility of 0 would be assigned to a value within a criterion which would most strongly disqualify a project for funding (decrease its priority). The data points supplied in the questionnaire were taken from a feasible range for a particular criterion, and therefore, it was not necessarily expected that the endpoints would be assigned a utility of 0 or 100.

The third questionnaire only requested utility information for six of the eight criteria. The two criteria which were omitted were 'Technical Feasibility', and 'Federal Facility Agreement'. No data were requested for these criteria because they are intended to be 'binary choice' criteria. Their utility values will either be 0 if not available (or not present), or 100 if available (or present).

The cover letter, distribution list, and questionnaire from the third round of the Delphi are included at Appendix H.

Responses to the third Delphi questionnaire were received from six of the twelve experts. Tables 3 through 8 give the compiled results of the experts' assignments of utility to each data point within the criteria.

Development of the Decision Support Model. As discussed in Chapter Three, the intent of the Delphi procedure was to collect data amenable for use in the construction of a simple additive weighting model using the criteria and utility measures elicited from the experts, under the assumption that the criteria would be

Table 3
Utility Results for
Threat to Human Health and the Environment

Data Point (DPM Score)	Expert Number 1	2	3	4	5	6
50	100	100	80	90	100	95
40	90	95	70	75	95	90
35	70	85	55	60	90	60
30	50	75	50	30	85	50
25	30	55	35	20	80	40
20	10	35	30	10	70	15
10	0	15	10	5	50	10

Table 4
Utility Results for Expected Reduction of Risk

Data Point	Expert Number 1	2	3	4	5	6
90%	100	100	90	100	100	95
75%	100	95	75	80	90	80
60%	100	85	60	60	80	75
50%	80	75	50	40	70	50
40%	60	55	40	0	50	35
30%	50	35	20	0	30	15
20%	20	15	10	0	10	10

preferentially independent. This would allow the model to compute a score for a project by convercing each of that project's attributes (data points within a criterion) into a utility value, previously defined as u_i, where u represents

Table 5
Utility Results for Cost

Data Point	Expert Number 1	2	3	4	5	6
$50,000	100	100	90	100	94	95
$200,000	90	85	85	90	90	85
$500,000	85	70	80	80	85	83
$1,000,000	75	55	70	70	80	40
$2,000,000	50	40	60	40	70	30
$4,000,000	20	25	50	20	50	20
$10,000,000	10	10	30	0	30	10

Table 6
Utility Results for Community Acceptance

Data Point	Expert Number 1	2	3	4	5	6
High	100	100	50	100	90	80
Medium	75	65	30	80	80	80
Low	50	25	10	0	50	60

the utility, and i refers to a specific criterion, and then multiplying this utility by a criterion-specific weighting factor, w_i. Thus, the score for a project would be the sum of each of these criterion-specific products, $w_i u_i$.

The weighting factors were determined through analysis of the responses to the second round questionnaire.

Table 7
Utility Results for Mission Impact

Data Point	Expert Number 1	2	3	4	5	6
Strong Pos.	100	100	30	100	90	95
Slight Pos.	20	100	20	50	75	50
No Impact	0	100	10	40	70	40
Slight Neg.	0	60	0	30	60	25
Strong Neg.	0	0	0	0	20	10

Table 8
Utility Results for Socioeconomic/Political Impact

Data Point	Expert Number 1	2	3	4	5	6
Strong Pos.	100	100	30	100	90	80
Slight Pos.	40	100	20	50	80	60
No Impact	0	100	10	40	50	35
Slight Neg.	0	60	0	10	45	20
Strong Neg.	0	0	0	0	30	5

Analysis of variance on these data identified a number of potential and probable outliers in the data which were removed in an effort to decrease the overall variance of the model output. The median values for each criterion were then used as the weight for that criterion. By summing the weights to arrive at a total, and then dividing each weight by the total, the weighting factors were normalized. Table 9 gives the median weights and normalized weighting factors for the criteria.

Table 9
Median Weights and Weighting Factors for Criteria

Criterion	Median Weight	Weighting Factor
Threat to HH & E	100.0	0.183
Expected Reduction of Risk	90.0	0.164
Technical Feasibility	85.0	0.155
Cost	80.0	0.146
Federal Facility Agreement	77.5	0.142
Community Acceptance	50.0	0.091
Mission Impact	50.0	0.091
Socioeconomic Impacts	15.0	0.027
Sum	547.5	

To extract a utility function from the responses provided by the experts, various analyses were performed on the utility data for each criterion. Again, analysis of variance identified a number of potential and probable outliers in the data which were removed prior to further analysis.

Linear regression was performed on the utility data for the 'Threat to Human Health and the Environment', 'Expected Reduction of Risk', and 'Cost' criteria. Because the data for cost clearly indicated a curving trend, as can be seen

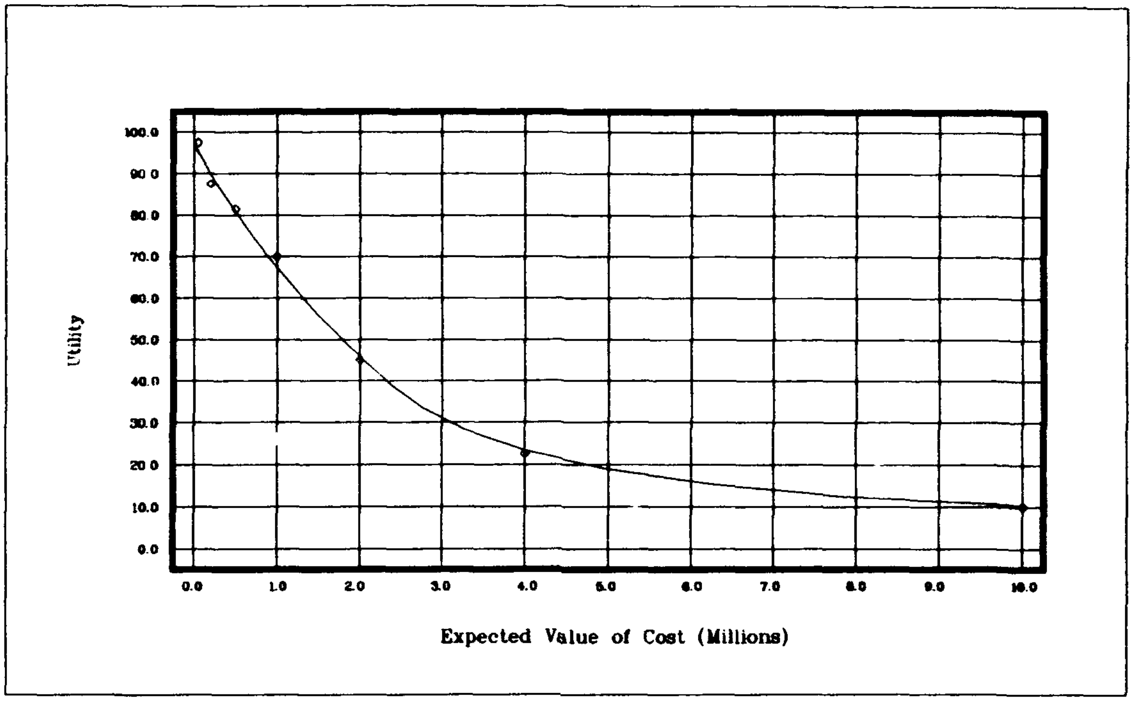

Figure 3. Plot of Expected Value of Cost vs. Utility

in Figure 3, these data were transformed using a cube root function prior to linear regression. This analysis resulted in a set of linear equations which 'best fit' the data, and defined the experts' preference structure. The resulting equations were:

$$U_{THREAT} = 2.418(\text{DPM Score}) - 18.726 \tag{4}$$

$$U_{RISK\ REDUCTION} = 1.214(\%\ \text{Reduction}) - 5.541 \tag{5}$$

$$U_{COST} = -0.492(\text{Cost})^{1/3} + 115.729 \tag{6}$$

Analysis of the 'goodness of fit' for these equations found the following statistics:

1) The coefficients of determination (r^2) for 'threat to human health and the environment', 'risk reduction', and 'cost' were 0.843, 0.875, and 0.884, respectively. These statistics indicate most of the variations between the criteria and utility values are explained by the regression equations.

2) The t-statistics for 'threat to human health and the environment', 'risk reduction', and 'cost' were 13.89, 15.67, and -16.98, respectively. These t-statistics indicate that the variables are significantly different than zero, which implies that the variable is significant in explaining the resulting utility scores.

3) The F-statistics were 192.81, 245.42, and 288.36 for 'threat to human health and the environment', 'risk reduction', and 'cost', respectively. For these simple, single-variable regressions, the F-statistic is simply the square of the t-statistic, and therefore implies again that the variable is significant in explaining the resulting utility scores.

The three remaining criteria for which the experts provided data; 'Community Acceptance', 'Mission Impact', and 'Socioeconomic/Political Impact' were analyzed for the median values at each possible data point. Since these data are ordinal, it would be inappropriate to attempt to perform linear regression. Table 10 shows the median values for these criteria.

The other two criteria, 'Technical Feasibility', and 'Federal Facility Agreement', required no analysis. These criteria are binary, and because this is a deterministic model (assumes there is no uncertainty associated with these values) the resulting utility values will be either 0 or 100.

<u>Analysis of Variance</u>. A statistical evaluation of the resulting model can be performed by analyzing the variance

Table 10
Median Utility Values for Ordinal Criteria

Community Acceptance		Mission Impact		Socioeconomic/Political Impact	
Data Point	Median Utility	Data Point	Median Utility	Data Point	Median Utility
High	100.0	Strong Positive	100.0	Strong Positive	100.0
Medium	80.0	Slight Positive	50.0	Slight Positive	55.0
Low	37.5	No Impact	40.0	No Impact	35.0
		Slight Negative	27.5	Slight Negative	10.0
		Strong Negative	0.0	Strong Negative	0.0

of the utility function. In his study on variability in engineering design, Morrison recited an equation for deriving the propagated variance of a function of multiple random variables (1957:134). The variance of each criterion score is expressed as:

$$\mathrm{Var}(\text{Criterion Score}_i) \cong u_i^2 \cdot \mathrm{Var}(w_i) + w_i^2 \cdot \mathrm{Var}(u_i) \quad (7)$$

As can be seen in this equation, the variance for each criterion is a multiplicative function of the variance for weights and utilities. Given the criteria independence as assumed for the simple additive weighting model, the total utility function variance would simply be the sum of the individual criterion variances.

While this research is interested in the variation of the overall utility function, this total variation is dependent on each criterion variability which in turn is dependent on the individual data points. For example, a low DPM score has a different variance than a medium or high DPM score. The selection of which data point to use for each criterion greatly influences the individual criterion variance and thus the overall utility function variance. Given this insight, the decision was made to calculate the maximum variance, to include outliers, that would result when using the data point for each criterion associated with the greatest variance. The calculation of this worst case variance is shown in Appendix I and equals 121.8 (standard deviation of 11.04). The total project score associated with that variation was 51.9.

Since real project data in the necessary format for scoring were not available, a population mean and variance cannot be calculated for a comparison with this variance. However, one would suspect that the calculated maximum variance for project scores could cast considerable suspicion on the final ranking produced. Therefore, using a small sample of real data, the actual variance for those data in lieu of the maximum variance, and the assumption that further iterations of the Delphi would have eliminated outliers (as assumed in the calculations for weights and utilities), the model was further tested as outlined in the following section.

Testing the Model. In order to perform a pilot test of the model's ability to rank projects, a sample of actual

DERP projects was selected from the Air Force Materiel Command FY94 funding requests. These requests are submitted annually by the individual Air Force bases to the MAJCOM CEVR. Data pertaining to these requests were taken from the Military Construction Project Data Form (DD Form 1391) and attached project summaries included in each submittal. Twelve projects were selected for use in the pilot test. Table 11 gives a description of each project.

Table 11
Projects Included in Pilot Test

Project Number	Location	Description	DERA Priority
94-0203	Hanscom AFB	RI/FS for Unit 1 Petroleum Spill	2
94-0816	Hill AFB	IRA for RVMF at OU 3	1A
94-0843	Hill AFB	RD/RA for OU 4	1A
94-1068	Tinker AFB	IRA Soils, B-3001, North Fuel Tank Area	1A
94-1411	Wright-Patterson AFB	RI/FS for OU 9	1A
94-1709	McClellan AFB	RI/FS for OU B	1A
94-1733	McClellan AFB	RD/RA for GW OU	1A
94-5008	AFP 44	PA/SI for Chip Yards	1A
94-7003	Newark AFB	RD/RA for Landfill 02	2
94-7022	Robins AFB	RD/RA for OU 1, Drum Removal	1A
94-7406	Edwards AFB	RI/FS for OU 4, Phillips Lab	1B
94-7890	Kelly AFB	IRA at Site S-4 (ST-006)	1A

The projects were selected without regard to location, DERA priority, or any of the individual criteria to be input in the model. The only goal in the selection process was to obtain a representative sample of projects in various stages of the DERP process (i.e., studies, designs, and remedial actions).

Because many of the criteria identified by the experts as being important in the DERP prioritization process are not currently measured, there were several gaps in the project summaries where data required for analysis was not available. Examples of this include 'Community Acceptance', 'Mission Impact', and 'Socioeconomic/Political Impact'; these types of information are not currently collected or reported. Where these data gaps existed, assumptions were made based upon experience and any situation-specific information which could be gathered from the project summaries. Table 12 gives the raw data gathered from these project submittals.

As a means of analyzing the variance caused by the range of responses which were received from the experts, two additional sets of weighting factors and utility functions were used to rank the projects. These weights and utilities were taken from the high and low extremes of the experts preference structures. By multiplying the weighting factors of the highest expert responses by the highest utility values, and similarly multiplying the weighting factors of the lowest expert responses by the lowest utility values, an 'envelope' would be created about the median weights and 'best-fit' utility functions. Identical rankings of the projects by each method would indicate that despite the variance which exists between individual expert opinions, the difference between the model produced using the median

Table 12
Raw Data Gathered from DERP Project Submittals

Criterion:	Hanscom RI/FS	Hill IRA	Hill RD/RA	Tinker IRA	WPAFB RI/FS	McClellan RD/RA
	Raw Data					
Threat to HH & E	20	34	48	41	35	28
Expected Reduction of Risk	0%	45%	80%	30%	0%	0%
Technical Feasibility	Yes	Yes	Yes	Yes	Yes	Yes
Cost	$22,190	$607,000	$3,500,000	$1,350,000	$1,104,000	$3,518,000
Federal Facility Agreement	No	Yes	Yes	Yes	Yes	Yes
Community Acceptance	Medium	High	Medium	High	Medium	Medium
Mission Impact	None	Sl. Neg.	Sl. Neg.	None	None	Sl. Pos.
Socioeconomic Impact	None	Sl. Pos.	Sl. Pos.	Sl. Pos.	None	Sl. Pos.

Criterion:	McClellan RD/RA	AFP 44 PA/SI	Newark RD/RA	Robins RD/RA	Edwards RI/FS	Kelly IRA
	Raw Data					
Threat to HH & E	38	12	34	22	20	39
Expected Reduction of Risk	40%	0%	55%	90%	0%	40%
Technical Feasibility	No	Yes	Yes	Yes	Yes	Yes
Cost	$2,000,000	$73,000	$4,500,000	$8,300,000	$4,578,504	$3,400,000
Federal Facility Agreement	Yes	Yes	No	Yes	No	Yes
Community Acceptance	Low	High	Medium	High	Medium	High
Mission Impact	None	Sl. Pos.	None	None	Sl. Pos.	Sl. Pos.
Socioeconomic Impact	Sl. Pos.	None	Sl. Neg.	None	Sl. Pos.	None

values for weighting factors and best-fit utility functions and models produced using the most extreme values for weights and utilities is not significant. Table 13 gives the values for the high and low weights and the normalized weighting factors associated with each resulting set of criteria.

The utility functions were again calculated using linear regression for the criteria 'Threat to Human Health

Table 13
High and Low Weights and Weighting Factors

Criterion	High Weight	Normalized Weighting Factor	Low Weight	Normalized Weighting Factor
Threat to HH & E	100.0	0.137	100.0	0.256
Expected Reduction of Risk	95.0	0.130	80.0	0.205
Technical Feasibility	98.0	0.135	70.0	0.179
Cost	97.0	0.133	60.0	0.154
Federal Facility Agreement	93.0	0.128	30.0	0.077
Community Acceptance	85.0	0.117	30.0	0.077
Mission Impact	80.0	0.110	20.0	0.051
Socioeconomic Impacts	80.0	0.110	0.0	0.000
Sum	728.0	1.000	390.0	1.000

and the Environment', 'Expected Reduction of Risk', and 'Cost', as shown below for the high utility values:

$$U_{THREAT} = 2.357(\text{DPM Score}) - 2.857 \qquad (8)$$

$$U_{RISK\ REDUCTION} = 1.197(\%\ \text{Reduction}) + 6.141 \qquad (9)$$

$$U_{COST} = -0.394(\text{Cost})^{1/3} + 115.795 \qquad (10)$$

and the low utility values:

$$U_{THREAT} = 2.262(\text{DPM Score}) - 27.143 \qquad (11)$$

$$U_{RISK\ REDUCTION} = 1.199(\%\ \text{Reduction}) - 16.102 \qquad (12)$$

$$U_{COST} = -0.560(\text{Cost})^{1/3} + 113.401 \qquad (13)$$

Analysis of the 'goodness of fit' for these equations found the following statistics:

1) For the high utility values, the coefficients of determination (r^2) for 'threat to human health and the environment', 'risk reduction', and 'cost' were 0.885, 0.892, and 0.987, respectively. For the low utility values, the coefficients of determination (r^2) for 'threat to human health and the environment', 'risk reduction', and 'cost' were 0.939, 0.986, and 0.948, respectively.

2) For the high utility values, the t-statistics for 'threat to human health and the environment', 'risk reduction', and 'cost' were 6.20, 6.42, and -19.09, respectively. For the low utility values, the t-statistics for 'threat to human health and the environment', 'risk reduction', and 'cost' were 8.77, 18.83, and -9.54, respectively.

3) For the high utility values, the F-statistics were 38.44, 41.23, and 364.46 for 'threat to human health and the environment', 'risk reduction', and 'cost', respectively. For the low utility values, the F-statistics were 76.87, 354.74, and 91.07 for 'threat to human health and the environment', 'risk reduction', and 'cost', respectively.

The three ordinal criteria; 'Community Acceptance', 'Mission Impact', and 'Socioeconomic/Political Impact' were analyzed at the high and low data points as well. Table 14 gives the utilities for each of the data points within these criteria.

The values of the two binary criteria; 'Technical Feasibility', and 'Federal Facility Agreement' did not change for this portion of the analysis, and still assumed values of 0 or 100.

<u>Results of the Decision Support Model Pilot Test</u>. By using the data provided by the AFMC/CEVR projects as input

Table 14
High and Low Utility Values for Ordinal Criteria

High Utility Values:

Community Acceptance		Mission Impact		Socioeconomic/Political Impact	
Data Point	High Utility	Data Point	High Utility	Data Point	High Utility
High	100.0	Strong Positive	100.0	Strong Positive	100.0
Medium	80.0	Slight Positive	75.0	Slight Positive	80.0
Low	60.0	No Impact	70.0	No Impact	50.0
		Slight Negative	60.0	Slight Negative	45.0
		Strong Negative	20.0	Strong Negative	5.0

Low Utility Values:

Community Acceptance		Mission Impact		Socioeconomic/Political Impact	
Data Point	Low Utility	Data Point	Low Utility	Data Point	Low Utility
High	80.0	Strong Positive	90.0	Strong Positive	80.0
Medium	65.0	Slight Positive	20.0	Slight Positive	40.0
Low	0.0	No Impact	0.0	No Impact	0.0
		Slight Negative	0.0	Slight Negative	0.0
		Strong Negative	0.0	Strong Negative	0.0

to the median, high, and low weight and utility models, three sets of scores were produced. From these scores, three rankings of the projects were assembled. Table 15 shows the scores and rankings for each project by each version of the model.

Inspection of the correlation between these rankings reveals similar results by all three methods. Only slight

Table 15
Scores and Rankings of Projects

Location	Action	High Score	Median Score	Low Score	High Rank	Median Rank	Low Rank
Hill	RD/RA	85.198	79.802	72.190	1	1	1
Hill	IRA	82.751	73.278	62.425	2	2	2
Tinker	IRA	82.421	72.672	60.562	3	3	3
Kelly	IRA	78.491	71.288	59.446	4	4	4
Robins	RD/RA	75.658	68.410	56.375	5	5	5
WPAFB	RI/FS	70.550	63.107	52.476	6	6	6
AFP 44	PA/SI	69.241	60.076	46.640	8	7	8
McClellan	RI/FS	69.583	57.961	45.241	7	8	9
Newark	RD/RA	62.199	53.399	49.094	10	9	7
McClellan	RD/RA	64.017	51.037	35.889	9	10	11
Hanscom	RI/FS	55.151	45.341	39.781	11	11	10
Edwards	RI/FS	53.467	39.219	31.705	12	12	12

variations in the rankings occur in the lower-priority projects.

Analysis of the variance among the rankings was performed using two methods proposed by Saaty: the root mean square (RMS) method, and the median absolute deviation about the median (MAD) method. Each of these methods provide a procedure to determine the accuracy of two sets of numbers in absolute terms. (Saaty, 1980:37) Given two sets of numbers $a_1, \ldots, a_n$, and $b_1, \ldots, b_n$, the general form of the RMS equation is:

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(a_i - b_i)^2}$$

The general form of the MAD equation is:

$$\text{MAD} = \text{median}\{|(a_i - b_i) - \text{median}\ (a_i - b_i)|\} \qquad (14)$$

By applying these methods to the rankings determined previously by the three methods, two measures of the closeness of the results are determined. Table 16 shows the RMS calculations for the rankings, and Table 17 shows the MAD calculations for the rankings.

Saaty suggests that the significance of both the RMS and the MAD methods may be determined by dividing their values by the average value of the vector components, 1/n, where n is the number of components. A ratio of 0.1 or less from either or both methods indicates that the vectors being compared are nearly the same. (Saaty, 1980:39)

In the RMS cases, these values are 6.6882 for the high value and median value comparison, and 9.7980 for the median value and low value comparison. In the MAD cases, however, these values are zero for the high-median comparison, as well as the median-low comparison. This indicates that the vectors are nearly the same since only one of the methods is required to produce a ratio below 0.1. Therefore, as noted above, although differences exist between individual opinions, the conglomerate of median weights and utilities produce a model which is not significantly different from a model produced using the extreme weights and utilities.

Table 16
Root Mean Square Calculations for Rankings

RMS Calculation for High vs. Median Rankings:

High Rankings (a)	Median Rankings (b)	(a - b)	(a - b)^2
1	1	0	0
2	2	0	0
3	3	0	0
4	4	0	0
5	5	0	0
6	6	0	0
8	7	1	1
7	8	-1	1
10	9	1	1
9	10	-1	1
11	11	0	0
12	12	0	0
		SSE =	4
		RMS =	0.57735

RMS Calculation for Median vs. Low Rankings:

Median Rankings (a)	Low Rankings (b)	(a - b)	(a - b)^2
1	1	0	0
2	2	0	0
3	3	0	0
4	4	0	0
5	5	0	0
6	6	0	0
7	8	-1	1
8	9	-1	1
9	7	2	4
10	11	-1	1
11	10	1	1
12	12	0	0
		SSE =	8
		RMS =	0.816497

Table 17
Median Absolute Deviation About the Median
Calculations for Rankings

MAD Calculation for High vs. Median Rankings:

High Rankings (a)	Median Rankings (b)	(a - b)	|(a - b) - median(a - b)|
1	1	0	0
2	2	0	0
3	3	0	0
4	4	0	0
5	5	0	0
6	6	0	0
8	7	1	1
7	8	-1	-1
10	9	1	1
9	10	-1	-1
11	11	0	0
12	12	0	0
	median(a - b) =	0	
		MAD =	0

MAD Calculation for Median vs. Low Rankings:

Median Rankings (a)	Low Rankings (b)	(a - b)	|(a - b) - median(a - b)|
1	1	0	0
2	2	0	0
3	3	0	0
4	4	0	0
5	5	0	0
6	6	0	0
7	8	-1	-1
8	9	-1	-1
9	7	2	2
10	11	-1	-1
11	10	1	1
12	12	0	0
	median(a - b) =	0	
		MAD =	0

This result implies that the median weights and utilities adequately represent the experts' opinions, taken as a whole.

Further sensitivity analysis of the data was performed to examine the effects of the outliers on the performance of the model. Again, three models were developed using the median data and the extreme high and low data. For these models, however, the outliers, which were previously omitted from the analysis, were included. This situation resulted in models which produced significantly different rankings. Therefore, it should be noted that the validity of the final model is dependent upon the degree of consensus reached among the experts in that the outliers will have a significant effect on the ordering of projects in the final model.

Analysis of Data from the MAUT Procedure

As noted in Chapter 3, there are five steps to the value-function measurement task. The first step is to familiarize the decision maker with the concepts and techniques of MAUT. The second is to identify the form of the utility function. The form is dependent on the relationships between the criteria of interest, which can be determined by the responses to the questionnaire.

The responses to questions 1-6 were used to test for preferential independence. In these six questions, the decision maker was given a hypothetical situation with two project alternatives. The odd numbered questions established the relative importance among two of the criteria while holding the third criterion fixed. Even numbered questions were used to alter the fixed criterion to determine if the relative importance established in the preceding question changed. In all cases, the relationship between the two criteria of interest remained the same, establishing preferential independence. That is, the value trade-off between every pair of attributes was not affected by a third attribute (Chan, 1993:41). Since all attributes were tested against one another, and all proved to be preferentially independent, the entire set of attributes is mutually preferentially independent (Winston, 1991:730).

Another important relationship to determine is mutual utility independence. If the relative utility of each criterion remains the same regardless of the value of other criteria, the criteria are said to be utility independent. Mutual utility independence implies that both a criteria set and its complement are utility independent (Chan, 1993:42,43). Questions 7-9 established that the criteria of risk, cost, and Major Command (MAJCOM) priority are not utility independent. With the exception of MAJCOM priority, the utility associated with a criterion changed as the other two criteria changed. With MAJCOM priority, the decision maker indicated that he had no utility for this criterion regardless of the value or DPM scores or costs.

Establishing mutual preferential independence implies that the resulting function will be an additive value function (Winston, 1991:730). This is consistent with the finding that mutual utility independence, which is required for multiplicative utility models, was absent. Unfortunately, the fact that mutual utility independence was not established also limits the conclusions one can draw when quantifying the intensity of choice which is required for cardinal utility functions (Chan, 1993:41,43).

The third step of the MAUT process, the overall measurement of utility, is based on the premise that "the utility of an alternative is [equal to] the sum of the utility of each of the possible outcomes" (Chan, 1993:34). To determine the univariate value functions, questions 10 and 11 tested the decision maker's utility for risk and cost. The utility for MAJCOM priority was pre-established as discussed in Chapter 3.

In both questions 10 and 11, lotteries are used to provide a measure of utility for use in the multicriteria decision model (MCDM). Figures 4 and 5 show plots of the responses to these two questions. On the x-axis, the expected value of the lottery choice is plotted. On the y-axis, the certainty equivalent is plotted. The certainty equivalent is defined as an amount such that the decision maker is indifferent between it with certainty and the expected value of the lottery amount (Chan, 1993:36).

As shown by the curve in Figure 4, the decision maker is risk averse for the utility associated with DPM score. Being conservative, he values the reduction in DPM scores associated with the 'certain outcome' over the higher 'expected' reduction of risk associated with the 'uncertain outcome'. His utility can be represented in algebraic form as:

$$Utility_{DPM} = 2.07(DPM)^{0.82} \tag{15}$$

The coefficient of determination (r^2 statistic) for this regression equation is 0.998, indicating that virtually all of the variance between the criterion data points and the utility data points is explained by the equation.

On the other hand, the decision maker is risk neutral on the utility associated with costs. In all cases, he would be willing to pay someone else exactly the expected value of the cost of corrective actions at a site for assuming the risk. Said differently, he would be indifferent to assuming the full cost of corrective actions at a site vice paying someone else the expected costs and requiring them to assume responsibility for the full cost.

The bottom line when using a questionnaire is to arrive at an overall value function. In order to represent the various alternatives in an overall value function, scaling

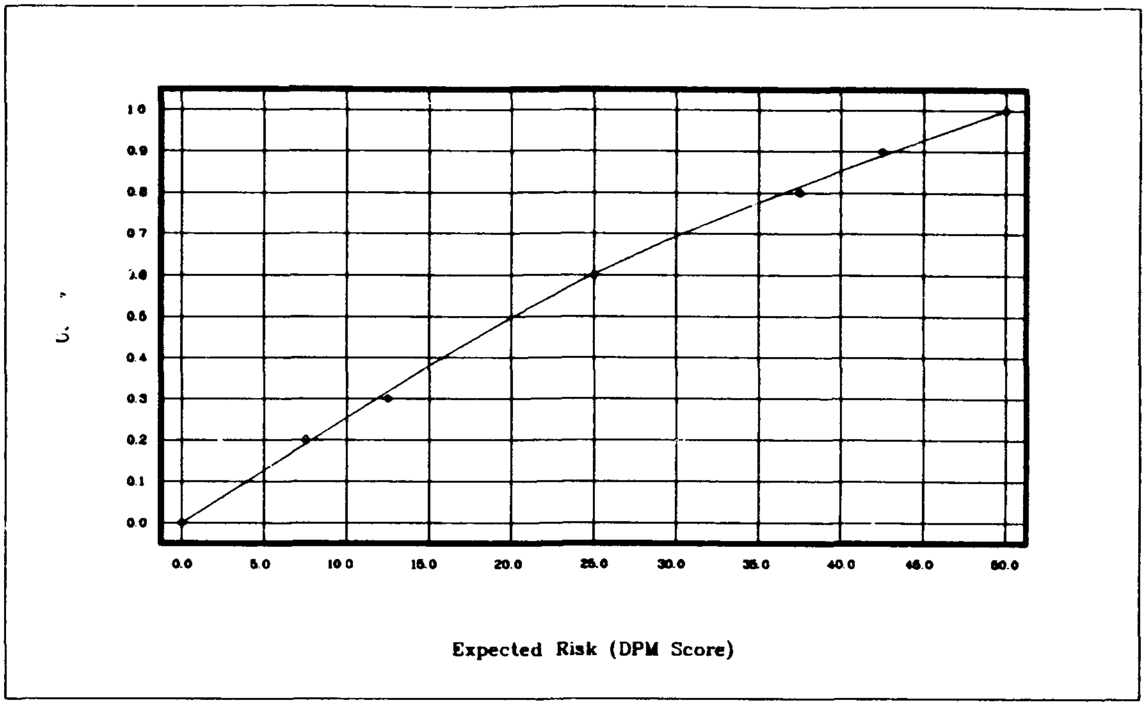

Figure 4. Plot of Expected Risk vs. Utility

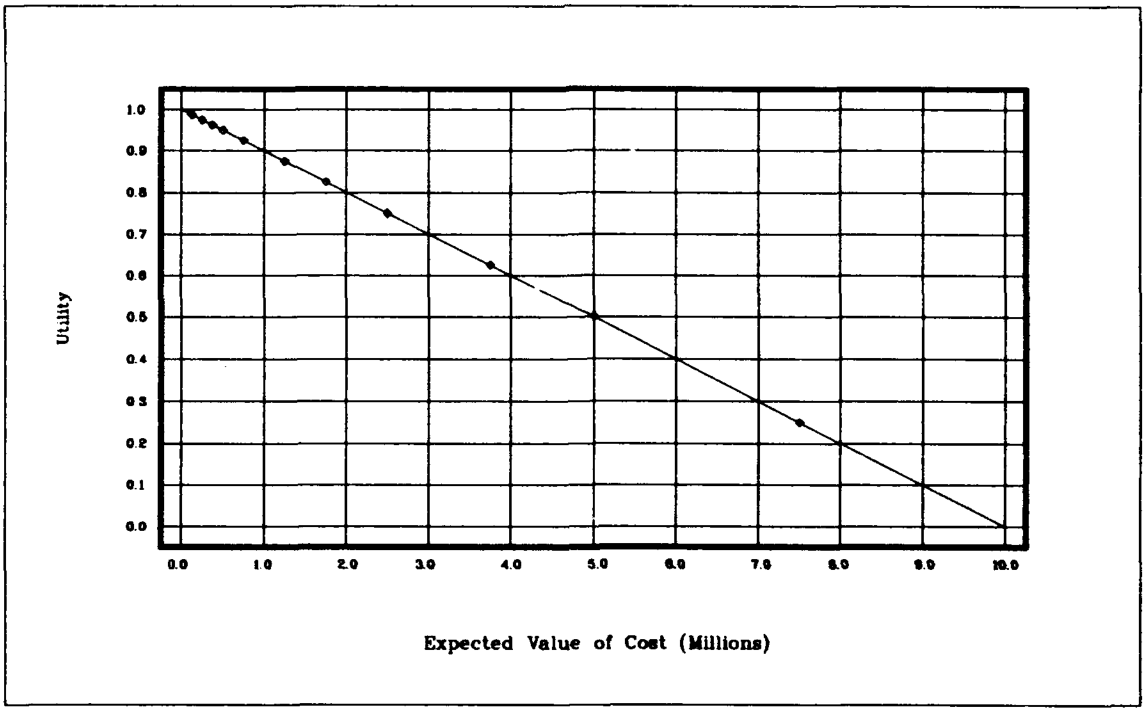

Figure 5. Plot of Expected Value of Cost vs. Utility

functions and the relative weights for each criterion must be determined. Scaling involves the transformation of data to a value between 0 and 1. Simple linear transformations can be performed by dividing the outcome by its maximum value. In the case of costs, the transformation is accomplished by taking the inverse of the outcomes (e.g., 1/outcome). The advantage to linear transformations is that they maintain the relative order of magnitude of outcomes (Hwang, 1981:30).

A scaled utility function for MAJCOM priority was given in equation (3) in Chapter 3 and is rephrased here:

$$\text{Value}_{MP} = 1 - (\text{priority} / \text{total \# of projects}) \quad (16)$$

This function converts all priorities to a scale of 0 to 1, with the highest priority project having a value almost equal to 1.

A scaling function for risk is also required. For this function, it is assumed that maximum utility is associated with any DPM score over 50 and that minimum utility is associated with any DPM score of 0. In actuality, the lower bound for DPM should be determined by the future land use of the site (Owendoff, 1993b); however, for the sake of simplicity, we will assume the lower bound to be 0. The ratio needed to convert the DPM score to a value in the range of 0 to 1 is simply the inverse of the maximum expected value, or 1/50. Combining this scaling ratio with the utility function given earlier yields a scaled utility function of:

$$\text{Value}_{DPM} = 0.0414(\text{DPM})^{0.83} \qquad (17)$$

The scaled utility function for cost was similarly determined. For cost, the maximum value used for utility comparisons was \$10 million. However, \$10 million may not be the upper limit on project costs. Since the utility for cost was linearly related to the expected value, there is no reason to limit the utility function to \$10 million. Therefore, the scaled utility function becomes:

$$\text{Value}_{COST} = 1 \;/\; \text{maximum project cost} \qquad (18)$$

The weights for each of the criteria can be determined algebraically from the responses in the questionnaire and a simplification to the following relationship for a three-variable multiplicative value function:

$$\begin{aligned}\text{Value}(y_1, y_2, y_3) = {} & w_1 v(y_1) + w_2 v(y_2) + w_3 v(y_3) + \\ & + k[w_1 w_2 v(y_1) v(y_2) + w_1 w_3 v(y_1) v(y_3) + \\ & + w_2 w_3 v(y_2) v(y_3)] + k^2[w_1 w_2 w_3 v(y_1) v(y_2) v(y_3)] \qquad (19)\end{aligned}$$

where w_i refers to the weights, k is a multiplicative scaling constant, and the subscripts 1, 2, and 3 refer to DPM scores, MAJCOM priority, and cost respectively (Chan, 1993:33). Since the decision maker noted at the end of Section A that his utility for MAJCOM priority was zero (i.e., $v(y_2)=0$) and confirmed this in his responses to questions 3, 4, and 8, and since the form of the function was determined to be simple additive weighting (i.e., $k=0$); the equation simplifies to:

$$\mathrm{Value}(y_1, y_2, y_3) = w_1 v(y_1) + w_3 v(y_3) \tag{20}$$

The relationship between DPM scores and costs can be calculated from the responses to questions 5, 6, and 14. In questions 5 and 6, the DPM score varies from 30 to 15 between the two hypothetical projects. The project cost at the higher risk site was given as $500,000. The decision maker was asked to chose a project cost for the second site that would make him indifferent between the two projects. The decision maker responded by saying he would always chose the higher risk site regardless of cost differences. This response indicates that although the decision maker has utility associated with the cost criterion, the weight he would assign cost in relation to risk is low (see Appendix J). This response was verified in a follow-on interview with the decision maker after the decision maker was informed of the implications (Edwards, 1993a). These results are also consistent with the responses to questions 7, 9, 14, and 15. (It should be noted that the response to 7.1 raises suspicion that the cost criterion does enter in to the overall value function; however, the decision maker indicated that a difference of 10 in DPM scores makes the comparison of risk less certain.)

Given that the weights and utilities associated with the cost and MAJCOM priority variables are zero, the final value function simplifies to the univariate risk function. Since the decision maker indicated that small differences in DPM may not have meaning, the requirement for a uniform preference intensity for a cardinal scale is violated and the ranking is strictly an ordinal ranking on DPM scores. Again, this is consistent with the fact that preferential independence was established but not mutual utility independence.

The obvious question at this point in the research is: "Why does the model only use one criterion to rank projects?" The explanation could be with the criteria determined from the pre-questionnaire, the metrics used to represent the criteria, or the questionnaire.

The questionnaire results appear to be consistent. Questions that made a pairwise comparison among similar criteria were answered in similar fashion. Additionally, the response to the 'control' question, question 15, rated DPM score as most important and MAJCOM priority as least important. Finally, the proposed prioritization scheme the decision maker sketched on the bottom of the questionnaire uses only DPM scores to choose among similar categories of projects. Neither cost, priority, nor any of the other criteria proposed by the experts are present in this scheme.

To gain further insight into these results, a brief, informal, post-questionnaire interview was conducted with the decision maker, Col. Owendoff. He indicated risk was of paramount importance and cost was secondary to risk. His rationale was that the Air Force must demonstrate to Congress that it is taking on all projects above a given level of risk. He also indicated that while the MAJCOMs currently play an important role in allocating funds and are closer to the problems than the Air Staff, the MAJCOM priority criterion was not 'concrete' enough. The stakeholders in the IRP need criteria that can be applied consistently across commands and have a less subjective basis for their use. (Owendoff, 1993c) In addition to the post-questionnaire interview with Col. Owendoff, a final copy of the analysis and the inferences drawn were provided to Mr. Edwards. Mr. Edwards, like Col. Owendoff, also indicated concurrence with the results (Edwards, 1993b).

Comparison of the Delphi and MAUT Procedures

The results of the two procedures can be analyzed in a manner similar to that of the results of the Delphi, that is, a direct comparison of the project rankings of the two methods. Table 18 shows the twelve AFMC projects as they were previously ranked by the Delphi model (median weights

Table 18
Comparison of Delphi and MAUT Project Rankings

RMS Analysis:

Project:		DELPHI Ranking	MAUT Ranking	error	error^2
Hill	RD/RA	1	1	0	0
Hill	IRA	2	6	-4	16
Tinker	IRA	3	2	1	1
Kelly	IRA	4	3	1	1
Robins	RD/RA	5	9	-4	16
WPAFB	RI/FS	6	5	1	1
AFP 44	PA/SI	7	12	-5	25
McClellan	RI/FS	8	8	0	0
Newark	RD/RA	9	6	3	9
McClellan	RD/RA	10	4	6	36
Hanscom	RI/FS	11	10	1	1
Edwards	RI/FS	12	10	2	4

SSE = 110
RMS = 3.02765

MAD Analysis:

Project:		DELPHI Ranking	MAUT Ranking	error	|error-median(error)|
Hill	RD/RA	1	1	0	1
Hill	IRA	2	6	-4	5
Tinker	IRA	3	2	1	0
Kelly	IRA	4	3	1	0
Robins	RD/RA	5	9	-4	5
WPAFB	RI/FS	6	5	1	0
AFP 44	PA/SI	7	12	-5	6
McClellan	RI/FS	8	8	0	1
Newark	RD/RA	9	6	3	2
McClellan	RD/RA	10	4	6	5
Hanscom	RI/FS	11	10	1	0
Edwards	RI/FS	12	10	2	1

median = 1
MAD = 1

and utilities), and compares them to the project rankings by the MAUT model (DPM score). This comparison also shows the calculations for root mean square (RMS) and median absolute deviation about the median (MAD). By dividing the RMS and MAD vectors by 1/n, their significance may be determined. In this case, the RMS analysis yields a value of

$$RMS/(1/n) = (3.02765)/(1/12) = 36.3318 \qquad (21)$$

and the MAD analysis yields a value of

$$MAD/(1/n) = (1)/(1/12) = 12 \qquad (22)$$

Since neither of these values is below 0.1, it cannot be stated that the rankings of the two models are nearly the same, and therefore, the prioritization models themselves must be significantly different.

Conclusion

The results of the above comparison indicate that the DERP experts and the decision maker may have different perceptions of the problem and different objectives from the prioritization process. Possible explanations for this can be derived by investigating the goals of the experts and the decision maker. The experts, having technical knowledge of the issues involved with the DERP, may be more concerned with the attributes involved in the projects. They do not have the responsibility of deciding which projects get funding. Viewed this way, the experts can be seen as examining the problem in a prospective manner. They will tend to be more concerned with investigating all relevant attributes of projects when prioritizing those projects, and less concerned with the outcomes of the process. A decision maker, on the other hand, may view the problem differently. A decision maker is required to provide outcomes and to make decisions, and therefore may have a more retrospective view of the problem. This view may cause the decision maker to limit the number of project attributes which are considered when prioritizing projects for funding.

Another possibility for the difference involves the number of inputs into the model. The Delphi procedure employed 12 experts who all had input into the criteria used. As noted earlier, this is likely to expand the range of issues considered. The MAUT procedure employed just one decision maker. If the decision maker didn't feel a particular criterion was valid, it was eliminated. In the Delphi, differences of opinion on the validity of criteria resulted in variance, but the criteria were still included. Despite these differences, both methods produced usable data for the resulting decision support system. The usefulness of the resulting decision support systems will be discussed in greater detail in the next chapter.

V. Conclusions and Recommendations

The two proposed multicriteria decision models (MCDMs) arrived at in Chapter 4 both provide an alternative to the research problem posed in Chapter 1, development of a means to differentiate Defense Environmental Restoration Program (DERP) projects. While the two methods do not arrive at a common solution, they both satisfy the key program objectives and respond to the overall needs. Either option could be used in a decision support system (DSS) to initially rank projects.

Program Objectives

Before developing an MCDM, the program objectives were researched. As determined from the literature review, the overriding goal in the statutes, Environmental Protection Agency (EPA) regulations, and Department of Defense (DoD) regulations is to protect the public health. Reducing site risk, attacking the worst sites first, controlling immediate threats, and a bias toward remedial action vice studies all are based on the protection of public health.

The regulatory objectives also matched DoD objectives in regards to cleaning up contaminated sites. Both sought quick, effective cleanup strategies with an end goal of meeting applicable or relevant and appropriate requirements (ARARs) and site closure. The overall objective with regards to cost-effectiveness were also similar; unfortunately, neither program really defined a measurable goal for this objective. Finally, both the regulators and DoD indicated streamlining procedures, meeting statutory deadlines and requirements, and complying with court orders or other forms of agreements were important.

Other objectives mentioned in the literature were either agency-specific or were less closely matched. For example, the EPA objective of encouraging innovation doesn't coincide with the DoD goal of standardizing cleanup methods. It does, however, match the DoD policy of funding research and development. From an investment perspective, research into innovative solutions could result in more efficient and effective solutions for future sites. From a practical standpoint, however, EPA's desire to test innovative solutions doesn't coincide with DoD's realization that innovation involves risking limited funds, takes time, can be difficult to implement, and may not show progress in cleaning up the environment.

<u>Model Development</u>

<u>Criteria</u>. As noted in the methodology section, the criteria selected for use in the model is one of the most critical elements. Both the Delphi and multiattribute utility theory (MAUT) procedures relied on the criteria mentioned in the literature as a starting point for

developing a model. The Delphi procedure sought the opinion of experts to refine the list, while the MAUT procedure relied on a pre-questionnaire interview and the opinion of the researchers to narrow the criteria to a suitable number.

The criterion most frequently mentioned in the literature and most heavily weighted in both models was risk. Risk, or the threat to the public health or environment, was represented in both models by the Defense Priority Model (DPM) score. Other possible criteria related to risk include risk reduction; the reduction in toxicity, mobility, or volume of contamination; and short-term effectiveness. Of these, only the expected reduction of risk as measured by the expected reduction in DPM score was included. It was the second highest weighted factor in the Delphi model, but it was not included in the MAUT MCDM.

Many of the other criteria mentioned in literature involved compliance. Compliance with regulatory agreement schedules, with statutory deadlines and requirements, with ARARs, or with DoD or Air Force goals all were possible criteria for use in the models. The Delphi model included federal facility agreement compliance, a binary criterion, as the fifth most important criterion. The MAUT procedure grouped all these measures together in a subjective 'MAJCOM priority' criterion, but the decision maker's responses to the questionnaire negated its use in the model.

Whether or not the proposed project is technically or contractually feasible is also important to the evaluation and prioritization of projects. Technical feasibility, as measured by the availability of generally accepted methods for remediation, was the third highest weighted criterion in the Delphi MCDM. In the MAUT model, technical feasibility was incorporated into MAJCOM priority (which was subsequently dismissed through analysis of the decision maker's responses).

Cost, like risk, was a criterion in both models. Since the overall cost of completing the cleanup of a site is very difficult to assess and the estimates for later stages depend on the results of studies in the earlier stages, the current year project cost was used as the only measure of cost. Cost was identified as the fourth most important criterion to be considered in the Delphi model. The decision maker for the MAUT procedure assigned a utility to cost, but his relative priority for the risk criterion completely dominated cost.

Community acceptance was the key parameter in the most recent study on IRP prioritization, the Keystone report. For this research, the Delphi experts gave community acceptance some consideration; however, the measurement is a subjective measure by the decision makers and is tied for next-to-last in importance. Again, for the MAUT procedure, community acceptance and concurrence of the technical review committee was included in MAJCOM priority and subsequently dismissed. State and federal EPA acceptance, while a valid criterion, was not considered in either model.

Finally, the impact of a project on the mission of the installation or the socioeconomic impacts of the project on the community were mentioned in the literature for possible consideration. Both criteria were included by the experts in the Delphi model, although mission impact was considered next-to-last in importance and socioeconomic impact contributed less than 3% to the overall score of a project. Both factors were also included in the MAUT model under the MAJCOM priority criterion, and subsequently dismissed.

Assumptions. Both the Delphi and MAUT MCDMs assume installation level personnel, along with the possibility of a technical review committee comprised of regulatory and community representatives, submit appropriate projects for funding consideration. By making this assumption, the MCDM does not have to specifically address the projects in relation to the types and extent of contamination present, site characteristics, and the expected future use of the site. Likewise, the uncertainties associated with the restoration method chosen, the risk assessment, feasibility, cost, and other criteria of interest were not specifically addressed in either model. It was assumed that the proponents of the project submitted an appropriate 'expected value' for these aspects of the project. Linking the MCDM to probability density functions would likely not improve the resulting priorities at this stage of model development and could overly complicate it in the eyes of the IRP community.

MCDM Procedures. In light of the numerous and conflicting opinions for criteria to be used in the resulting MCDM, two procedures were chosen for this research. Each procedure has resulted in a usable model which can be modified to fit changing future requirements, new information, or valid criticism from stakeholders.

The strength of the Delphi procedure lies in its ability to identify criteria for the model. It solicits and incorporates a broad range of ideas from DERP experts and builds a consensus among them for the final model. In contrast, the strength of the MAUT procedure was its ability to quantify the preference among the criteria by means of pairwise comparisons and to check the independence of the variables.

The results of the Delphi are limited by the variance among the experts for the utility and weights to be applied to the criteria. While a small variance indicates general agreement and increases the confidence of the measure, larger variances cast doubt as to whose judgment is representative of the population. In addition to the variance of the experts, multiple expert interpretations of the best solution must be aggregated into a consensus single group interpretation. Each expert uses their own frame of reference, and individual judgments of the best solution may not be reflected in the aggregate. (Lewis, 1993:1) A limiting factor in the MAUT procedure stems from the fact that a single decision maker's opinion is solicited for the resulting value function. There is no check on the decision maker's inputs or the analyst's interpretation of the responses, although follow-on interviews were used in an attempt to minimize these problems.

MCDM Results. The MCDM weighting factors derived in Chapter 4 are as follows. The utility functions shown in the text are not repeated here.

Delphi weighting factors:

1)Threat to Human Health and the Environment	= 0.183
2)Expected Reduction of Risk	= 0.164
3)Technical Feasibility	= 0.155
4)Cost	= 0.146
5)Federal Facility Agreement	= 0.142
6)Community Acceptance	= 0.091
7)Mission Impact	= 0.091
8)Socioeconomic/Political Impacts	= 0.027

MAUT weighting factors:

1)Threat to Human Health and the Environment	= 1.0
2)Cost	= 0.0
3)MAJCOM Priority	= 0.0

Both rank discretionary projects on the criteria of importance to the experts and decision makers. However, many projects submitted for funding do not need to be prioritized. A DSS provides for these non-discretionary type decisions.

A final DSS was not developed as part of this research. Instead, the research focused on the MCDM portion of the DSS. A DSS framework was under development at the Air Force installation restoration program (IRP) headquarters. The DSS provides funding for 'must pay' requirements such as personnel, program management, long-term operations and monitoring, and initial site investigation work (Owendoff, 1993b). These requirements must be funded to provide continuity in the IRP, to supply the information needed to prioritize future work, and to fulfill the obligations incurred under earlier work. After these requirements have been funded, the DSS attempts to prioritize IRP projects based on risk. Using an MCDM proposed by this research could improve that portion of the DSS, or at least provide a rationale for using only DPM to prioritize the projects.

Using the proposed DSS in conjunction with the MCDM does meet the objectives of this research. First and foremost, it provides a distinct, objective, funding hierarchy. Second, the projects' priorities will be consistent with the current laws and regulations governing the program. The projects submitted will have been approved by both the installation and Major Command (MAJCOM) level managers as meeting the statutory and Department of Defense (DoD) regulatory requirements. Furthermore, projects submitted for high risk sites will likely have been approved by a technical review committee composed of Air Force, U.S. and state environmental protection agency (EPA) personnel, and community representatives. Finally, the DSS and resulting prioritization should be acceptable to the MAJCOMs, Congress, the EPAs, and the public. Many of these groups participate in the process and most of their concerns have been addressed. More will be said about improving this portion of the DSS in the recommendations section.

Recommendations For Further Study

Criteria. Further research could include an attempt to incorporate project-specific criteria such as the suitability of the proposed work given the site and contaminant characteristics. Furthermore, an attempt could be made to model the uncertainties involved in the various project attributes. Finally, new metrics could be examined for measuring the criteria of interest.

Delphi Procedures. The principal improvement in this area of the research would entail expanding the scope of respondents to include a wider spectrum of stakeholders. More regulatory personnel, industry consultants, community representatives, and environmental groups should be included to better represent the interests of the stakeholders and build support for the resulting model. Additionally, the respondents should be required to specify their choice of metrics for the various criteria proposed. In this manner, several related criteria and other subjective criteria may be further collapsed before an MAUT procedure is employed, and the weights given to those criteria may change.

MAUT Procedures. Given the time constraints of this research and the level of experience of the analysts, the MAUT procedure suffered from inadequate criteria and a single decision maker. Improvements would include following the Delphi procedure with the MAUT questionnaire so that resulting Delphi criteria could be utilized in the pairwise comparisons. The subjects for the MAUT questionnaire should be expanded to include either the original Delphi respondents or someone at the next higher level of management within their organization. Examining the value functions of additional subjects should increase the generalizability of the results and reduce the tendency for the function to change as new decision makers take office. The techniques for this type of interactive, multi-person, multiobjective decision research have been advanced in several recent studies (Lewis and Butler, 1993:1).

Construction of DSS. Because the DERP involves non-discretionary as well as discretionary projects, the use of an MCDM for prioritization is limited to a subset of the overall range of projects submitted. Therefore, a DSS that simplifies use of the MCDM is desirable. This research left the development of the DSS to the DoD and Air Force decision makers. Future research could entail development of a DSS in addition to improvements in the MCDM.

Conclusion

Prioritizing IRP projects is a complex and arduous task. While it is not difficult to identify the key objectives of the program, it is very difficult to gain a consensus among the stakeholders concerning the relative importance of those objectives and the metrics to be used in prioritizing the proposed projects.

This research has utilized two widely accepted research techniques in developing an MCDM to resolve this problem. The findings indicate two distinct solutions that could be employed at the Air Force decision making level to provide a tentative ranking of discretionary projects. Future research, feedback, and modification of the proposed MCDMs will give the Air Force and DoD a widely accepted, objective means of ensuring the most critical DERP projects are funded despite shrinking budgets.

Appendix A: Glossary of Acronyms

This appendix contains an alphabetical listing of the acronyms used in the text and an explanation of their meaning.

AFCEE	Air Force Center for Environmental Excellence.
AFIRM	Air Force Installation Restoration Management.
AFIT	The Air Force Institute of Technology.
AFMC	Air Force Materiel Command.
AHP	Analytic Hierarchy Process.
ARAR	Applicable or Relevant and Appropriate Requirement.
ATSDR	Agency for Toxic Substances and Disease Registry.
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980, as amended (also known as 'Superfund' Legislation).
CEVR	Civil Engineering, Environmental Restoration Branch.
CWA	Clean Water Act.
DERA	Defense Environmental Restoration Account.
DERP	Defense Environmental Restoration Program.
DOE	The Department of Energy.
DoD	The Department of Defense.
DPM	Defense Priority Model.
DSMOA	Defense-State Memorandum of Agreement.
DSS	Decision Support System.
EPA	The Environmental Protection Agency.
FFA	Federal Facility Agreement.
FFER	Federal Facilities Environmental Restoration.
HRS	Hazard Ranking System.
IAG	Interagency Agreement.
IRA	Interim Remedial Action.
IRP	Installation Restoration Program.
MAD	Median Absolute Deviation About the Median.
MAJCOM	Major Command.

MAUT	Multi-Attribute Utility Theory.
MCDM	Multicriteria Decision Model.
NCP	National Contingency Plan.
NPL	National Priorities List.
OSWER	Office of Solid Waste and Emergewncy Response.
PA/SI	Preliminary Assessment/Site Inspection.
PRP	Primarily Responsible Party.
RAAS	Remedial Action Assessment System.
RACER	Remedial Action Cost Engineering and Requirements System.
RCRA	Resource Conservation and Recovery Act of 1980, as amended.
RD/RA	Remedial Design/Remedial Action.
RI/FS	Remedial Investigation/Feasibility Study.
RMS	Root Mean Square
SARA	Superfund Amendments and Reauthorization Act of 1986.
SAB	Scientific Advisory Board.
SAW	Simple Additive Weighting.
SSAB	Site-Specific Advisory Board.
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution.
USC	United States Code.

Appendix B: AFCEE Remediation Matrix - Hierarchy of Preferred Alternatives

This appendix contains a copy of the AFCEE remediation matrix showing the preferred remediation alternatives for specific contamination scenarios.

AFCEE REMEDIATION MATRIX - HIERARCHY OF PREFERRED ALTERNATIVES

	POL-Vadose Zone (i.e., jet fuel, diesel)	POL-Excavated Soil	Floating Product Deep (>20ft)	Floating Product Shallow (<20ft) Low Permeability	Floating Product Shallow (<20ft) High Permeability	Dissolved Fuel in Ground Water (BTEX)	Chlorinated Solvents in Vadose Zone (i.e., TCE)	Dissolved Chlorinated Solvents in Ground Water	Heavy Metals in Vadose Zone	Heavy Metals in Excavated Soil	POL Vapor Treatment	Chlorinated Solvent Vapor Treatment
Natural Attenuation/Assimilation	1	1	1	1	1	1	1	1	1	1		
Bioventing	2	4					3 co-metabolism					
Soil Vapor Extraction	3	5					2					
Heat Enhanced Vapor Extraction	4						4					
Low Permeability Cover/Cap	5						6		3			
Excavate and/or Haul	6	8					7		4	4		
Composting (no tilling)		2										
Land Farming		3								2		
Low Temp Thermal Desorp		6										
Incineration (High Temp)		7										
Apparent vs Actual Studies			2	2	2							
Passive Extraction Wells			4	5	4							
Hand Bail if Appropriate			3	3	3							
Vacuum Assist Pumping				4	5							
Dual Pump System			5									
Air Sparging						2		2				
Passive Treatment Wall						3		3				
Conventional Pump and Treat						4		4				
Slurry Wall						5		5				
Stabilization							5		2	3		
Permitted Direct Emission											1	1
Flare											2	
Biological Filter											3	2 co-metabolism
Catalytic Incineration											4	3
On-site Regenerated Polymer											5	4
Carbon Adsorption											6	5

THIS MATRIX IS AN ATTEMPT TO RANK TECHNOLOGIES THAT SHOULD BE CONSIDERED FOR USE AT COMMON AIR FORCE SITES. MANAGERS SHOULD USE THIS HIERARCHY FOR SCREENING TECHNOLOGIES AND SHOULD BE ABLE TO JUSTIFY WHY A PARTICULAR TECHNOLOGY WAS SELECTED OVER OTHERS WITH LOWER NUMBERS. FOR INSTANCE, IF SOIL VAPOR EXTRACTION (3) IS THE SELECTED TECHNOLOGY FOR POL IN THE VADOSE ZONE, THEN MANAGERS SHOULD BE ABLE TO JUSTIFY WHY NEITHER NATURAL ATTENUATION (1) NOR BIOVENTING (2) WAS SELECTED. THE NATURAL ATTENUATION/ASSIMILATION ALTERNATIVE SHOULD ALWAYS BE CONSIDERED FIRST AND, IF SELECTED, SHOULD BE BASED ON A SCIENTIFICALLY DEFENSIBLE RISK ASSESSMENT. SELECTION OF THIS TECHNOLOGY SHOULD BE ACCOMPANIED BY FIELD SAMPLING AND MODELLING TO QUANTIFY AND PREDICT NATURAL ATTENUATION RATES. A LONG-TERM MONITORING PROGRAM SHOULD BE IMPLEMENTED TO VERIFY NATURAL ATTENUATION MODEL PREDICTIONS.

Appendix C. Pre-Questionnaire for MAUT Procedure

This appendix contains the pre-questionnaire used in the MAUT procedure to familiarize the decision maker with the MAUT process, and to elicit the criteria of importance in the DERP.

The responses indicated in bold, italicized type are primarily attributable to the decision maker. Note: not all questions were asked/answered.

Prequestionnaire Outline:

Goals:

1. Familiarize Col. Owendoff with concepts and techniques.

   - x, y, and z space (alternatives, criteria, preference)
   - ordinal/cardinal, discrete/continuous, independence among variables (preferential, utility)

2. Determine objectives, criteria, and metrics.

3. Discuss potential DSS framework.

Questions for Col. Owendoff:

1) What is the alternative space, or in other words, do you prefer scoring sites or projects? ***Prefer to prioritize by site.***

2) What is the criterion set, or in other words, what parameters do you consider important enough to include in a decision support system? Which must be met at a minimum level and which can be evaluated on a graduated scale? What measures should we use to evaluate them? (want to reduce # of judgements required and complexity of DSS)

a) Protection of human health and the environment. (DPM score at site? DPM before and after? Urgency measure?)
Important, DPM & urgency.

b) Meeting ARARs. (Peer review? Base judgement?)

c) Long-term effectiveness/permanence. (post-project DPM?)
Effectiveness is important, but ? metric.

d) Reduction in toxicity, mobility, volume of waste. (contaminant remaining? post-project DPM?)

e) Short-term effectiveness/risk of action. (Peer review?)

f) Implementability/feasibility. (Peer review?, MAJCOM review? Past track record?)
Peer review already used for RA's.

g) Cost-effectiveness. ($'s for project?, $'s for overall fix?)
Important, $ for project.

h) Acceptability by State. (IAW agreements?)
Maybe, but agreements weren't built with today's fiscal constraints in mind.

i) Acceptability by public. (IAW CERCLA/ROD?, MAJCOM review? Urgency measure?)

5) Are the parameters of importance discrete or continuous? (has been funding as continuous but may be forcing the MAJCOMs to make "discrete" choices)

6) What actions are underway to develop priority model for AF?

Working with ACC to use DPM and DPM Quick to prioritize projects.

Other Comments (interactive discussion/brainstorming):

- ***Keep DSS simple, ensure consistency across commands (no gaming)***

- Could use a system where projects are prescreened and the MCDM could be applied to those that aren't "must-pay" projects or projects that could obviously be deferred:

  -- Fund management & monitoring up-front.

  -- Rank "best" projects IAW MCDM. Results could be categorized as "superior" projects for immediate funding, "inferior" projects for deferral, and "marginal" projects for further consideration. MCDM would provide breakout for all three and initial ranking for "marginal" projects.

- ***Research should develop solutions that we can evaluate and get ideas from.***

Appendix D. Questionnaire for MAUT Procedure

This appendix contains background information and the questionnaire used to elicit the preference structure of the decision maker for use in the MAUT procedure.

The decision maker's responses are indicated by bold, italicized, and underscored type.

Background Information:

Criteria: The criteria used to evaluate projects submitted for DERA funding were determined from the literature review and reflect an aggregation of the broad range of suggested criteria. By combining similar criteria, it should be possible to maintain independence among the criteria and simplify the model. The criteria have been left general enough to apply to all types of projects while still providing a discriminatory ability. The criteria chosen include:

a. Site risk. This criterion has been identified in most previous studies, is a statutory consideration, and is emphasized in Air Force regulations and guidance. A project associated with a high risk site will be assumed to be strongly correlated with protection of human health and the environment, risk reduction, and reduced future liability.

b. Major Command (MAJCOM) priority. This measure is an attempt to combine several subjective criteria mentioned in the literature while recognizing the difficulty of establishing a meaningful, quantitative measure to those criteria. MAJCOMs with 50 or more sites would be asked to rank the projects submitted each fiscal year on the basis of the:

1) urgency of the requirement (whether or not it is required in the current fiscal year by statute, agreement, or as a result of other pending actions like new construction on the site),

2) feasibility of the technology to be employed,

3) political sensitivity of the site,

4) compliance with established planning documents and concurrence of the technical review committee and affected public, and

5) environmental equity (site goals are commensurate with other sites),

6) overall compliance with Air Force goals (10% of the sites closed each year, 60% of the funds spent on remedial actions, and complete all sites by the year 2000).

MAJCOMs and other activities with fewer than 50 sites would have their projects evaluated and prioritized by a committee from the Air Force Center for Environmental Excellence (AFCEE). AFCEE has a good understanding of overall Air Force requirements and provides technical support to many of the smaller commands.

c. Cost. The need for a prioritization model is predicated on an overall funding shortfall. The literature consistently cited cost effectiveness as an important factor to the resulting decision, and several studies used cost/benefit ratios to prioritize the alternatives. This model will not seek to optimize the ranking of projects by using costs in this manner; rather, the decision maker's utility for project costs will be combined with the other factors in a determination of the overall value function.

Metrics: The following metrics were used to represent the three criteria selected for use in the decision support system. The metrics were selected because they can be represented on a ratio scale. The appropriate scaling functions and weights will be determined from the questionaire.

a. Risk: Risk will be measured using a DPM score. DPM was developed to assist DoD in prioritizing sites and is a reflection of the overall risk presented by the site. While a reduction in risk is perhaps a better metric for projects like removal actions and remedial actions, other categories of projects have no potential to reduce risk. Therefore, the site risk represented by the DPM score will be used for all projects.

b. MAJCOM priority: The MAJCOM priority will be converted into a value between zero and one with the following equation:

$$\text{Value} = 1 - [\text{priority} / \text{total number of projects}]$$

A MAJCOMs highest priority project will have a value almost equal to one. The lowest priority project will have a value of zero. Since this process establishes a zero to one scale and establishes mid-management's utility for the projects, the questionaire will only be used to determine the decision maker's preference for the weight to given to this criterion in the overall utility function.

c. Cost: Cost is the most straightforward measure, yet the magnitude of the potential disparity between the highest cost project and the lowest could reduce the discriminatory power for low and moderate cost projects (e.g. if the most expensive project cost $10 million and the scale was based on total cost divided by the most expensive project, all projects under $1 million would be be scaled between 0.9 and 1.0). Therefore, in addition to weight, a utility scale associated with costs must be determined from the questionnaire and it may be non-linear.

Questionnaire to Determine A Value Function
For IRP Prioritization

A. Assume for the following questions you are comparing two projects that fall very close to the funding cutoff point.

1. Site A has a DPM score of 35. Site B under a different MAJCOM has a DPM score of 15. Similar RD projects are submitted for both sites at a cost of $100,000. What difference in MAJCOM priorities would make you chose the project at the Site B over Site A?

   a. I would always chose Site A.
   b. A difference of at least ___/100.
   c. I would be indifferent to the two projects.

2. Given the same DPM scores as in question 1 but RA project costs of $2.5 million, what difference in MAJCOM priority would make you chose the Site B over Site A?

   a. I would always chose Site A.
   b. A difference of at least ___/100.
   c. I would be indifferent to the two projects.

3. Site A has a DPM score of 15. A similar Site B has the same DPM score. The RI/FS project submitted for Site A cost $150,000 and the RA project for Site B costs $2,000,000. What difference in MAJCOM priorities would make you chose the project at Site B over Site A?

   a. I would always chose Site A.
   b. A difference of at least ___/100.
   c. I would be indifferent to the two projects.

4. Site A has a DPM score of 35. A similar Site B has the same DPM score. The RI/FS project submitted for Site A cost $150,000 and the RA project for Site B costs $2,000,000. What difference in MAJCOM priorities would make you chose the project at Site B over Site A?

   a. I would always chose Site A.
   b. A difference of at least ___/100.
   c. I would be indifferent to the two projects.

5. Site A has a DPM score of 30. Site B under a different MAJCOM has a DPM score of 15. The same priority of 50 out of 100 was assigned to the projects by their respective MAJCOMs. How much would you have to save to make you chose the RI/FS project at the Site B over the $500,000 RI/FS project at Site A?

   a. I would always chose Site A.
   b. A difference of at least $_____.
   c. I would be indifferent to the two projects.

6. Given the same DPM scores as in question 5 but priorities of 20 out of 100, what difference in costs would make you chose the Site B over the $500,000 RI/FS at Site A?

a. I would always chose Site A.
b. A difference of at least $_____.
c. I would be indifferent to the two projects.
No difference from question 5. No utility in MAJCOM priority.

B. The following questions will be used to determine how much the value you associate with each criterion changes as the other criteria change. Assume for the following questions you are concerned with ranking two projects along just one criterion. Determine the degree you would rank the projects differently based on only the subject criterion while noting the change in the other criteria.

7. MAJCOM X submits Project A for an RA at $4,000,000. MAJCOM Y submits Project B for an RA at $7,000,000.

Case	DPM Score		Priority		Utility Associated With The Difference in Project Cost
	A	B	A	B	None -------- Some -------- Great
#1)	30	40	5	10	X--------X-------**X**-------X--------X
#2)	20	20	20	40	X--------X-------X-------X--------**X**
#3)	50	10	1	20	**X**--------X-------X-------X--------X

8. MAJCOM X submits Project A as their top priority project and MAJCOM Y submits Project B as their middle priority project (50 out of 100).

Case	DPM Score		Cost		Utility Associated With The Difference in MAJCOM Priority
	A	B	A	B	None -------- Some -------- Great
#1)	30	10	$3M	$.2M	**X**--------X-------X-------X--------X
#2)	20	20	$2M	$1M	**X**--------X-------X-------X--------X
#3)	50	10	$5M	$.2M	**X**--------X-------X-------X--------X

9. MAJCOM X submits Project A with a site DPM score of 40. MAJCOM Y submits Project B with a site DPM score of 20.

Case	Priority		Cost		Utility Associated With The Difference in Site DPM Scores
	A	B	A	B	None -------- Some -------- Great
#1)	30	10	$3M	$.5M	X--------X-------X-------X--------**X**
#2)	20	20	$2M	$1M	X--------X-------X-------X--------**X**
#3)	50	80	$.5M	$.2M	X--------X-------X-------X--------**X**

C. Assume for the following questions that you are faced with a situation where you have a choice between a project with an uncertain outcome and a project with an outcome that is guaranteed. You are to chose the cost or DPM score that you would associate with the guaranteed alternative that would make you indifferent between it and the uncertain alternative.

10. You have a choice of contracting options on a "turn-key" project at a newly discover site. You can chose a "cost-plus" type option that places all the risk on the government for the cost incurred at the site. If it turns out the initial report was wrong, your cost is nothing. If it turns out that you have significant contamination, your cost will be $10 million to clean it up. There's a 50/50 chance for either situation. You also have the option of a "firm-fixed-price" contract whereby the contractor would assume all the risk for the site. You would pay him a set fee. The contractor's profit equals the fee your willing to pay minus his costs for cleaning up any contamination found. If the site is clean, his profit equals the fee you've chosen. If it's contaminated, he will lose the difference between the fee your willing to spend and the $10 million. How much would you be willing to pay him for the "firm-fixed-price" contract?

$***5M***____ vs 50/50 chance for $0 or $10M

Now suppose you know that the cost would not exceed $5 million to clean up the site. How much would you be willing to spend for the guaranteed outcome (FFP contract)?

$***2.5M***____ vs 50/50 chance for $0 or $5M

What if the cost would not exceed $2.5 million?

$***1.25M***____ vs 50/50 chance for $0 or $2.5M

What if the cost would not exceed $1 million?

$***.5M***____ vs 50/50 chance for $0 or $1M

New information is uncovered that shows that the contamination will not be a problem. However, you still need to document that to the regulators before you close the site out. The cost of documentation could either $0 or $500,000 with a 50/50 likelihood for either. How much would you be willing to pay for a FFP contract that guarantees the reports will be accepted?

$***.25M***____ vs 50/50 chance for $0 or $.5M

What if the cost would not exceed $250,000?

$***.125M***____ vs 50/50 chance for $0 or $.25M

Now suppose that you authorized the contractor to initiate work under a "cost-plus" basis. At varying stages of the contract you have the option to stop work and change the contract to a "firm-fixed-price" contract. How much would you be willing to pay for the FFP contract under the following scenarios:

50/50 chance costs would be either \$.25M or \$.5M? \$***.375M***

50/50 chance costs would be either \$.5M or \$1M? \$***.75M***

50/50 chance costs would be either \$1M or \$2.5M? \$***1.75M***

50/50 chance costs would be either \$2.5M or \$5M? \$***3.75M***

50/50 chance costs would be either \$5M or \$10M? \$***7.5M***

11. An IRP contractor has recently made headlines with a new strain of microbes that he claims will "render any contamination at any site harmless." You're skeptical, but you're considering giving him a try. You have a contaminated site that has a DPM score of 50. You believe that the new contractor has a 50/50 chance of success at the site. If he succeeds, the site can be closed out permanently. If not, you've neither lost or gained anything at the site. Another contractor, one that you've dealt with before, also offers to work at the site for you under the same terms as the new contractor. You know this contractor cannot completely clean up the site with his technology, but he can reduce the DPM score significantly. At what reduced DPM score would you be indifferent to the two proposals?

DPM of ***30*** vs 50/50 chance of 0 or 50

Before you made your decision in the above problem, new information came in that reduced the existing DPM score at the site to 25. The situation and odds remain as before. At what reduced DPM score would you be indifferent to the two proposals?

DPM of ***15*** vs 50/50 chance of 0 or 25

Once more, new information surfaced. Now the DPM is 15. At what reduced DPM score would you be indifferent to the two proposals?

DPM of ***10*** vs 50/50 chance of 0 or 15

The new contractor with the "miracle microbes" has visited your site and has revised his claims. You now have a choice of using the new contractor who says he can reduce the DPM score from 50 to 25 or the old contractor who can guarantee his work. You still feel the new contractor has a 50/50 chance of success. At what reduced DPM score would you be indifferent to the two proposals?

DPM of ***40*** vs 50/50 chance of 25 or 50

You've been promoted to MAJCOM and have many sites to consider. The scenario is the same at each. Please indicate the reduced DPM you'd be indifferent to given the new contractors claims with their 50/50 uncertainty:

DPM of ***20*** vs 50/50 chance of 15 or 25

DPM of ***30*** vs 50/50 chance of 25 or 35

DPM of ***45*** vs 50/50 chance of 35 or 50

D. As in Section A., again assume for the following questions that you are comparing two projects that fall very close to the funding cutoff line.

12. An RA project for Site A with a DPM score of 30 has been submitted at a cost of $4,000,000. An RI/FS project for Site B with a similar DPM score of 30 has been submitted at a cost of $1,500,000. What MAJCOM priorities would make you indifferent between the two projects?

NONE Site A: ______ vs Site B: ______

If the cost for Site A were only $2,000,000?

NONE Site A: ______ vs Site B: ______

13. An RD project for Site A with a DPM score of 15 has been submitted at a cost of $1,000,000. An RI/FS project for Site B with a DPM score of 35 has also been submitted at a cost of $1,000,000. What MAJCOM priorities would make you indifferent between the two projects?

NONE Site A: ______ vs Site B: ______

If the DPM at Site A was 25?

NONE Site A: ______ vs Site B: ______

14. An RD project for Site A with a DPM score of 15 has been submitted with a priority of 50 out of 100. An RI/FS project for Site B with a DPM score of 35 has also been submitted with a priority of 10 out of 100. What project costs would make you indifferent between the two projects?

NONE Site A: ______ vs Site B: ______

If the DPM at Site A was 25?

NONE Site A: ______ vs Site B: ______

E. As a control on the calculations of your utility function, please take a few minutes to answer the following questions:

15. Which of the criteria do you feel is most important in ranking IRP projects?

DPM Score at a Site _X_ MAJCOM Priority ___ Cost ___

The least important?

DPM Score at a Site ___ MAJCOM Priority ___ Cost _X_

16. Do you believe there are other more important criteria that aren't accounted for in the questionaire? (Please list them in order of importance.)

All of the important criteria have been used (risk,cost). Need to define the statistical ranges for DPM values (high, med, low).

17. How much flexibility would you estimate a project manager has in scaling back their projects if a fair share allocation of all eligible projects is used rather than a ranking method?

Very Flexible.

Proposed alternative priority system:

manpower
mgt (MAP, TRC, CRP)
LTO
LTM
PA/SI (SARA Docket)
RI/FS, RD/RA where DPM>40
TPS
Off-base migration
Source removal/free product IRAs
RI presumptive remedies
RI --> RA DPM between 10 and 40, In situ remedies
RI --> RA DPM between 10 and 40, Non-In situ remedies

Appendix E. Suggested List of DERP Experts

This appendix contains the electronic mail note from Captain Rob Wilson of AFIT/DE with the list of suggested DERP experts for use in the Delphi procedure.

From: SMTP%"rdwilson@AFITDE.AFIT.AF.MIL"
To: TELLINGS@CSC.AFIT.AF.MIL <TELLINGS@CSC.AFIT.AF.MIL>,
CC:
Subj: DERP Experts

Date: 05 Mar 93 11:25:28 EST
From: Capt Rob Wilson <rdwilson@AFITDE.AFIT.AF.MIL>,
Subject: DERP Experts
To: TELLINGS@CSC.AFIT.AF.MIL
<TELLINGS@CSC.AFIT.AF.MIL>,
X-Office_CC: Capt Rob Wilson

Maj Stuart Nelson	HQ USAF/CE	(202)767-4616 -6245	DSN-297-4616 -6245
Mr Bob James	OO-ALC/EMR	(801)777-6741	DSN 458-6741
Mr Mario Ierardi	SM-ALC/EMR	(916)643-0531	DSN 633-0531
Mr Ron Lester	645 ABW/EMR	(513)257-2201	DSN 787-2201
Mr Tony Sculimbrene	645 ABW/EM	(513)257-5586	DSN 787-5627
Mr Ron Sharpe	AFCEE/ESRR	(210)536-5218	DSN 240-5218
Mr Tony Zugay	AFCEE/ESRR	(210)536-5211	DSN 240-5211
Maj Ross Miller	AFCEE/ESRCT	(210)536-4329	DSN 240-4333
Mr Michael Trimeloni	HQ AFMC/CEVR	(513)257-7053	DSN 787-7053

Also recommend MAJCOM Reps.

(MAJCOM Rep names from Maj Stu Nelson)
MAJCOM Reps:

Ms Martha Shelby	USAFA/DEI	(719)472-4483	DSN 259-4483
Mr James A Rumbley	HQ AU/CEV	(205)953-6976	DSN 493-6976
Mr Robert Akridge	HQ AFRES/CEV	(912)327-1070	DSN 497-1070
Mr Timothy Corbett	HQ AMC/CEVR	(618)256-XXXX	DSN 576-XXXX
Mr Bob Matsumoto	HQ PACAF/CEVR	(808)486-8920	DSN 448-0470
Mr Bob Moore	HQ ACC/CEVR	(804)764-3108	DSN 574-3108
Capt Frank Miles	HQ ATC/CEV	(210)652-3240	DSN 487-3240
Capt William A. Thacker	1100CES/CEV	(202)767-5443	DSN 297-5443
Mr K. Jeff Mundey	HQ AFMC/CEVR	(513)257-7053	DSN 787-7053
Mr Gary Hinkle	ANGRC CEV	(301)981-8146	DSN 858-8146
Maj Mary Vroman	HQ SPACECOM/CEV	(719)554-5187	DSN 692-5187

Note: List is not even close to all inclusive.

Regards,

Rob

--------------------- Original Memo ----------------------

To: Capt Rob Wilson From:
TELLINGS@CSC.AFIT.AF.MIL
Subject: DERP Experts Date Sent: 03/04/93

RETURN-PATH: <TELLINGS@CSC.AFIT.AF.MIL>
RECEIVED: FROM CSC.AFIT.AF.MIL BY AFITDE.AFIT.AF.MIL ; 04 Mar 93 16:26:51 EST
Date: Thu, 4 Mar 1993 16:25:54 -0500 (EST)
From: TELLINGS@CSC.AFIT.AF.MIL
Message-Id: <930304162554.24a09bb8@CSC.AFIT.AF.MIL>
Subject: DERP Experts
To: rdwilson@afitde.afit.af.mil
X-Vmsmail-To: SMTP%"rdwilson@afitde.afit.af.mil"

Capt. Wilson,

Thanks again for the guidance materials on IRP management. I was hoping I could get you to repeat that list of recommended MAJCOM-level DERP experts, and any other experts you think might be helpful in reaching a consensus on prioritization criteria for DERP projects.

Also, if you do happen to get a copy of the Air Staff guidance from Maj. Nelson, I'd sure like to have a look at it, and would appreciate it if you'd give a call.

Thanks,

Tom Ellingson AFIT/ENV/GEE

Appendix F. Cover Letter and Questionnaire for Delphi Round One

This appendix contains the cover letter and questionnaire used to determine the experts' preferences for criteria to be used in the prioritization of DERP projects.

From: Thomas E. Ellingson (Commercial 513-427-0041)
AFIT/ENV-93S
Wright-Patterson AFB, OH 45433

Subj: IRP Prioritization Research

To:

1. As part of a collaborative master's thesis, my colleague, Mr Gene Gallogly, and I are analyzing the decision process involved in prioritizing Installation Restoration Program (IRP) projects. We need your assistance in identifying some critical factors in the prioritization effort. Please take a few minutes, at your earliest convenience, to read through the following pages and answer the questions included with this package. I would appreciate it if you could return your completed questionnaire via fax to Tom Ellingson, Box 4122, AFIT/ENV (Fax: DSN 986-4943 / Commercial 513-476-4943) before 28 May 1993.

2. As I am sure you are aware, prioritizing IRP projects is a rigorous, time-consuming task. Lack of critical information, the diversity of projects, the multi-phased nature of projects, and the uncertainties inherent in the various technical requirements of these projects further complicate the prioritization effort. Through this research, my colleague and I hope to enumerate key factors which would assist IRP decision makers to more easily determine the relative importance of a given project. From this starting point, we hope to develop a decision support system which can be easily manipulated to accommodate the changing requirements of the Installation Restoration Program. An executive summary of the findings of this process will be made available to you, if desired, upon completion in September 1993.

3. I am asking for your assistance in participating in a Delphi-style process which will take place in a number of iterations.

a. This first round of questions will attempt to establish a set of criteria, upon which comparisons between IRP projects may be based to determine priority. You are asked to: 1) examine the criteria listed and add others which you feel should be included, or delete those criteria which you feel should not be included, when considering the priority of IRP projects, 2) suggest a means of measuring each criterion, and 3) assign a weight to each criterion to indicate its relative importance. Please provide a short justification for any criteria which are added/deleted.

b. After receiving responses from the first round of questions, I will compile the responses and send the results of all participants back to you. This will allow you to see how other IRP managers placed emphasis on the various criteria, give you the opportunity to see any new criteria which have been added, and also allow you to re-weight the new set of criteria in light of this compiled information.

c. Subsequent iterations of questions may be used to further refine the weighting factors, or to gather other data as needed for the construction of the decision support system.

4. Identifying the critical factors and their relative importance will be a big step toward a decision support system to assist in prioritizing IRP projects. Awareness of these factors will also help define the information requirements necessary to support the decision making process. If you have any questions or concerns about this research, please do not hesitate to contact my thesis advisor, Dr. Yupo Chan, at DSN 785-2549 / Commercial 513-255-3362. Thank you for your assistance.

Thomas E. Ellingson
AFIT Graduate Student

1 Atch
1. Questionnaire #1

Factors in Prioritizing IRP Projects
Questionnaire #1

Name:____________________________________

<u>Part I</u>

As an IRP manager, you have experienced the task of determining the relative importance of IRP projects. Please examine the nine criteria listed below (promulgated by the National Contingency Plan [The NCP, 40 CFR 300.430(e)(9)]) for their appropriateness in prioritizing Air Force IRP projects. Please feel free to delete any criteria which you feel are not appropriate for any reason, or to add any criteria which you feel have been excluded. Please provide a brief justification for any deletions or additions. Also, please suggest a means of measurement for all criteria which you feel are appropriate for use in the prioritization of IRP projects.

Examples: Criterion: <u>Cost</u>
Measured by: Total lifetime project cost

Criterion: <u>State acceptance</u>
Measured by: Compliance with federal facility agreement (yes/no)

---

1. Criterion: <u>Protection of human health and the environment</u>
Measured by:

2. Criterion: <u>Compliance with applicable or relevant and appropriate requirements (ARARs)</u>
Measured by:

3. Criterion: <u>Long term effectiveness and permanence</u>
Measured by:

Part I (cont.)

4. Criterion: Reduction in toxicity, mobility, and volume of contaminant
   Measured by:

5. Criterion: Short term effectiveness
   Measured by:

6. Criterion: Implementability
   Measured by:

7. Criterion: Cost
   Measured by:

8. Criterion: State acceptance
   Measured by:

9. Criterion: Community acceptance
   Measured by:

10. Criterion:
    Measured by:

Part I (cont.)

11. **Criterion:**
    Measured by:

12. **Criterion:**
    Measured by:

13. **Criterion:**
    Measured by:

14. **Criterion:**
    Measured by:

Part II

Using your answers in Part I, please rank the factors in order of importance, from most to least important. Weight these criteria using a scale of 1 to 100. Assign a weight of 100 to the criterion you feel is most important, and judge all others in light of that criterion. For example, one almost as important might be 95; half as important would be 50.

	Rank Ordered Criteria:	Relative weight:
1.		100
2.		
3.		
4.		
5.		
6.		
7.		
8.		
9.		
10.		
11.		
12.		
13.		
14.		

Appendix G. Cover Letter and Questionnaire for Delphi Round Two

This appendix contains the cover letter and questionnaire used to refine the criteria and weights which were determined from the first round of the Delphi procedure.

From: Thomas E. Ellingson (Commercial 513-427-0041)
AFIT/ENV-93S
Wright-Patterson AFB, OH 45433

Subj: IRP Prioritization Research

To:

1. Thank you for your response to the first Delphi questionnaire. I have compiled the results from all respondents, and based upon the responses gathered, I have prepared the second round of questions. Please take a few minutes to complete the attached questionnaire (Atch 1). Please note that if you did not return or participate in the first questionnaire, you are still encouraged to participate in, and give your input to this second questionnaire. I would appreciate it if you could return your completed questionnaire via fax to Tom Ellingson, Box 4122, AFIT/ENV (Fax: DSN 986-4943 / Commercial 513-476-4943) before 18 June 1993.

2. a. As can be seen in the Round One Summary of Results (Atch 2), responses to the Delphi questionnaire produced a rich list of criteria considered to be important in the prioritization of IRP sites.

b. As shown in the Summary of Results, there were eight participants in Round One. These IRP experts identified 21 criteria of importance in IRP site prioritization Twelve of these criteria were identified by more than one respondent, and nine of the criteria were identified by six or more respondents.

c. The final weight assigned to each criterion is simply the average of all weights assigned to that criterion by the respondents.

3. In compiling the resonses to the first round of questions, I noticed that a nimber of criteria returned by different responses held only slight semantic differences. As the coordinator of this Delphi study, I attempted to narrow the breadth of the study by 'collapsing' several of the criteria into similar categories. In some cases, the exact wording of the criteria may have been changed in order to facilitate categorization of the criteria. This is evident in Questionnaire #2, as you will notice that I have taken the 21 criteria from Round One, and collapsed them into eight criteria for this round. The eight criteria are ranked roughly in the order of importance as derived from the criteria returned from Round One. In Attachment 3 I have given a definition for each of the criteria, as well as a proposed method of measurement, arrived at by taking the majority of responses for that particular criterion.

4. For this round you are given the information from all Round One responses. You are asked to examine these data, and re-weight the the IRP prioritization criteria in light of the information compiled from the first round of questions. If you do not agree with the grouping of the criteria as they now stand, the definitions presented, or the proposed means of measurement for the criteria, please feel free to make comments on Questionnaire #2.

5. If you have any questions or concerns about this research, please do not hesitate to contact my thesis advisor, Dr. Yupo Chan, at DSN 785-2549 / Commercial 513-255-3362. Thank you for your assistance.

Thomas E. Ellingson
AFIT Graduate Student

3 Atch
1. Questionnaire #2
2. Round One Summary of Results
3. Criteria Definitions and Proposed Means of Measurement

Attachment 1

Development of Factor Utility in Prioritizing IRP Projects
Questionnaire #3

Name:________________________________

The following is a summary of the responses to the recent questionnaire on criteria involved in the prioritization of Department of Defense (DOD) Installation Restoration Program (IRP) projects. The list of criteria has been 'collapsed' from the 21 criteria returned in response to Round One, into the following list of eight criteria. The original 21 criteria were scored based upon the average weight assigned by the respondents (no response to a criterion amounted to a weight of zero being assigned by that respondent).

Please take a few minutes to review the summary (Atch 2), and weight the following criteria using a scale of 0 to 100. Assign a weight of 100 to the criterion you consider to be the most important in prioritizing DOD IRP projects, and judge all others according to that standard. For example, one almost as important might be given a weight of 95; one half as important would be given a weight of 50, and so on. Assign a weight of zero to any criterion that you feel should not be considered. Remember that the order shown is merely an approximation of the composite ranking from the first round; your ordering of these criteria will most likely not match the printed order.

Criteria	Relative Weight
1. Threat to Human Health and the Environment (Incorporates Criteria 1, 10 & 12)	________
2. Technical Feasibility of Site Remediation (Incorporates Criteria 2 & 9)	________
3. Cost (Incorporates Criteria 2, 3, 4, 15 & 18)	________
4. Expected Reduction of Risk (Incorporates Criteria 4, 6, 7 & 14)	________
5. Federal Facility Agreement (FFA/IAG) (Incorporates Criteria 8, 11, 13, 16 &17)	________
6. Community Acceptance (From Criterion 5)	________
7. Socioeconomic/Political Impacts (Incorporates Criteria 19 & 20)	________
8. Mission Impact (From Criterion 21)	________

Attachment 3

Definitions of Proposed Criteria
and
Means of Measurement

1. Threat to Human Health and the Environment:
The relative risk presented by a site to human health or the environment. Measured by Defense Priority Model (DPM) score.

2. Technical Feasibility of Site Remediation:
The availability of an acceptable, proven remediation technology which will meet the site-specific applicable or relevant and appropriate requirements (ARARs). Measured in binary (yes/no), by availability.

3. Cost:
The total estimated lifetime cost of all projects associated with the site. This includes project costs associated with implementing and maintaining institutional controls (to meet ARARs), such as A/E design costs and remedial action costs; costs of potential delays if work in progress is not completed in a timely manner; prevention of future costs through immediate action or pollution prevention; etc. Measured by present value of the total dollar cost estimate over the lifetime of the remediation effort.

4. Expected Reduction of Risk:
The estimated amount of risk (actual or potential) which can be reduced through remediation efforts. This will include both short- and long-term expected effectiveness of remedial actions. Measured by estimated reduction in DPM score.

5. Federal Facility Agreement (FFA/IAG):
The presence of a Federal Facility Agreement (FFA) or an Interagency Agreement (IAG) which specifies a procedural framework and time schedule for the site. Measured in binary (yes/no), by presence.

6. Community Acceptance:
Degree to which the local community, including all stakeholders, supports the proposed remediation effort. This will be determined by communication with the Technical Review Committee and Public Affairs. Measured as high, medium, or low level of support.

7. Socioeconomic/Political Impacts:
The anticipated impacts of site remediation efforts on the quality of life, local economy, and/or local politics in the neighboring areas. Measured as varying degrees of impact (positive, no impact, or negative).

8. Mission Impact:
The anticipated impact of site remediation efforts on the ability of various base organizations to perform their designated missions. Measured as varying degrees of impact (positive, no impact, or negative).

Appendix H. Cover Letter and Questionnaire for Delphi Round Three

This appendix contains the cover letter and questionnaire used to determine the experts' utilities for specific data points within the criteria.

From: Thomas E. Ellingson (Commercial 513-427-0041)
AFIT/ENV-93S
Wright-Patterson AFB, OH 45433

Subj: IRP Prioritization Research

To:

1. Thank you for your response to the second Delphi questionnaire. The uniformity of the results seem to indicate a great degree of consensus among the respondents, and based upon these responses, I have prepared the third and final round of questions. Please take a few minutes to complete the attached questionnaire (Atch 1). Please note that if you did not return or participate in either of the previous questionnaires, you are still encouraged to participate in, and give your input to this final questionnaire. I would appreciate it if you could return your completed questionnaire via fax to Tom Ellingson, Box 4122, AFIT/ENV (Fax: DSN 986-4943 / Commercial 513-476-4943) before 02 July 1993.

2. a. As can be seen in the Round Two Summary of Results (Atch 2), responses to the second Delphi questionnaire seem to indicate a strong consensus regarding the criteria considered to be important in the prioritization of IRP sites.

b. As shown in the Summary of Results, there were six participants in Round Two. Each of these IRP experts confirmed the eight criteria of importance which were produced by collapsing the results of the previous input from Round One. The scoring of the criteria by the respondents indicates that there is some degree of variance of opinion among the experts, but taken as a whole, the rank order of the criteria changed very little between Round One and Round Two. This seems to indicate a strong preference structure for the criteria as they are now ordered.

c. Once again, the final weight assigned to each criterion is simply the average of all weights assigned to that criterion by the respondents.

3. For this round, you are given the information from all Round Two responses. However, no further changes will be made to the criteria of importance or the weighting factors for these criteria. Instead, I will ask you to examine a set of data points for each criterion and give your utility for that set of data points. The utility function is a method of bringing each of the measurements for the criteria to a common scale, and is essential in the creation of a model for use as a decision support system. Further directions and explanations are included in the questionnaire

4. I wish to give my deepest thanks for your participation in this series of questionnaires. Your input to the research being done by myself and my thesis partner, Mr Gene Gallogly, has been invaluable to our research effort, and will hopefully result in a decision support system that will be a small step toward better Installation Restoration Program management, priority-setting, and decision making. The scheduled completion date for our work is 01 September 1993. After that time, Mr Gallogly and I would be very happy to send you an executive summary of our work.

5. If you have any questions or concerns about this research, please do not hesitate to contact my thesis advisor, Dr. Yupo Chan, at DSN 785-2549 / Commercial 513-255-3362. Once again, thank you very much for your assistance.

Thomas E. Ellingson
AFIT Graduate Student

2 Atch
1. Questionnaire #3
2. Round Two Summary of Results

Attachment 1

Development of Factor Utility in Prioritizing IRP Projects
Questionnaire #3

Name:____________________________________

The following set of questions is intended to determine your utility for specific values within each of the criteria which were determined in the previous two iterations of Delphi questionnaires. The Summary of Results for Round Two is included as Attachment 2, and it details how individual respondents weighted each of the criteria.

Please take a few minutes to examine each of the questions before beginning. Then return to the beginning of the questionnaire and assign utility values to the given data points on questions which require input. Please use a scale of 0 to 100 when assigning your utility values. A utility score of 100 would indicate a situation within the criterion parameters which would most strongly qualify a site for immediate attention; a utility score of 0 would indicate a situation within the criterion parameters which would most strongly discourage a site from receiving immediate attention. Please be sure to take into account the entire range of all possible data points within a particular criterion when assigning your utility values.

As an example of a possible response, the utility for net present worth of total remediation effort cost might look like the following:

Cost:

	Data Point	Utility
Total Site	$50,000	– 95
Remediation	$200,000	– 90
Cost:	$500,000	– 85
	$1,000,000	– 70
	$2,000,000	– 50
	$4,000,000	– 35
	$10,000,000	– 15

Please note that questions 2 and 5 do not require input, as they are binary choice criteria. For these criteria, a 'yes' response will be scored as a utility of 100 (best case), and a 'no' response will be scored as a 0 (worst case).

Also, please note that it is not the intent of this set of questions to identify the highest or lowest feasible values for any particular criterion being considered. Therefore, it is not expected that the first data point should necessarily be given a value of 100, nor that the last be given a value of 0. This set of questions is simply attempting to extract an individual utility for a set of data points which fall in the typical range of values for a particular criterion. Following this step, the individual utility data points will be combined into a composite group utility function which will be used as the basis for the decision support system.

1. ***Threat to Human Health and the Environment:***

The relative risk presented by a site to human health or the environment. Measured by Defense Priority Model (DPM) score.

	Data Point		Utility
DPM Score:	50	–	________
	40	–	________
	35	–	________
	30	–	________
	25	–	________
	20	–	________
	10	–	________

2. ***Technical Feasibility of Site Remediation:***

The availability of an acceptable, proven remediation technology which will meet the site-specific applicable or relevant and appropriate requirements (ARARs). Measured in binary (yes/no), by availability.

This criterion will be measured by assigning a utility of 100 if site remediation is feasible, or a utility of 0 otherwise. Determination of availability is to be made by the Technical Review Committee.

3. ***Cost:***

The total estimated lifetime cost of all projects associated with the site. This includes project costs associated with implementing and maintaining institutional controls (to meet ARARs), such as A/E design costs and remedial action costs; costs of potential delays if work in progress is not completed in a timely manner; prevention of future costs through immediate action or pollution prevention; etc. Measured by net present worth of the total dollar cost estimate over the lifetime of the remediation effort.

	Data Point		Utility
Total Site	$50,000	–	________
Remediation	$200,000	–	________
Cost:	$500,000	–	________
	$1,000,000	–	________
	$2,000,000	–	________
	$4,000,000	–	________
	$10,000,000	–	________

4. ***Expected Reduction of Risk:***

The estimated amount of risk (actual or potential) which can be reduced through remediation efforts. This will include both short- and long-term expected effectiveness of remedial actions. Measured by estimated percent reduction in DPM score. Determination of the expected DPM score reduction is to be performed by the Technical Review Committee.

	Data Point	Utility
% Reduction	90%	– ________
of DPM Score:	75%	– ________
	60%	– ________
	50%	– ________
	40%	– ________
	30%	– ________
	20%	– ________

5. ***Federal Facility Agreement (FFA/IAG):***

The presence of a Federal Facility Agreement (FFA) or an Interagency Agreement (IAG) which specifies a procedural framework and time schedule for the site. Measured in binary (yes/no), by presence.

This criterion will be measured by assigning a utility of 100 if an FFA/IAG is in place and requires site remediation, otherwise, a utility of 0 will be assigned.

6. ***Community Acceptance:***

Degree to which the local community, including all stakeholders, supports the proposed remediation effort. This will be determined by communication with the Technical Review Committee and Public Affairs. Measured as high, medium, or low level of support.

Data Point	Utility
High Support	– ________
Medium Support	– ________
Low Support	– ________

7. ***Mission Impact:***

The net of all anticipated impact of site remediation efforts on the ability of various base organizations to perform their designated missions. Measured as varying degrees of impact (positive, no impact, or negative).

Data Point	Utility
Strong Positive Impact	– ________
Slight Positive Impact	– ________
No Impact	– ________
Slight Negative Impact	– ________
Strong Negative Impact	– ________

8. ***Socioeconomic/Political Impacts:***

The net of all anticipated impacts of site remediation efforts on the quality of life, local economy, and/or local politics in the neighboring areas. Measured as varying degrees of impact (positive, no impact, or negative). Determination of the anticipated impact level is to be performed by the Technical Review Committee.

Data Point		Utility
Strong Positive Impact	–	________
Slight Positive Impact	–	________
No Impact	–	________
Slight Negative Impact	–	________
Strong Negative Impact	–	________

Appendix I. Analysis of Variance Calculations

This appendix contains the calculations performed in association with the analysis of variance for the Delphi weights and utilities.

Criteria	Utilities Mean	Utilities Variance	Normalized Weights Mean	Normalized Weights Variance	(1) Contribution To Score	(2) Criterion Variance
Community Acceptance	32.50	597.46	0.10970	0.00196	3.565	9.260
Risk Reduction	40.00	469.98	0.14240	0.00403	5.696	15.978
Threat to Human Health & Env.	28.33	526.66	0.18430	0.00000	5.221	17.889
Cost	30.83	224.16	0.14290	0.00100	4.406	5.528
Mission Impact	43.33	1386.60	0.09100	0.00473	3.943	20.363
Socioeconomic/Political Impact	39.17	1244.10	0.06430	0.00467	2.519	12.309
Technical Feasibility	100.00	0.00	0.15240	0.00053	15.240	5.300
Federal Facility Agreement	100.00	0.00	0.11290	0.00352	11.290	35.200

Sum of all criteria contributions = 51.880

Sum of all variances of criteria = 121.827

Standard deviation of criteria = 11.038

(1) Criterion contribution to total score = (weight) * (util)

(2) Var(Criterion) = ((util)^2) * (Var(weight)) + ((weight)^2) * (Var(util))

Appendix J. MAUT Calculations

This appendix contains the calculations performed in association with the MAUT procedure to arrive at the weighting factors for the MAUT multi-criteria decision model.

Simplified additive weight function:

$$\text{Value}(y_1, y_2, y_3) = w_1 v(y_1) + w_3 v(y_3)$$

Indifference between projects implies:

$$\text{Value}(_A) = \text{Value}(_B),$$

therefore:

$$w_1 v(y_{A1}) + w_3 v(y_{A3}) = w_1 v(y_{B1}) + w_3 v(y_{B3})$$

Question 5: $DPM_A = 30$ $\quad U_{DPM} = 0.414(30)^{0.02} = 0.67$
$DPM_B = 15$ $\quad U_{DPM} = 0.414(15)^{0.02} = 0.35$

$Cost_A = \$500{,}000$ $\quad U_{Cost} = \$0.5M/\$10M = 0.05$

(Utility for $Cost_B$ can be assumed to be 1.0 since decision maker always preferred site A regardless of cost.)

Question 14.1: $DPM_A = 15$ $\quad U_{DPM} = 0.35$
$DPM_B = 35$ $\quad U_{DPM} = 0.76$

Difference in utility for cost can be assumed to be 1.0 since the decision maker always prefers site B regardless of difference in cost.

$$w_1(0.76) + w_3(0) > w_1(0.38) + w_3(1)$$

also, $\quad w_1 + w_3 = 1$

Simultaneous solution yields: $0 \le w_3 < 0.27$

$0.73 \le w_1 \le 1$

Question 14.2: $DPM_A = 25$ $\quad U_{DPM} = 0.58$
$DPM_B = 35$ $\quad U_{DPM} = 0.76$

$$w_1(0.76) + w_3(0) > w_1(0.58) + w_3(1)$$

also, $\quad w_1 + w_3 = 1$

Simultaneous solution yields: $0 \le w_3 < 0.15$

$0.85 \le w_1 \le 1$

Given the three solutions, we can say that $0.85 \leq w_1 \leq 1$ is the only solution that holds for all three conditions. The decision maker was asked to further interpret these results to pin down a final, single value. The decision maker indicated that he would set $w_1=1$ and let $w_3=0$. In other words, he would not let a difference in cost influence his decision when there existed a difference in site risk.

Bibliography

Air Force Environmental Restoration Division. FY 1993/1994/1995 Defense Environmental Restoration Program Management Guidance for Non-Closure Bases, Guidance Memorandum, HQ AF/CEVR, 15 APR 1992.

Applied Decision Analysis, Inc. Illustrative Application of Three Conceptual Defense Priority Systems (DPS). Report to the U.S. Department of Defense. Menlo Park, CA: May 1990.

Baca, Thomas. Clear and Simple Order at DoD Environmental Program: Comply, Clean Up, Prevent. HMC Plenary Session, 51-55 (March/April 1992).

Barill, Terryn. Risk Communication, Notes from Workshop Series on Investigation and Cleanup of Alaska's Groundwater Resources, Alaska Department of Environmental Conservation, May 1991.

Barron, F. Hutton and Don N. Kleinmuntz. "Sensitivity in Value Loss of Linear Multiattribute Value Models to Attribute Completeness," New Directions in Research on Decision Making. Eds. Berndt Brehmer, and others. Amsterdam: Elsevier Science Publishers B.V., 1986.

Brown, Bernice B. Delphi Process: A Methodology Used for the Elicitation of Opinions of Experts. Santa Monica: The Rand Corporation, 1968.

Center for Technology, Policy and Industrial Development, The. Breaking the Backlog: Improving Superfund Priority Setting. Report to the Coalition on Superfund. Cambridge, MA: Massachusetts Institute of Technology, February 1992.

Chan, Yupo. Multicriteria Decision-Making: A Tutorial, Working Paper WP 91-6. Department of Operational Sciences, School of Engineering, Air Force Institute of Technology, Wright-Patterson AFB, OH, 1991.

-----. Multicriteria Decision-Making. Unpublished working paper. Department of Operational Sciences, School of Engineering, Air Force Institute of Technology, Wright-Patterson AFB, OH, 1993.

Chankong, Vira, and Yacov Y. Haimes. Multiobjective Decision Making, Theory and Methodology. New York: Elsevier Science Publishing Company, Inc., 1983.

Chiras, Daniel D. Environmental Science, Action for a Sustainable Future (Third Edition). Redwood City, CA: The Benjamin/Cummings Publishing Company, Inc., 1991.

Cohrssen, John J. and Vincent T. Covello. Risk Analysis: A Guide to Principles and Methods for Analyzing Health and Environmental Risks. Springfield, VA: U.S. Department of Commerce, 1989.

Dalkey, Norman C. Delphi. Santa Monica: The Rand Corporation, 1967.

-----. The Delphi Method: An Experimental Study of Group Opinion. Santa Monica: The Rand Corporation, 1969.

Department of Defense. Annual Report to Congress for F.Y. 1991. Washington DC: February 1992 (ADA 244196).

Doty, Carolyn B., and Curtis C. Travis. Risk Assessment and Remedial Technology Effectiveness at Superfund Sites, Contract No. DE-AC05-840R21400. Oak Ridge TN: Oak Ridge National Laboratory, 1990.

Earth Technology Corporation, The, and ERM Program Management Company. User's Manual for the Defense Priority Model, FY 93 Version. Office of the Deputy Assistant Secretary of Defense (Environment), The Pentagon, Washington, DC, May 1992.

Edwards, Scott, Jr. Risk Reduction as a Criterion for Measuring Progress of the Installation Restoration Program. MS Thesis, AFIT/GEE/CEV/92S-8. School of Civil Engineering and Services, Air Force Institute of Technology (AU), Wright-Patterson AFB, OH, September 1992.

-----, Air Force Environmental Restoration Division, Bolling AFB, Washington, DC. Telephone interview. 20 July 1993a.

-----, Air Force Environmental Restoration Division, Bolling AFB, Washington, DC. Telephone interview. 20 August 1993b.

Environmental Protection Agency. Federal Facilities Compliance Strategy, EPA 130/4-89/003, November 1988.

-----. National Oil and Hazardous Substances Pollution Contingency Plan, Part II, 40 CFR Part 300, Final Rule. Federal Register, March 1990a.

-----. Reducing Risk: Setting Priorities and Strategies for Environmental Protection, Report of the Science Advisory Board, Washington: GPO, September 1990b.

-----. Superfund: Focusing on the Nation at Large, a Decade of Progress at National Priorities List Sites, EPA/540/8-90/009, September 1990c.

Fox, Catherine A. "Status and Trends in Bioremediation Treatment Technology," Remediation, 1:(3) 293-303 (Summer 1991).

Gregory, Rita A., and Richard R. Rast. "Racing for Cleanup," The Military Engineer, 84:(551) 32-35 (August 1992).

Hattis, Dale, and John A. Smith, Jr. "What's Wrong With Quantitative Risk Assessment?," Biomedical Ethics Reviews, Eds. Robert Armeder and James Humber. Humana Press, 1987.

Hushon, Judith M. "Defense Priority Model Overview." Briefing Slides. Air Force Institute of Technology, 13 May 1993.

Hwang, Ching-Lai and Kwangsun Yoon. Multi Attribute Decision Making Methods and Applications, A State-of-the-Art Survey. New York: Springer-Verlag, 1981.

Janssen, R. and others. "A Methodology for Multiple Criteria Environmental Plan Evaluation," Multiple Criteria Decision Methods and Applications, Selected Readings of the First International Summer School, Acireale, Sicily, September 1983. Berlin: Springer-Verlag, 1985.

Keystone Center, The. Recommendations for Improving the Federal Facilities Environmental Restoration Decision-Making and Priority-Setting Processes. Interim report of the Federal Facilities Environmental Restoration Dialog Committee. Keystone, CO, February 1993.

Kroenke, David M. Management Information Systems. Westonville, CA: Mitchell McGraw Hill, 1992.

Lave, Lester, and Howard Gruenspecht. "Increasing the Efficiency and Effectiveness of Environmental Decisions: Benefit-Cost Analysis and Effluent Fees," Journal of the Air and Waste Management Association, 41:(5) 680-693 (May 1991).

Lewis, Holly S., and Timothy W. Butler. "An Interactive Framework for Multi-Person, Multiobjective Decisions," Decision Sciences, 24: 1-22 (1993).

Long, Gil. A Guide to On-Site Remediation of Hydrocarbons, Special Report. ENSR Consulting and Engineering, 1992.

Lucero, Gene and others. Superfund Handbook (Third Edition). ENSR Consulting and Engineering, and Sidley and Austin, 1989.

Masters, Gilbert M. Introduction to Environmental Engineering and Science. Englewood Cliffs NJ: Prentice Hall, 1991.

Messick, David M. "Decision Making in Social Dilemmas: Some Attributional Effects." New Directions in Research on Decision Making. Eds. Berndt Brehmer, and others. Amsterdam: Elsevier Science Publishers B.V., 1986.

Morgan, M. Granger. "Probing the Question of Technology-Induced Risk," IEEE Spectrum, 18 (11): 58-64 (November 1981).

Morgan, M. Granger, and Max Henrion. Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis. Cambridge, MA: Cambridge University Press, 1990.

Morrison, S. James. "The Study of Variability in Engineering Design." Applied Statistics, VI (2): 133-138 (June 1957).

Myers, Michael, HQ USAF Environmental Compliance Division. Briefing Slides. Washington, DC, 05 December 1991.

Office of Emergency and Remedial Response, US Environmental Protection Agency. Superfund Program Implementation Manual, FY 83, Vol. 1. OSWER Directive 9200.3-01H-1. Washington, DC: US Department of Commerce, June 1992.

Owendoff, James, and others. "Peer Reviews, Program Reviews, and Validation." Briefing at the Air Force Installation Restoration Managers Meeting. Denver, CO, 02 February 1993a.

Owendoff, James, Air Force Environmental Restoration Division, Bolling AFB, Washington, DC. Personal interview. 29 April 1993b.

Owendoff, James, and Scott Edwards, Air Force Environmental Restoration Division, Bolling AFB, Washington, DC. Telephone interview. 08 July 1993c.

Oxenfeldt, Alfred R. Cost-Benefit Analysis for Executive Decision Making. New York: AMACOM, 1979.

Pasternak, Douglas, and Peter Cary. "A $200 Billion Scandal," US News & World Report, 113: 34-47 (14 December 1992).

Preslo, L. M. and others. Remedial Technologies for Leaking Underground Storage Tanks. Lewis Publishing, Inc., 1989.

Putnam, Hayes and Bartlett, Inc. Prioritization of Actions at Superfund Sites. Report to the Coalition on Superfund, 30 March 1992.

Reed, Marcia W., Office of the Deputy Assistant Secretary of Defense for the Environment. Personal memorandum. Arlington, VA, 06 May 1993.

Research and Education Association. Handbook of Economic Analysis. Research and Education Association, 1982.

Rodricks, Joseph V. Calculated Risks. Cambridge: Cambridge University Press, 1992.

Rohrmann, Bernd. "Evaluating the Usefulness of Decision Aide: A Methodological Prospective." New Directions in Research on Decision Making. Eds. Berndt Brehmer, and others. Amsterdam: Elsevier Science Publishers B.V., 1986.

Ruckelshaus, William D. "Risk, Science, and Democracy," Issues in Science and Technology, 1 (3): 19-38 (Spring 1985).

Saaty, Thomas L. The Analytic Hierarchy Process. McGraw-Hill, Inc., 1980.

-----. Decision Making for Leaders. Belmont, CA: Wadsworth, Inc., 1982.

Schooff, Richard M. Design of a Group Decision Support System for Prioritizing Air Force Logistics Needs. MS Thesis, AFIT/GOR/ENS/90M-16. School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB, OH, March 1990.

Spectrum Sciences and Software, Inc. U.S. Air Force Commander's Guide to Environmental Quality, May 1990.

Splitstone, D. E. "How Clean is Clean...Statistically?," Pollution Engineering, 23:(3) 90-94 (March 1991).

Travis, Curtis C., and Carolyn B. Doty. "Superfund: A Program Without Priorities," Environmental Science Technology, 23:(11) 1333-1334 (November 1989).

Tusa, Wayne K. "Reassessing the Risk Assessment," Civil Engineering, 62:(3) 46-48 (March 1992).

Vari, Anna and others. "Supporting Problem Structuring in Decisions: The Case of the Siting of a Hazardous Waste Incinerator," New Directions in Research on Decision Making. Eds. Berndt Brehmer, and others. Amsterdam: Elsevier Science Publishers B.V., 1986.

Vest, Gary. Deputy Assistant Secretary of the Air Force for Environment, Safety, and Occupational Health. Briefing to Engineering and Environmental Management students and faculty. Air Force Institute of Technology, Wright-Patterson AFB, OH, 23 July 1992.

West, Joseph. "AF Plans to Triple Spending on Environmental Cleanup," Air Force Times, 20 May 1991.

Winston, Wayne L. Operations Research: Applications and Algorithms (Second Edition). Boston, MA: PWS Kent Publishing Company, 1991.

Vita

Thomas Eric Ellingson was born on 12 March 1966, in Detroit, Michigan. He was raised in Niles, Michigan, where he was educated in the Brandywine public school system. In 1983, he participated in the American Field Service, and traveled to Bonn, [then]West Germany, as an exchange student. He graduated from Brandywine Senior High School with honors in 1984. He attended Michigan State University, and in 1989, earned the degree of Bachelor of Science in Civil Engineering. Upon graduation, he was recruited as an intern in the Palace Acquire program and was assigned to Hanscom Air Force Base, Massachusetts. During this assignment, he rotated through positions in Civil Engineering Design, where he was part of a multi-disciplinary team designing, reviewing, and revising civil engineering projects; Contract Management, where he monitored civil engineering contracts and represented the government during contract negotiations; and Environmental and Contract Planning, where he designed and performed contract management on environmental projects, and monitored the removal of hazardous materials from the base. In 1992, he was selected to attend the Engineering and Environmental Management program at the Air Force Institute of Technology. Upon graduation, he will rejoin the Environmental and Contract Planning Flight at Hanscom AFB.

Permanent Address: 1551 S. 13th Street
Niles, MI 49120

Vita

Thomas Gene Gallogly was born in Chicago, Illinois on 25 August, 1958. He grew up in Colorado Springs and later attended college in Colorado, obtaining a bachelor of science degree in Engineering Science (Mechanics Option) from Colorado State University in May 1981. Upon graduation, he accepted a job as an aerospace engineer at Tinker AFB in Oklahoma. He worked in the B-52 Division specializing in aircraft materials and structures. In August 1985, he transferred to the Air Force Academy to work as a project programmer in civil engineering. Mr. Gallogly earned an MBA from the University of Colorado while working at the Academy. After two years as Chief of the Program Development Division, he was promoted to head the 11th Air Force Environmental Planning Division at Elmendorf AFB, Alaska. In this position, he was responsible for overseeing all environmental programs for the Air Force in Alaska. Mr. Gallogly was selected to attend the Engineering and Environmental Management program at the Air Force Institute of Technology in 1992.

Permanent Address: 2675 Norwich Drive
Colorado Springs, CO 80920

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 1993	Master's Thesis

4. TITLE AND SUBTITLE

Development of a Multicriteria Decision Model for Prioritizing Air Force Environmental Restoration Program Projects

5. FUNDING NUMBERS

6. AUTHOR(S)

Thomas E. Ellingson
T. Gene Gallogly

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Institute of Technology,
WPAFB, OH 45433-6583

8. PERFORMING ORGANIZATION REPORT NUMBER

AFIT/GEE/ENS/93S-2

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Cleaning up hazardous and toxic wastes left from past activities has become one of the major goals of the Department of Defense. Within the Air Force, individual major commands (MAJCOMs) annually review numerous projects submitted under the Defense Environmental Restoration Program (DERP) and forward these projects to HQ USAF/CEVR for funding. Until recently, adequate resources have been available to fully fund all projects. However, within the last two years, funding shortfalls have been experienced, and projects have received only partial funding. The Air Force needs a decision support system that will assist in determining funding priorities for these projects.

This thesis presents two possible methodologies and resulting multicriteria decision models for determining funding priorities within the constraints of a limited budget. The first method utilizes a Delphi procedure to elicit pertinent criteria, weights, and utilities from DERP experts. The second method utilizes multiattribute utility theory to determine the preference structure of a single decision maker. Each method results in a working model which can be used to prioritize DERP projects. Both models resulted in risk being the primary decision criterion. Additionally, the Delphi model also utilized cost, community acceptance, technical feasibility, mission impact, and socioeconomic impact.

14. SUBJECT TERMS Environmental Restoration, Environmental Cleanup, Installation Restoration Program, Defense Environmental Restoration Program, Prioritization, Multicriteria Decision Model, Delphi, Multiattribute Utility Theory.

15. NUMBER OF PAGES 184

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL