ABSTRACT

Joyce M. Perdek. Decision Analysis of Incineration Costs in Superfund Site Remediation. (Under the direction of Dr. DEBORAH A. AMARAL)

This paper examines the decision making process of the Remedial Design (RD) phase of on-site incineration projects conducted at Superfund sites. Decisions made during RD affect the cost and schedule of the remedial action (RA). Decision analysis techniques are used to determine the extent of information on the waste characteristics that should be released to prospective bidders on a fixed-price RA contract for a specific site. The decision maker has two alternatives: to prepare the project specifications including only the description of the waste provided in the remedial investigation/feasibility study or obtain additional information on the waste characteristics during RD. The dilemma facing decision makers is that costs, in both time and money, are associated with acquiring additional information, while having more information may result in cost savings since bidders base their cost estimates on the description of the waste characteristics. In the analysis, the net benefits of providing bidders with additional information are determined for the subject site. The results show that the benefits of obtaining information outweigh the costs only when the cost of obtaining the information is not too great.

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LIST OF ABBREVIATIONS

ACE	Army Corps of Engineers
APC	Air Pollution Control
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
EMV	Expected Monetary Value
EPA	Environmental Protection Agency
FAR	Federal Acquisition Regulations
HRS	Hazard Ranking System
IFB	Invitation for Bids
MIS	Mobile Incineration System
NCP	National Contingency Plan
NPL	National Priorities List
O&M	Operation and Maintenance
RA	Remedial Action
RD	Remedial Design
RFP	Request for Proposals
RI/FS	Remedial Investigation/Feasibility Study
ROD	Record of Decision
PRP	Potentially Responsible Party
SARA	Superfund Amendments and Reauthorization Act

I. INTRODUCTION

Incineration is an established technology for the treatment and destruction of hazardous waste. Since the mid-1980s, on-site incineration has been a frequently-selected technology for remediating Superfund sites.

The decision making process in the Remedial Design (RD) phase of on-site incineration remediation projects at Superfund sites is examined in this paper. Decisions made during RD affect the cost and schedule of the Remedial Action (RA). The U.S. Environmental Protection Agency (EPA), state environmental departments, and private industry all bear responsibility for conducting these projects and making decisions affecting their outcomes.

This analysis focuses on one particular decision: determining the optimal amount of information on the waste characteristics that should be obtained during RD and released to prospective bidders on the RA contract. The bidders use the information on the waste characteristics to develop their cost proposals for incinerating the waste. Therefore, the amount of information included in the RD documents directly affects the RA cost.

The cost of on-site incineration RAs is significant. A search of EPA's Records of Decision (ROD) System database shows that this technology has been selected as the RA in 56

RODs signed between 1985 and 1990. The total cost for these projects, as estimated in the RODs, is \$1.4 billion, which is an average of over \$25 million per site (U.S. EPA OERR, 1992). The incineration component of RA cost is significant. For three projects reviewed with RA costs ranging from \$14 million to \$52 million, the incineration cost component was between 45 and almost 75 percent of the total contract cost (U.S. EPA OERR DCMB, 1993). Therefore, decisions affecting remedial actions have the potential to result in significant costs being incurred or cost savings.

In a recent Brookings Institution book on problems in Government contracting, Kettl (1993) states that the uncertainty about the magnitude of the problems at Superfund sites contributes to the difficulties EPA has in obtaining services from contractors through effective competition. The problems caused by inadequate waste characterization are exemplified in events surrounding the RA of the Motco site near Galveston, Texas. Remediation efforts have been interrupted because the incineration contractor, International Technology Corporation, has filed a lawsuit against the site's potentially responsible parties (PRP) claiming breach of contract. The lawsuit contends that information describing the material to be incinerated included in the request for proposals (RFP) was inaccurate and misleading, causing major cost increases (ENR, 1991).

Although inadequate waste characterization is cited as

a significant problem, costs in terms of time and money are incurred in obtaining this information. In this paper, decision analysis is applied to determine the net benefits of providing prospective bidders with various levels of information on the waste characteristics for a particular site to be remediated by on-site incineration.

In order to provide an understanding of the regulatory framework and technical considerations surrounding the decision, background information on incineration and the Superfund program is included in Chapter 2. Chapter 3 includes a description of decision analysis as it is used here, presentation of the model for the analysis, and the data used in the analysis. The decision is illustrated in influence diagrams and decision trees. The results and discussion in Chapter 4 present the costs and benefits of obtaining information for many sets of conditions. Chapter 5, the conclusion, includes a discussion on areas of further study.

II. BACKGROUND

Incineration Technology

- Process Description

Incineration is an engineered process using controlled flame combustion to thermally degrade the organic fraction of waste materials. The combustion principle upon which incineration technology is based is the burning reaction between oxygen and organic compounds that produces carbon dioxide and water vapor. An advantage of using incineration as a method for treating hazardous wastes is that it destroys the organic contaminants and, therefore, the associated toxicity. Incineration may also reduce the volume of the wastes (Oppelt, 1987).

Products from the combustion of hazardous waste generally consist of more than just carbon dioxide and water. Incineration systems are designed to handle these byproducts by having air pollution control equipment and a mechanism for ash collection. What byproducts are formed depends on the content of the waste feed and the design and operating conditions of the incinerator. Hydrogen chloride is formed during the incineration of chlorinated hydrocarbons. Similarly, hydrogen fluoride and hydrogen bromide are formed during the incineration of organic fluorides and organic bromides, respectively. Sulfur oxides

are formed from sulfur present in the waste material and auxiliary fuels. Nitrogen oxides are formed from nitrogen contained in the waste material and in the combustion air. Suspended particulate emissions and bottom ash are produced and include mineral oxides, salts from the mineral constituents in the waste material, and metals from the waste materials and auxiliary fuel. The volatile metals present in the waste may enter the gaseous phase. A variety of organic compounds may be formed due to incomplete combustion of organic compounds present in the waste and auxiliary fuel (Oppelt, 1987).

Mobile or transportable incinerators are transported to contaminated sites for their remediation. These systems have been developed in response to concerns about the dangers and costs of transporting hazardous waste off-site to stationary treatment units. This technology was first demonstrated by the U.S. EPA whose Office of Research and Development constructed a prototype system. EPA's Mobile Incineration System (MIS) was demonstrated successfully in New Jersey and Missouri in the 1980s. Private companies have followed suit and developed a variety of units that have been used for site remediation (Oberacker, 1991).

Mobile or transportable incineration systems consist of the following process operations: waste preparation; waste storage; waste feed; incineration; air pollution control, which may include wastewater treatment; and residue or ash

handling. A schematic of a mobile/transportable incineration system is presented in Figure 1 (U.S. EPA OERR and ORD, 1990).

Waste preparation includes excavation of soils, pumping of liquids from drums or lagoons, blending of waste materials to achieve desirable moisture content or BTU content, and screening or shredding to reduce the size of the materials entering the incinerator. Wastes are typically staged on contained concrete pads or in tanks for feeding to the incinerator.

In the incinerator, organic contaminants in solids and liquids are treated by subjecting them to high temperatures, typically over 1000 °F, in the presence of oxygen, which causes the volatilization, combustion or oxidation, and destruction of these compounds. Residence time, temperature, and turbulence are the three major design parameters that affect the degree of combustion. Different incinerator designs and operating conditions are used to obtain the time, temperature, and turbulence necessary to destroy the contaminants in various types of waste (U.S. EPA OERR and ORD, 1990). Very often there are two incineration chambers: primary combustion chamber and afterburner or secondary combustion chamber.

Solids from which the organic contaminants have been volatilized, known as bottom ash, are collected after travelling through the primary incineration chamber.

Figure 1
Mobile/Transportable Incineration Process

Systems are designed to maximize the solids removed from the incinerator, minimizing the carryover of particles into the flue gas stream. A vertical secondary combustion chamber or an air pollution control (APC) device such as a cyclone installed between the incinerator and afterburner are two practices for reducing particulate carryover (Stumbar, 1990).

Upon leaving the afterburner, flue gases are cooled in a quench and subsequently pass through an APC system and are released to the atmosphere through a stack. An induced-draft fan located at the outlet end of the system maintains a negative pressure in the system and draws gases through to be released through the stack. APC devices include cyclones, electrostatic precipitators, wet scrubbers, and baghouses. APC devices are often used in combination with each other since they each are effective on different types of impurities in the gases. Cyclones, electrostatic precipitators, and baghouses all remove particles from the gas stream, with the highest efficiency generally achieved in baghouses. The particles collected in these devices are residues that must be disposed of. Scrubbers are used to remove acid gases from the flue gas in waste incineration applications. Scrubbers and wet electrostatic precipitators use water, and, therefore, wastewater treatment systems are required in conjunction with them (U.S. EPA OERR and ORD, 1990).

- Incinerator Performance

The two major measures of incinerator performance are capacity and availability. Capacity is the amount of material incinerated per unit time. Availability is the percentage of time the incinerator is operational. Incinerator performance directly impacts the cost of incineration since it affects the amount of time necessary to incinerate a given quantity of waste.

Both the physical and the chemical properties of waste feed materials determine incineration system performance. Important physical properties include: heating value, morphology, density, rheology, ash particle-size distribution, and fusion characteristics. Important chemical properties include the composition of the feed as shown by: organic content, organic hazardous constituents, acid forming elements such as sulfur and the halogens, moisture content, and inorganic ash components. These properties can affect the operating parameters, the capacity, and the availability of the incineration system. The manner in which these properties affect the performance of incineration systems, based on experience with EPA's MIS, is summarized in Table 1 (Stumbar, 1990).

The effect of heating value on incinerator capacity was observed during the MIS's final year of operation. Soil with low heating value was incinerated at a rate approximately twice that of a high heating value sludge. As

TABLE 1. PROPERTIES AFFECTING INCINERATION SYSTEM PERFORMANCE

Property	Hardware affected	Operating parameter affected	Effect on performance	Feed of concern
Heating value increased	Rotary kiln	Rotary kiln temperature, Flue gas residence time in Secondary Combustion Chamber (SCC)	Feed capacity decreased, Fuel usage increased	Plastics, Trash, Wooden pallets, Brominated sludge
Morphology (Structure or form)	Feed system, Ash gates		Caused feed interruptions	Steel barrels, Steel rings, Plastics, Wooden pallets
Density decreased	Rotary kiln, Corbel	Volume of material held by kiln	Feed capacity decreased	Vermiculite
Rheology (Flow of material)	Feed system, Rotary kiln	Frequency of feeding, Ash Purity, Kiln rotation speed	Feed capacity decreased	Brominated sludge
Halogen and sulfur content increased	Quench system, Air pollution control equipment design and operation	Pump cavitation, pH control, Blowdown rate, Particulate emissions	Feed capacity decreased, Caustic usage increased	Trial burn mixture, Brominated sludge
Moisture increased	Feed system, SCC	Flue gas residence time in SCC, Rotary kiln temperature	Feed capacity decreased, Fuel usage increased	Muddy soil, Brominated sludge
Particle size distribution increased	Cyclone, SCC, Ducts, Wet Electrostatic Precipitator (WEP), Instrumentation	Kiln draft, Particulate emissions, Excess oxygen control, Temperature control	Fouling of ducts, cyclone, SCC, process water system, instruments	Erwin Farm soil, Brominated sludge, Vermiculite
Ash fusion characteristics increased	Rotary kiln, Cyclone, Ducts, Quench elbow, Instrumentation	Kiln draft, Temperature, Excess O ₂ control	Kiln Slagging, Plugging of instruments and downstream equipment	Plastics, Trash Brominated sludge

heating value of feed material increases, kiln temperature increases due to the heat released by the combustion reactions, and greater amounts of oxygen are required to complete combustion. Feed rate of high heating value materials is limited due to limitations in the amount of oxygen available for combustion and kiln heat capacity (Stumbar, 1990).

Determining a waste's properties is useful for projecting incinerator performance on that waste and estimating the cost of incineration. The decision analysis in this paper evaluates the costs and benefits of obtaining these data during RD for a particular site.

The Superfund Program

The authority under which the decision examined in this paper resides is the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), commonly known as Superfund. Congress passed CERCLA in December 1980 to give the Federal Government the authority to clean up hazardous waste sites and respond to spills of hazardous substances. Section 221 of CERCLA established the Hazardous Substance Response Fund, which provided the Government with funding to carry out these activities. On October 17, 1986, Congress enacted the Superfund Amendments and Reauthorization Act (SARA), which became effective on January 1, 1987. SARA strengthened the authorities under CERCLA for remediating

hazardous waste sites and responding to hazardous substance spills (U.S. Congress, 1986).

The EPA is the federal agency with the lead responsibility of administering the Superfund program with the exception of cases of spills in coastal areas and inland waterways where the Coast Guard has the authority (Lee et al., 1991). The procedures that must be followed in responding to the tasks mandated in SARA are printed in the Federal regulations for the Act, which are entitled the National Oil and Hazardous Substances Pollution Contingency Plan or, more simply, National Contingency Plan (NCP).

Section 300.400 of the NCP establishes the extent of response authorized by SARA. When there is a release of a hazardous substance, pollutant, or contaminant into the environment, the Government is authorized to evaluate the release to determine the need for response. If it is determined that the release constitutes a threat to public health and that no other appropriate party could respond in a timely manner, a removal or remedial action shall be undertaken by the Government. Removal actions are generally short-term actions to abate an immediate and actual threat to public health and the environment. In most cases, removals are limited to \$2 million and a duration of 12 months. Remedial actions are generally longer-term activities involving greater cost with the goal of obtaining permanent solutions (U.S. EPA, 1990).

Sites remediated through the long-term remedial actions are those that have been placed on the National Priorities List (NPL). Criteria for determining eligibility for inclusion on the NPL are provided in Section 300.425 of the NCP. In accordance with these criteria, EPA developed a Hazard Ranking System (HRS), a numerical system for evaluating and scoring sites. Sites are placed on the NPL based on the HRS scores they receive (Lee et al., 1991). A remedial investigation/feasibility study (RI/FS) is conducted on NPL sites for the purposes of determining the nature and extent of contamination and evaluating remedial alternatives. Alternatives are evaluated on the following nine criteria (U.S. EPA, 1990):

- a) overall protection of human health and the environment;
- b) compliance with applicable or relevant and appropriate requirements;
- c) long-term effectiveness and permanence;
- d) reduction of toxicity, mobility, or volume through treatment;
- e) short-term effectiveness;
- f) implementability;
- g) cost;
- h) state acceptance; and
- i) community acceptance.

Based on the alternatives evaluation, a remedy is selected in a ROD issued by the lead agency, either the State or EPA. Upon completion of a ROD, RD is initiated. RD is the development of the design of the selected remedy, which includes preparation of RFPs or invitations for bids (IFB) for RA. RA is implementation of the remedy through

construction. Once the RA has achieved its objectives, which include the remediation goals stated in the ROD, and is determined to be operational and functional, any necessary operation and maintenance (O&M) measures are initiated. The states are responsible for O&M (U.S. EPA, 1990).

Upon completion of RA and any necessary O&M, EPA can recommend deletion of a site from the NPL if one of the following deletion criteria has been met (U.S. EPA, 1990):

- EPA, in consultation with the State, has determined that responsible parties have completed all appropriate response actions.
- EPA, in consultation with the State, has determined that all appropriate Fund-financed response actions have been completed and that no further cleanup by responsible parties is appropriate.

The lead on remedial activities can be either the EPA, the State, or the PRPs. Federal-lead RI/FS activities are conducted by EPA. Most federal-lead RD/RA activities are conducted by the U.S. Army Corps of Engineers (ACE) under the authority of an Interagency Agreement between EPA and that Agency (Thomas and Dawson, 1984), although EPA retains ultimate responsibility for RD/RA activities. The NCP encourages EPA to use the ACE because of its expertise in providing design services, construction, and contract writing and administrative services (U.S. EPA, 1990). State-lead remedial activities are conducted by the states through cooperative agreements between EPA and the states. Responsible party-lead remedial activities are conducted by

the responsible parties with oversight by EPA, the states, or both.

Remedial Design

As stated above, design of the selected remedy and contractor procurement occur during the RD phase of the Superfund process. The amount of information on the waste characteristics that is to be made available to prospective bidders on RA contracts is decided during RD. Determining the net benefits of providing various levels of this information to assist in the decision making process is the subject of this analysis. Since this decision is made during RD, the RD phase of the Superfund process is more fully described below.

Remedial design is the preparation of plans and specifications for conducting the RA selected in the ROD. The plans and specifications are incorporated into an RFP or IFB, which is used to procure a contractor for conducting RA. During RD, it may be decided that the amount of information describing the characteristics of the waste to be incinerated available in the RI/FS is inadequate for the development of cost estimates by prospective bidders and that additional data are needed. Therefore, site investigations and bench- and pilot-scale studies may be conducted during RD in order to acquire additional data. Detailed procedures for conducting RD are provided in EPA's

Superfund Remedial Design and Remedial Action Guidance

(1986), which is currently being updated.

The following sections discuss important aspects of the RD process that are related to the decision examined in this paper: procurement and contractor selection, specifications, and contract type.

- Procurement and Contractor Selection

- Negotiated Bidding Process

- A negotiated bidding process initiated with the issuance of an RFP is one of the methods by which contracts are awarded for complex projects such as on-site incineration. Contracts are negotiated rather than awarded to the lowest bidder as is done in the sealed bidding process. Using performance-based specifications is more common than using detailed design specifications in negotiated procurement. The basis for evaluation in a negotiated bidding process is a combination of technical merit and cost (U.S. EPA OERR, 1990).

- A disadvantage of negotiated procurement is that the negotiation process can be lengthy (U.S. EPA OERR, 1990). Another disadvantage is that protests causing lengthy delays may result if the low bidder is not selected (Keyes, 1990).

Two-Step Sealed Bidding

Another possible procurement method for site remediation by incineration is two-step sealed bidding. In this process, offerors initially submit technical proposals without cost information. Contractors successfully completing step one by submitting acceptable proposals are eligible to submit sealed bid cost proposals on their own technical proposals in step two in response to an IFB. Upon successful evaluation of compliance with the terms and conditions of the IFB, the low bidder is awarded the contract (U.S. EPA OERR, 1990).

Two step sealed bidding has advantages similar to those of negotiated procurement. It relieves the contracting party of the burden of preparing a detailed design and it allows for a variety of possible approaches to be considered. It does, however, retain the cost competition due to the sealed bidding step. With the sealed bidding on the individual technical proposals, the contracting party is not able to consider an award on the basis of relative technical merit (U.S. EPA OERR, 1990).

- Specifications

Specifications are a description of the technical requirements to be met by the contractor conducting the RA. There are three basic types of specifications: design, performance, and purchase description. Often, a set of specifications may consist of a mixture of two or three of these (Keyes, 1990). In the procurement of contractors for conducting complex work such as on-site incineration, performance-based specifications are often used (U.S. ACE - 1988a, 1988b, 1990a, 1990b, 1991). Performance specifications provide performance requirements rather than design criteria. Performance criteria are used to make it possible for vendors with various system designs able to achieve the required levels of treatment to bid on these jobs. Contractors must supply the detailed design drawings of their equipment with their proposals and present their plan for achieving the required specifications. Performance specifications are used with the contracting mechanisms described below.

- Contract Type

The term "contract type" is used here to indicate the type of pricing arrangements in contracts. The two most common are fixed-price and cost-reimbursement. Fixed-price contracts are preferred where possible since they provide greater cost control than cost-reimbursement contracts.

Fixed-price contracts are generally used for on-site incineration projects (U.S. ACE - 1988a, 1988b, 1990a, 1990b, 1991; ENR, 1991).

Fixed-Price Contracts

Fixed-price contracts provide for a firm price for the materials and services being acquired. The offerors or bidders are asked to provide a fixed price for the project's various components. The costs for the individual line items are added together to arrive at a total cost for the project. This figure is the bid price and is used as the basis of comparison for evaluating all the proposals submitted to determine who will be awarded the RA contract. For tasks where the exact quantity of material or service required is unknown, such as incineration of waste material, the bidders are asked to provide a unit price when provided with an estimate of the quantity. The product of the unit price and estimated quantity is the figure used in the summation of the individual items (U.S. ACE - 1988a, 1988b, 1990a, 1990b, 1991; U.S. EPA OERR, 1990; Sawyer, 1992).

For on-site incineration contracts, incineration of the waste materials is generally represented as an individual line item indicating the estimated waste quantity. For a site with different types of waste, the contract solicitations may include line items for

incineration of each waste type. Besides incineration, other line items include: mobilization, demobilization, excavation, health and safety, preparation of required plans, trial burn, site work, and sampling and analysis. These items may be either fixed price or unit price (U.S. ACE - 1988a, 1988b, 1990a, 1990b, 1991).

During RA, the contractor charges the contracting party on a regular basis for work as it is completed. In Government contracts, additions or reductions to the scope of the project that arise during RA require the negotiation of change orders between the contractor and contracting party. In order to avoid having to negotiate change orders or going to court to settle contract disputes, specifications should be as thorough and complete as possible.

In most cases, the contractor originates the change to the contract by requesting the Government to issue an order under the Changes clause of the Federal Acquisition Regulations (FAR), Part 52.243-1. During change order negotiations, the contractor must continue performance of the required work. Once the terms are agreed upon, the Government issues the change (Keyes, 1990). In cases where the contractor and the Government do not agree on the terms of a change order, the contractor may appeal. Appeals are made to an

Agency Board of Appeals or to the U.S. Court of Claims, where a final decision is made (Peacock, 1986).

For those work items for which a unit price was provided in the bid, the amount charged by the contractor is based on the actual quantity purchased during construction. Part 52.212-11 of the FAR allows contractors to make change order claims for adjustment of the unit price based on a difference in the quantity stated in the original contract. This rule applies if the actual and estimated quantities differ by more than 15 percent. This regulation takes into account the effects of quantity on unit price.

A contingency clause entitled "Differing Site Conditions" is required in fixed-price Government construction contracts. Superfund RAs are construction projects. Pursuant to this clause, the contractor shall notify the Government Agency of "subsurface or latent physical conditions at the site which differ materially from those indicated in this contract, or unknown physical conditions at the site, of an unusual nature, which differ materially from those ordinarily encountered and generally recognized as inhering in work of the character provided for in this contract." This notification is followed by an investigation by the Agency of the site conditions

and if they "materially so differ and cause an increase or decrease in the contractor's cost of, or the time required for, performance of any part of the work under the contract, whether or not changed as a result of such conditions, an equitable adjustment is to be made" (FAR 52.236-2; Keyes, 1990).

Through this clause, the Government assumes the risk of discovering subsurface conditions during performance that cause a delay or increase in the cost of performance. Without this clause, the contractor would have incentive to "pad" the bid price for such a contingency, which would result in the Government paying a greater price than necessary in many cases. This clause does not eliminate such padding completely, however, since the contractor cannot be sure that the Government and contractor would be in agreement should an occurrence of differing site conditions arise. Such cases are settled through the negotiation of change orders through an initial request or through an appeal, if necessary (Keyes, 1990).

It is also required that the clause entitled "Site Investigation and Conditions Affecting the Work" be included in fixed-price Government

construction contracts. In this clause, the contractor acknowledges that it has investigated and is satisfied with the conditions that can affect the work or its cost as well as "the character, quality, and quantity of surface and subsurface materials or obstacles to be encountered insofar as this information is reasonably ascertainable from an inspection of the site, including all exploratory work done by the government" (FAR 52.236-4).

Cost-Reimbursement Contracts

Cost-reimbursement contracts provide for payment to the contractor of all allowable, allocable, eligible, and reasonable costs, as well as a fee or profit. The contracting party has less control over the cost of a project conducted using this type of contract than it does over those conducted using fixed-price contracting arrangements since the amount of labor and materials necessary and resulting cost have not been predetermined. Cost-reimbursement contracts are suitable when the cost of performance cannot be estimated with the accuracy necessary for a fixed-price contract (U.S. EPA OERR, 1990).

This chapter has outlined the context of the decision faced by the decision maker. The current practice in RD for on-site incineration remediation projects is to advertise the contract using either an IFB or RFP with performance specifications. The projects are conducted through fixed-price contracts. The information included in the IFB or RFP on the waste characteristics provides vendors with information on which to base the cost of incineration.

The contractor develops the incineration cost estimate based on the following four items: labor and overhead, materials, profit, and time to complete. The time necessary to incinerate the waste is determined using the contractor's estimate of incinerator capacity and on-line factor for the waste to be incinerated. The time to complete is influenced by the information on waste and site characteristics included in the RFP.

Without adequate information, the bidders may overestimate or underestimate the time required to incinerate the waste and, therefore, overestimate or underestimate the incineration cost. A bidder may overestimate the cost so as not to assume risk in the event the unknown portion of the waste is difficult to incinerate (sludge), having a low capacity and availability. A bidder may underestimate the cost in order to have a greater chance of being awarded a contract at the risk of not making money on it by assuming much of the waste is easy to incinerate

(soil), having a high capacity and availability. A bidder who bids low may request a change order based on discrepancies between the description of the waste included in the specifications and the actual waste characteristics. The basis for such a request and any subsequent change order awards or court settlements is the "Differing Site Conditions" clause described earlier. Contracting parties generally prefer to avoid change orders since they result in additional costs.

The dilemma facing the decision maker is that collecting additional information to obtain more accurate bids, reduce the chance of change orders, and possibly obtain a savings in the RA cost, adds to the RD cost and may add to its duration. The task facing decision makers is to determine the appropriate amount of information to acquire for individual sites. In the next chapter, decision analysis techniques are introduced and applied to this decision for a specific site.

III. METHOD, MODELS, AND DATA

Decision Analysis Tools

The technique used to examine the decision in this paper is known as Decision Analysis. Decision analysis has been an accepted management tool in some portions of government and the corporate world since the early 1980s (Ulvila and Brown, 1982). Decision analysis provides decision makers with a systematic approach to a decision.

Decisions are difficult due to the inherent uncertainty in their outcomes. They may be complex because more than one issue is involved, and there are often multiple objectives and various people involved in making decisions that add to their complexity. The elements of the decision making process are: (1) decisions to make; (2) uncertain events; and (3) the value of specific outcomes. This process can be modeled using influence diagrams and decision trees (Clemen, 1991).

An influence diagram is a simple illustration of a decision problem. The three elements of the decision making process are represented using squares for decisions, circles for uncertain events, and rectangles with rounded corners for values of outcomes. A simple investment decision is represented in the influence diagram in Figure 2. The decision is how an investor should invest her money

Figure 2
Simple Influence Diagram

Figure 3
Simple Decision Tree

(business venture or savings account). The uncertainty is the future economy and its effect on the prospective business venture. The value of the investment is its payoff (Clemen, 1991).

A decision tree is used to represent more details of the decision process, including the sequence of events. In a decision tree, decisions are represented by squares, and uncertain events are represented by circles (Clemen, 1991; Behn and Vaupel, 1983). A decision tree for the investment decision discussed above is represented in Figure 3. The investment decision, represented by the square at the left, is the first event to occur. The two choices the decision maker has are to invest in savings or in the business venture, shown on the two branches to the right of the square. Investing in a savings account will result in a certain, but small, profit. Investing in the business venture could result in either making a large profit or losing part or all of the initial investment.

One useful criterion for the decision making process is the expected monetary value (EMV) of each of the options. The EMV is calculated using the values of the possible outcomes and the probabilities of the possible outcomes occurring. In determining the EMV, the decision maker starts at the right side of the tree and moves left. The expected value of a chance node is the weighted average of the possible outcomes, the weights being their

probabilities. By calculating the EMV in this way, uncertainty about outcomes can be represented and incorporated into the choice. When a decision node is encountered as moving left in the decision tree, the branch with the highest value or expected value is chosen. The process is continued until the initial decision node is encountered (Clemen, 1991).

The process for determining the EMV is demonstrated using the decision tree in Figure 4. This figure represents the same decision as Figure 3, but it includes values for the outcomes and for the probabilities of the outcomes occurring. The expected value of the chance node representing investing in the business venture is \$250. This value is greater than the amount of \$100 that would be earned by investing in a savings account. The double dash through the "savings account" branch indicates that this option would not be chosen. The EMV for this decision tree is \$250.

In Figures 3 and 4, the chance node is presented with two discrete outcomes. It is also possible that uncertain events have a range of possible outcomes. The decision tree in Figure 4 is modified to illustrate a range of outcomes for the chance event and is shown in Figure 5.

In order to calculate the expected value of a continuous distribution, the continuum of outcomes can be approximated by one with discrete outcomes. The decision

Figure 4
EMV Calculations

Decision is to invest in business venture.

Figure 5

Decision Tree Showing Range of Possible Outcomes for Chance Event

Figure 6

Decision Tree Using Three-Branch Approximation to Represent Range of Possible Outcomes

tree in Figure 5 is modified to include the discrete approximations and is shown in Figure 6. In determining the values associated with the branches for this approximation, it is assumed that each amount in the range has an equal probability of occurring. The continuum is divided into thirds, and the midpoint of each third is the value assigned to the branch, which are the $1/6$, $1/2$, and $5/6$ fractiles of the continuum. The probability for each branch is $1/3$. The EMV is \$250.

The tools of decision analysis introduced above are applied to the "information" decision examined in this paper. In the decision tree that corresponds to this decision, uncertainty about its outcomes are represented as branches from chance nodes, and expected values are calculated to indicate the path of highest payoff in the decision process.

Decision Problem

For purposes of illustration, a hypothetical site is described. Its characteristics have been chosen to be representative of those from actual sites. The site is a lagoon whose 50,000 tons of soil and sludge will be incinerated on-site, as stated in the ROD. The data in the RI/FS provide the following information about the waste characteristics. Twenty-five percent of the waste, by weight, is soil with low heating value, density, and

moisture content. Twenty-five percent of the waste is a high heat content sludge with high moisture content, high ash and metals content, which flows irregularly through process equipment. The characteristics of the remaining fifty percent of the site are unknown, although it is some combination of the easy-to-incinerate soil and difficult-to-incinerate sludge.

The EPA has the lead responsibility for remediating the site and is beginning the RD. The fixed-price remediation contract will be advertised through an RFP with performance specifications. The EPA must decide whether or not to conduct additional studies during RD to better characterize the waste and to demonstrate its behavior in an incinerator.

This decision is modeled using the decision tools introduced above. An influence diagram illustrating the decision, uncertain events, and the outcome is presented in Figure 7. The outcome is the incineration component of the RA cost. The incineration cost is influenced by the following chance events in addition to the information decision: winning contractor's bid, waste's actual characteristics, change order requests, change orders awarded, any awards to cost disputes settled in court or through the appeals process, monetary and time costs of conducting a study to collect additional information during RD, and information revealed by the study about the waste characteristics. The specifications for the required work

Figure 7
Influence Diagram for the
Incineration Cost Component
of the RA Cost

is not included as a decision node since decisions determining those have been made prior to RD and documented in the ROD for the site.

The "information" decision is also represented in decision trees in Figures 8 and 9. This decision tree illustrates the acquisition of information that perfectly represents the waste's actual characteristics and results in having a bid that accurately reflects this information. Although it is not possible to acquire perfect information before the entire site is excavated and incinerated, analysis of this decision tree provides useful results.

Figure 8 begins with the decision to proceed with soliciting bids for the RA contract or to conduct a study to acquire additional information on the waste's characteristics and behavior in an incinerator. Two branches emanate from this decision node representing each of these alternatives: proceed with RA contract and conduct study to acquire additional information.

The upper branch, proceed with RA contract, has the following chance nodes: winning bid price, waste's actual characteristics, change order requests, change order awards, and court settlements. The order the events appear in the tree represents the actual sequence of events. The bid price is received once the contract is advertised and the RA begins. During RA, excavation and incineration of the waste material is conducted, which reveal the waste's actual

Figure 8
Decision Tree for the
Information Decision
Assuming Information is Perfect

Figure 9

Decision Tree for the Information Decision
Using Three-Branch Approximation
Assuming Information is Perfect

characteristics. Based on these characteristics, change orders may be requested, awarded, and settled in court or through the appeals process.

There is a range of possible outcomes associated with the winning bid price. For this analysis, the winning bid price is based on the contractor's estimated cost of incinerating the waste plus a standard profit. Since some of the information about the waste is unknown for this alternative, the bidder has to make assumptions about its characteristics in order to develop a bid. The winning bid price may be anywhere in a range of bids, ranging between a low and high bid. A low bid is based on the assumption that there will be a high capacity and on-line factor, that the unknown portion is all soil. A high bid is based on the assumption that there will be a low capacity and on-line factor, that the unknown portion is all sludge. All possible bid amounts are equally likely.

There is a range of possible outcomes for the actual characteristics node. The possible characteristics of the unknown portion of the waste are the same as those upon which the winning bid is based, ranging from its being all soil to all sludge. All possible characteristics have an equal likelihood of occurring.

The nodes representing change order requests and awards, and court settlements each have two branches emanating from them: yes, that the event will occur, and

no, that the event will not occur.

The probability that a change order is requested is indicated in the tree as p . The change order amount is the difference between the bid amount and the actual cost (AC) of incineration based on the waste's actual characteristics and behavior in the incinerator during RA. The amount of a change order request ranges between zero and the difference between the bid price and the actual cost of incinerating a waste that is all sludge. Amounts within this range represent the possible compositions of difficult-to-incinerate sludge and easy-to-incinerate soil.

The branch representing that a change order is requested is followed by a chance node representing whether or not the change order is awarded. The probability that a change order is awarded is indicated in the tree as q .

If the change order is not awarded, the contractor appeals it in court or through the appeals process. The court's decision (or outcome of the appeal) is represented by a chance node with two branches emanating from it, the change order is awarded or it is not awarded. The probability that the court awards the change order is indicated in the tree as r . In the event the case goes to court or is appealed, additional costs are incurred to review the request, no matter what the outcome. These costs are indicated in the tree as court costs. Administrative costs associated with the initial review of the change order

request are not considered in the decision tree. It is assumed that reviewing and deciding on change order requests are part of the contracting party's operating costs. However, the cost of appeals may be significant.

The lower branch, conduct study, includes the following chance nodes: study cost, in terms of time and money; information revealed by the study; and bid price. Each of these nodes has a range of possible outcomes associated with it.

The study's cost is known to the decision maker prior to making the decision. It is shown as a range in the decision tree to show that there are many possible costs for conducting a study. A range is considered in the EMV calculations presented in Chapter 4. The monetary cost of conducting the study is represented by the variable SC. The cost in time is converted to a monetary value by multiplying the time delay (TD) by the dollar value of time (DVT). Therefore, the study cost equals $SC + TD(DVT)$.

The information revealed about the waste can show that the unknown portion of the waste is anywhere between all soil and all sludge. This is the same range of actual characteristics shown in the upper tier of the tree as described above.

The winning bid price ranges between a low and high bid. This is the same range as the range following the winning bid price node in the upper tier of the tree.

However, in this case, the bidder has been provided with complete information upon which to base the bid and, therefore, does not have to make assumptions to develop it. Since the bid is based on perfect information, the lower tier of the tree ends at this point. It is not necessary to have a node representing the waste's actual characteristics since that event is identical to the "information revealed about waste" node. Since the bid is based on perfect information about the waste's characteristics, there are no change order requests, awards, and court settlements.

The decision tree in Figure 9 is expanded to include greater detail than Figure 8, so that calculations can be conducted to determine the EMV and preferred alternative. In the upper tier of the tree, the continuum of outcomes emanating from the bid price chance node is substituted with three discrete outcomes using the three-branch approximation described above. The terms used to represent the amounts associated with the three branches are low bid (LB), medium bid (MB), and high bid (HB). The change order amount for the low bid is indicated as $CO(L)$, the change order amount for the medium bid is indicated as $CO(M)$, and the change order amount for the high bid is indicated as $CO(H)$. Court costs are represented in the tree as $CC(L)$, $CC(M)$, and $CC(H)$ for the low, medium, and high bids, respectively. The range of possible outcomes for the node representing the waste's actual characteristics remains in this figure just as it

appears in Figure 8. The change order and court cost amounts are calculated for several AC values across the range of possible values. Although the probabilities of change order requests, awards, and court settlements may be different for different bid amounts, it is assumed that these probabilities (p , q , and r) are equal in this analysis.

In the lower tier of the tree, the continuum of outcomes emanating from the node representing the cost of the study remains, just as it appears in Figure 8. The EMV is calculated for each value of the study cost. This node is followed by the chance node representing the possible outcomes of the information collection activities. This is substituted with the three-branch approximation. The branches are labeled sludge, 50% soil/50% sludge, and soil. Each of these branches is followed by a winning bid price node, which has the value of the bid based on the information revealed. The bid amounts are HB, MB, and LB, respectively.

The decision tree variables and their definitions are summarized below in Table 2.

Table 2
Decision Tree Variables

Variable	Definition
p	Probability that change order is requested.
q	Probability that change order is awarded upon request.
r	Probability that change order is awarded in court or through appeal.
AC	Actual cost of incineration.

Table 2 (continued)
Decision Tree Variables

Variable	Definition
LB	Low bid.
MB	Medium bid.
HB	High bid.
CO(L)	Change order amount for low bid. (AC-LB)
CO(M)	Change order amount for medium bid. (AC-MB)
CO(H)	Change order amount for high bid. (AC-HB)
CC(L)	Court costs for low bid.
CC(M)	Court costs for medium bid.
CC(H)	Court costs for high bid.
SC	Study cost.
TD	RD time delay.
DVT	Dollar value of time.

Expected Monetary Value Models

The EMV for the upper tier of the decision tree in Figure 9 is calculated as follows. Three separate equations representing the high, medium, and low bids and subsequent events are presented below.

$$\begin{aligned} EV(H) &= HB + p[(1-q)[r(CO(H) + CC(H)) + (1-r)CC(H)] + q(CO(H))] \\ EV(M) &= MB + p[(1-q)[r(CO(M) + CC(M)) + (1-r)CC(M)] + q(CO(M))] \\ EV(L) &= LB + p[(1-q)[r(CO(L) + CC(L)) + (1-r)CC(L)] + q(CO(L))] \end{aligned}$$

The products of the solutions to these equations and their probability weights are added together to determine the EMV of proceeding with advertising the contract. This is represented by the equation:

$$EMV(\text{Proceed}) = (EV(H))/3 + (EV(M))/3 + (EV(L))/3.$$

The lower tier of the decision tree is simpler than the upper tier and is represented by the equation:

$$EMV(\text{Study}) = SC + TD(DVT) + (HB)/3 + (MB)/3 + (LB)/3.$$

Data for the Decision Analysis

- Incineration Costs

The incineration costs used in the decision tree are based on industry experience. The labor requirements for operating an on-site hazardous waste incineration system were provided by an incineration vendor. The labor rates used are those provided in a guide for construction industry costs (Means, 1992), commonly known as the Means' Guide. Materials costs for operating EPA's MIS are used as the basis for materials costs in these cost calculations. Finally, performance information for commercial transportable incinerators is used to determine the time to complete the incineration of the waste at the site examined in this paper.

Labor requirements were obtained from an interview with a transportable incineration vendor (Sawyer, 1992). The Contractor's Overhead & Profit Table (Table 6) in the Means' Guide provides average billing rates for various labor categories. The total hourly rate is comprised of a base rate including the usual negotiated fringe benefits, workers' compensation, and average fixed overhead. The values for workers' compensation are based on national averages of state rates established for each trade. Average fixed overhead is a total of average rates for U.S. and State Unemployment, Social Security, Builders' Risk, and Public Liability (Means, 1992). For labor categories not

included in the Means' Guide, the hourly rates used are rates for equivalent duties listed in the table or are estimated based on this author's prior experience with managing the operations of the EPA MIS. The labor requirements, hourly and weekly rates, and weekly labor cost are provided below in Table 3.

Table 3
Incineration Labor Cost

Labor Category	Quantity (no. people)	Hourly Rate (per person)	Weekly Rate (total)
Helper	1	\$24.07	\$ 1,011
Clerical	2	24.07	2,022
Laborer	10	25.32	10,634
Operator	11	31.31	14,465
Health & Safety	1	34.27	1,439
Accountant	1	34.27	1,439
Shift Supervisors	4	34.27	5,757
Project Manager	1	50.00	2,100
TOTAL WEEKLY LABOR COST			\$38,868

The materials cost used in the incineration cost calculations for this decision analysis are based on the materials costs for EPA's MIS. The MIS's materials cost during 1988 and 1989 for this two-ton-per-hour unit was \$7400 per day. To arrive at a materials cost estimate for this analysis, this figure is adjusted for inflation and multiplied by 10 to arrive at an estimate for a 20-ton-per-hour unit, which is representative of many of the commercially developed transportable units that exist today (Oberacker, 1991). These calculations result in a daily materials cost of \$80,000 and a weekly cost of \$560,000.

The weekly labor cost of approximately \$40,000 plus the weekly materials cost of \$560,000 are added to arrive at a weekly cost of \$600,000. Factoring in a 12 percent profit, the weekly cost is \$672,000. Assuming a 20 ton per hour maximum rate for incinerating soil with an 80 percent capacity and availability, the unit cost for incinerating soil is \$250 per ton. Assuming a 10 ton per hour maximum rate for incinerating sludge with an 80 percent capacity and on-line factor, the unit cost for incinerating sludge is \$500 per ton.

The bounds of the continuum of possible bids ranges between a low bid and high bid. Of the 50,000 tons of waste at this site, 12,500 tons is soil, 12,500 tons is sludge, and the ratio of soil to sludge in the remaining 25,000 tons is unknown. A low bid assumes a soil fraction of 0.75 and a sludge fraction of 0.25, or 37,500 tons soil and 12,500 tons sludge. A high bid assumes a soil fraction of 0.25 and a sludge fraction of 0.75, or 12,500 tons soil and 37,500 tons sludge. The median equates to a soil fraction and sludge fraction of 0.50 each, or 25,000 tons each.

This continuum of bids is represented by the three-branch approximation described above. The dollar values for the bounds of the continuum and the median for the subject site are presented in Table 4 for the 50,000-ton site using the costs calculated above for incinerating soil (\$250/ton) and sludge (\$500/ton).

Table 4
Bids for 50,000 Tons Waste

Bid Type	Soil (tons)	Sludge (tons)	Bid Price (\$)
Low	37,500	12,500	\$15,625,000
Medium	25,000	25,000	\$18,750,000
High	12,500	37,500	\$21,875,000

The bid amounts in Table 4 are used to determine the values for the 1/6, 1/2, and 5/6 fractiles of the continuum, expressed as LB, MB, and HB, which are presented below in Table 5. The range of bid prices shown in Table 4 is also the range of possible values for AC: \$15,625,000 to \$21,875,000.

Table 5
Fractiles for Three-Branch Approximation

Variable	Fractile	Price
LB	1/6	\$16,666,667
MB	1/2	\$18,750,000
HB	5/6	\$20,833,334

- Duration and Cost of Conducting Additional Studies

Additional studies consist of two components: site characterization work and bench- or pilot-scale incineration tests. Pilot studies on waste from Superfund sites conducted at EPA's Incineration Research Facility cost between \$150,000 and \$400,000 (Carroll, 1993). The amount of site characterization work required depends on the amount of data acquired during the RI/FS, which varies for every site. Additional site characterization work consists of drilling borings into the soil to determine the depth and

extent of contamination. It also requires analysis for various properties as listed in Table 1. This type of site characterization work costs on the order of one to several hundred thousand dollars. In this analysis, the range between \$250,000 and \$1,000,000 for the total cost of additional studies is considered.

Conducting these studies may result in a longer RD duration than there would be if the studies were not conducted. It is hard to estimate what the extension would be since these activities are conducted concurrently with other RD activities. The former EPA Remedial Project Manager (RPM) for the Bog Creek Farm site, which was remediated by on-site incineration in 1990, believes the RD for that project was extended by three months due to the studies conducted to better characterize the waste and determine its behavior in an incinerator (Schwarz, 1993). It is likely that these activities would take longer in many cases since in recent years work handled through EPA contracts is taking longer to be approved than it did at the time that site was in the RD stage. In this analysis, the range of zero to twelve months is considered for the amount of time RD is extended to acquire additional information (TD).

The manner by which the cost of time delays is considered in this decision analysis is to equate a portion of time to a dollar value. The dollar value of time (DVT)

varies between projects and between decision makers. Interviews with four decision makers verifies the difference in values placed on time. Two EPA RPMs (Tomchuk, 1993; Schwarz, 1993), an EPA branch chief in the Superfund program (LaPadula, 1993), and a representative from the environmental compliance office in a private company (McDonald, 1993) were interviewed. RPMs are EPA's staff level managers of Superfund site remediations. The EPA branch chief is a middle manager. The representative of private industry is responsible for managing Superfund site remediations financed by her company, which is a PRP. People in different positions were interviewed since the "information" decision is influenced by decision makers in each of these positions.

Those interviewed were questioned to determine the amount of time they would be willing to delay a \$30 million project in order to save \$1 million. The total RA cost of the hypothetical site used in this paper is on the order of \$30 million. The branch chief and one RPM do not think \$1 million is a significant amount for a project of this size, so the question was asked again substituting the savings of \$1 million with \$3 million. The results of the interviews conducted are presented below in Table 6.

Table 6
Results of Interviews with Decision Makers

Decision Maker	Time to Save \$1MM (months)	Time to Save \$3MM (months)	DVT (\$1000/month)
EPA Branch Chief	3-6	6-12	167-500
EPA RPM	---	12	250
EPA RPM (former)	12	---	83
PRP	infinite	infinite	0

The branch chief responded with ranges of time associated with cost savings rather than discrete periods of time. He is the most cautious of all the responders about delaying projects. This caution is represented by his placing a value on time as high as \$500,000 per month. The two RPMs interviewed have different attitudes about the value of time and the cost of delays: the RPM who values time at \$250,000 per month is less comfortable with delaying the project than is the RPM who values time at \$83,000 per month. The RPM placing the lower value on time places a higher value on saving the Government money. The primary concern of the representative from industry is the cost of a project, not the delays. The Government representatives are concerned about delays since they receive pressure from the public and Congress to expedite the remediation of Superfund sites. Based on the results of these interviews, a range of values between \$0/month and \$500,000 for the DVT is considered in the analysis.

- Costs of Going to Court

Costs incurred by the contracting party for going to court to settle a dispute with a contractor are difficult to estimate since it is uncertain how much work would be required. An interview with two attorneys in the Chief Counsel's Office of the ACE affirms this statement. This type of action would require involvement by personnel from various branches of the contracting party's organization: engineers and scientists, attorneys, and contracting personnel (Guris and Kelly, 1993). Since there is so much uncertainty associated with court costs, a range of court costs is considered in this analysis. The range used is from 0 to 50% of the change order amount.

- Summary of Data for Decision Analysis

The data presented in the sections above are included in a table presenting values for all the decision tree variables listed in Table 2. Most of the variables have ranges associated with them as discussed in the sections above, except for LB, MB, and HB, which are discrete values. Table 7 includes nominal values for the probability weights: p , q , and r , which could each range from zero to one. In addition to the ranges associated with the variables, a base value for each variable is presented in the table. The base value is a discrete value within the range used as a starting point for the decision analysis.

Table 7
Values for Decision Tree Variables

Variable	Range	Base Value
p	0-1	0.5
q	0-1	0.5
r	0-1	0.5
AC	\$15,625,000-\$21,875,000	\$20,000,000
LB	-----	\$16,666,667
MB	-----	\$18,750,000
HB	-----	\$20,833,334
CO(L)	\$0-\$5,208,333	\$ 3,333,333
CO(M)	\$0-\$3,125,000	\$ 1,250,000
CO(H)	\$0-\$1,041,666	\$ 0
CC(L)	0-50% CO(L)	10% CO(L)
CC(M)	0-50% CO(M)	10% CO(M)
CC(H)	0-50% CO(H)	10% CO(H)
SC	\$250,000-\$1,000,000	\$ 600,000
TD	0-12 months	6 months
DVT	\$0-\$500,000/month	\$ 250,000

In the next chapter, results of the decision analysis are presented. Various combinations of these data are inserted into the models to determine the EMV for each tier of the decision tree. The EMVs for different sets of conditions are compared to determine the preferred alternative for that set of conditions.

IV. RESULTS AND DISCUSSION

Results

- Expected Value Calculations

Determination of the expected value of the decision tree in Figure 9 begins with calculations using the base values of the variables presented in Table 7. The values of the variables are shown in the appropriate locations on the decision tree in Figure 10. The decision analysis is completed by calculating the expected values for the upper and lower tiers of the tree using the equations presented in Chapter 3. The expected value for proceeding with advertising the RA contract ($EMV(\text{Proceed})$) is \$19.4 million, which is less than the \$20.9 million EMV for conducting a study to acquire information first ($EMV(\text{Study})$). The preferred alternative is the one with the lowest EMV or expected cost. Therefore, the preferred decision for the variables at their base values is to proceed with awarding the contract without acquiring additional information.

- Sensitivity Analysis

The EMV calculations for Figure 9 can be repeated for many other values of the variables producing varying results. Sensitivity analysis is conducted to determine the sensitivity of the EMV to changes in values of the variables

Figure 10

EMV Calculations at
Base Values of Variables

Note: All costs are millions of dollars

(Clemen, 1991). Some variables have a significant effect on the expected value, while others have a negligible effect. Variables that have a significant effect can be the focus of further analysis. Determination of the significant variables is known as Deterministic Sensitivity Analysis.

The significant variables are determined by adjusting the value of one variable while keeping the other variables at their base values and calculating the expected value. The result is a range of expected values associated with the range of the subject variable. Displaying the ranges of expected values associated each variable on a graph makes the most influential variables visually apparent.

Deterministic sensitivity analysis is used to determine the variables with the greatest effect on the expected values of both the lower and upper tiers of the decision tree in Figure 9. Graphs showing ranges of the expected values of each alternative associated with adjustment of each variable are presented in Figure 11. The results of the calculations are included in the appendix. Two variables have a significant effect on EMV(Proceed): probability of a change order request (p) and the actual cost of incineration (AC). The variables with the most significant effect on EMV(Study) are the time RD is delayed (TD) and the dollar value of time (DVT). The expected value of each alternative with all variables at their base values are indicated in each graph. These are the same values

Figure 11

Deterministic Sensitivity Analysis

shown in Figure 10.

Since the EMVs of each alternative change with different values of the variables, the preferred alternative is different for different combinations of the variables. For example, for high dollar values of time, the EMV of gathering information is greater than the entire range of EMVs for proceeding without obtaining information. Therefore, for high dollar values of time, the preferred alternative is to proceed with advertisement of the RA contract. For low dollar values of time and high values of p and AC , the EMV of collecting information is less than the EMV of proceeding with the RA contract. Therefore, for these conditions, the preferred alternative is to acquire the information.

The graphs in Figure 11 provide rough interpretations of the preferred alternative. They are useful in selecting the variables that are to be the focus of further analysis. One approach to further analysis is to calculate the EMV of an alternative for several values of one variable to see the effect that variable has on the EMV. The results can be plotted on a graph with the variable as the x axis and the EMV as the y axis. Plotting the EMV for the other alternative on the same graph illustrates the preferred alternative associated with all values of the x variable. For example, plotting $EMV(\text{Proceed})$ on the y axis for various values of AC on the x axis shows the effect that AC has on

EMV(Proceed). Also plotting EMV(Study) on the graph shows the effect that AC has on it. The preferred alternative is the one whose EMV is lower for a particular value of AC. If the lines intersect, the preferred alternative switches at that point, which is known as the "switch point."

The effect of a second variable can also be determined. For this example, EMV(Proceed) can be calculated for several values of p for each value of AC. The result is a graph with several EMV(Proceed) curves, each representing a different value of p . All other variables remain at their base values in these calculations.

The decision tree in Figure 9 is solved in this manner for several values of p and AC with all other variables at their base values, and the graph is shown in Figure 12. EMV(Proceed) is calculated for several values of AC and p . AC is on the x axis, and the EMV is calculated for values of AC ranging between \$15,625,000 and \$21,875,000. The EMV is calculated for $p=0.25$, $p=0.5$, $p=0.75$, and $p=1.0$ for the range of AC values.

Curves representing EMV(Proceed) for each p value are plotted on the graph. EMV(Study), calculated for the base values of the variables, is also plotted and is a horizontal line. EMV(Study) is constant in this graph since it is not dependent on AC. The graph shows that the EMV for conducting a study to acquire information, with a study cost of \$600,000 and an RD delay of 6 months valued at \$250,000

Figure 12: Sensitivity to Change in
Actual Site Conditions (Base Values)

Figure 13: Sensitivity to Change in
Actual Site Conditions

per month, is greater than most values of the EMV for proceeding. The one switch point is on the $p=1.0$ curve for AC equal to approximately \$21 million. Only for sites with an AC value greater than \$21 million is the EMV of acquiring information less than the EMV of proceeding with the RA contract, for $p=1.0$. Therefore, for this small range of conditions ($AC > \$21$ million, $p=1.0$), the preferred alternative is to acquire the information.

The effect of the value of time on the EMV of acquiring information is apparent if Figure 12 is compared with Figure 13. In this figure, $EMV(\text{Study})$ is calculated using dollar values of time lower than the base value: \$83,000/month and \$0/month. $EMV(\text{Study})$ decreases with a decreasing value of time, and more conditions exist for which conducting a study to acquire information is the preferred alternative, as shown in Figure 13.

The placement of the variables p and AC can be reversed. Two graphs with the p variable on the x axis and $EMV(\text{Proceed})$ calculated for four different values of AC are included in the appendix (Figures A-1 and A-2). As is shown in Figures 12 and 13, with a decreasing DVT, more conditions exist for which conducting a study is the preferred alternative.

The graph in Figure 14 is configured with the x axis representing the dollar value of time between \$0 and \$500,000 per month. $EMV(\text{Study})$ increases with increasing

Figure 14: Sensitivity to Change in
Dollar Value of Time

dollar values of time. $EMV(\text{Proceed})$ is presented for four different values of p . Each $EMV(\text{Proceed})$ line is horizontal since $EMV(\text{Proceed})$ is not dependent on the x variable. The two lines representing $EMV(\text{Study})$ have RD delays of six and three months associated with them, respectively. Other variables are at their base values. There are switch points for both of these lines. Acquiring information is the preferred alternative for a wider range of probabilities and dollar values of time for the $EMV(\text{Study})$ line associated with the lower value of time.

Curves representing conditions for which $EMV(\text{Proceed}) = EMV(\text{Study})$ are shown on the graph in Figure 15. The axes are p and AC , and each curve represents a specified dollar value of time. Curves are plotted for the values of time at the lower end of the range for which there are switch points on the previous graphs. The curves on the graph represent dollar values of time of \$0/month and \$83,000/month. The region above and to the right of the curves represents the areas in the previous graphs where $EMV(\text{Study})$ is less than $EMV(\text{Proceed})$. Therefore, points located in this region represent conditions for which information should be acquired. Points located below and to the left of the curves are conditions for which the preferred alternative is to proceed without acquiring the information.

Figure 15: $EMV(\text{Study}) = EMV(\text{Proceed})$

- Decision Tree Expansion for Imperfect Information

The previous expected value calculations all assume that the additional information acquired during RD provides such an accurate representation of the waste's characteristics that no change orders are filed in the event this information is obtained. Since there is no assurance that change orders would not be requested, the decision analysis is expanded to address the possibility of change order requests and awards after information is acquired. The expanded decision tree is shown in Figure 16.

The lower tier of the tree is expanded in a manner resembling the upper tier. As in Figure 9, the first, second, and third chance nodes in the lower tier represents the study cost, information revealed about the waste by the studies, and the winning bid price. A chance node is inserted on each of the three bid price branches representing the uncertainty about the waste's characteristics. The possibility exists that the waste exhibits different characteristics than the studies revealed, upon which the bid was based, and that change orders will be requested by the contractor.

As in the upper tier of the tree, three nodes representing change order requests are inserted after the "actual characteristics" nodes. These nodes are each followed by two branches, that a change order will be requested or that it will not be requested. The probability

Figure 16
Decision Tree Assuming Information is Imperfect

that a change order will be requested after information is obtained is indicated as p' . The branches representing change orders are requested are followed by chance nodes representing the uncertainty of whether or not the change orders are awarded. The probability that change orders are awarded is indicated by q' . Finally, the branches representing change orders are not awarded are followed by chance nodes representing the uncertainty of the court settlement or appeal. The probability that the change order is awarded in court or through an appeal is indicated by r' .

The equations used to determine the EMV of the upper tier of the decision tree in Figure 16 are identical to those for Figure 9. The equations representing the three parts of the lower tier of Figure 16 are:

$$\begin{aligned} EV(H') &= HB + p' [(1-q') [r' (CO(H) + CC(H)) + (1-r') CC(H)] + q' (CO(H))] \\ EV(M') &= MB + p' [(1-q') [r' (CO(M) + CC(M)) + (1-r') CC(M)] + q' (CO(M))] \\ EV(L') &= LB + p' [(1-q') [r' (CO(L) + CC(L)) + (1-r') CC(L)] + q' (CO(L))] \end{aligned}$$

The expected value for the decision to conduct a study to acquire information is determined by the equation:

$$EMV(\text{Study}) = EV(H')/3 + EV(M')/3 + EV(L')/3 + SC + TD(DVT).$$

The EMV for the decision tree is calculated using the base values for the EMV calculations completed above as well as the following values for the new variables: $p'=0.25$, $q'=0.5$, and $r'=0.5$. The base value chosen for p' , the probability of a change order being requested once information is acquired, is 0.25 rather than 0.5 since acquiring information is likely to reduce the occurrence of

change order requests. The EMV for the decision to acquire additional information, at the base values of the variables, is \$21.1 million, which is greater than the \$19.4 million EMV for proceeding without acquiring the information.

The types of sensitivity analyses conducted assuming perfect information are repeated for the decision tree in Figure 16 to illustrate the effect of change orders on the value of $EMV(\text{Study})$. In the first analysis, the decision tree is solved using several values of p and AC with all other variables at their base values. The results of this analysis are shown in the graph in Figure 17. Figure 18 displays the results of EMV calculations using lower dollar values of time. The graphs are configured in the same manner as those in Figures 12 and 13.

The graph in Figure 17 shows that the EMV for acquiring information is greater than the EMV of proceeding without doing so for all probabilities of a change order request being made, for the entire range of possible site conditions. Therefore, the information should not be acquired. There are switch points in Figure 18 that cross the curves representing p values of 0.75 and 1.0. In Figures 18 and 19, the curves representing $EMV(\text{Study})$, for $p'=0.25$, are identical to the curves representing $p=0.25$. However, the $EMV(\text{Study})$ curve is at a higher point on the graph due to the costs of acquiring the information.

Two graphs with the placement of p and AC reversed are

Figure 17: Sensitivity to Change in AC
for Expanded Tree (Base Values)

Figure 18: Sensitivity to Change in AC
for Expanded Tree

included in the appendix (Figures A-3 and A-4). The lines representing EMV (Study) are at higher points than on the previous graphs representing the same conditions since the possibility of change orders is considered.

Figures 19 and 20 are configured in the same manner as Figure 14 with the dollar value of time as the x axis. The EMV for proceeding without acquiring the information is presented for four different values of p . The EMV for acquiring information increases with increasing dollar values of time and p' . Figure 20 includes no switch points; proceeding with the RA contract is the preferred alternative for all conditions represented. The two EMV(Study) curves in Figure 19 have switch points on the EMV(Proceed) curve for $p=1$ at \$50,000 and \$100,000 per month.

Discussion of Results

As the cost in time and money of acquiring information decreases, this becomes the preferred alternative. Some of the decision makers interviewed consider delays to be a significant cost for acquiring information. This "time cost" is a significant component of the EMV for acquiring information. The extent to which the EMV is affected by the "time cost" can be seen in the lower graph in Figure 11. There is a three million dollar range in the EMV for acquiring information associated with both the length of the time delay and the dollar value of time.

Figure 19: Sensitivity to Change in
DVT for Expanded Tree (1)

70

Figure 20: Sensitivity to Change in
DVT for Expanded Tree (2)

By comparing the EMVs in both graphs in Figure 11, it is evident that the EMV for acquiring information is greater than the EMV for proceeding without it for all delays and dollar values above the lower end of the range. Therefore, proceeding without acquiring information is preferred for most cases where RD is extended, based on the values of time obtained from those interviewed. Acquiring information may be preferred in those cases for which the decision maker places a lower value on delays in the project schedule.

The graphs presented in Figures 12 through 20 provide more specific determinations of the preferred alternative for specified values of each variable. The interpretations of these graphs confirm the conclusions based on an interpretation of Figure 11. $EMV(\text{Study})$ is lower, and, therefore, acquiring information is preferred, for lower dollar values of time and time delays, and higher values of AC and p. Higher values of AC correspond to waste that is more sludge than soil, and for higher values of p, there are greater probabilities that the waste characterization provided to bidders does not accurately describe the waste.

Conducting a study to acquire perfect information is the preferred alternative for a small range of conditions. Since considering that the information acquired is imperfect increases $EMV(\text{Study})$, the corresponding set of sensitivity analyses show this as the preferred alternative for an even smaller range of conditions.

V. CONCLUSIONS AND AREAS FOR FURTHER STUDY

This paper examines the decision-making process of the remedial design phase of on-site incineration projects conducted at Superfund sites. It identifies decisions affecting the cost and schedule of the remedial action. The decision at the focus of the analysis is the information on the waste to be incinerated that is to be included in the performance specifications for the remedial action, which is to be conducted through a fixed-price contract. This information is used by contractors bidding on the project in developing their cost estimates and, therefore, directly affects project costs. The decision maker's dilemma is that costs are associated with acquiring this information, while having it may result in cost savings.

The decision maker has two alternatives: to prepare the project specifications including only the description of the waste provided in the remedial investigation/feasibility study; or to acquire additional information on the waste characteristics during remedial design. The decision process is examined in this paper for a particular site. The possible outcomes associated with each decision are considered in the decision analysis.

The advantage to acquiring information and providing it to bidders is that the bids received are likely to be more

accurate and, therefore, result in a decreased likelihood of change order requests and awards. However, since there are costs in time and money associated with acquiring this information, this is the preferred alternative only when the cost savings outweigh the costs incurred. For the hypothetical site described in this paper, the preferred alternative is to acquire information only when there is not a great cost in obtaining it. The cost of delays in the remedial design, considered to be significant by some of the decision makers that were interviewed, often cause the preferred alternative to be proceeding without the additional information.

Since this analysis is for one site with a specific set of conditions, it cannot be concluded that the results pertain to all sites being remediated by on-site incineration. However, individuals making decisions on actual sites could use this model to determine the preferred alternative for their specific situations. In addition to being applied to decisions on sites being remediated by incineration, this approach can be used for other remediation technologies.

Decision makers using this approach would have to determine the known and unknown information about the waste and the range of reasonable treatment costs for the possible types of waste characteristics. The decision makers must determine the costs for acquiring additional information.

This includes their placing a dollar value on time. Conducting further research to obtain information on the probabilities associated with change order requests, awards, and court settlements would be useful to obtain more accurate results. These probabilities could be ascertained by reviewing site files and interviewing contract administrators.

This analysis could be expanded to consider the decision on the type of remediation contract to be used. In cases where there are many unknowns about the waste's characteristics, it may be advantageous to use cost-reimbursement contracts rather than fixed-price. Using a cost-reimbursement contract could reduce or eliminate the need to acquire information on the waste's characteristics prior to issuing the contract since the contractor is paid for the work performed.

Applying decision analysis techniques to the information decision examined in this paper compelled this decision maker to consider the possible outcomes of each of the alternatives, resulting in a more informed decision. Applying these techniques to other decisions that occur during the Superfund site remediation process would produce the same result.

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Appendix

Calculations for Deterministic Sensitivity Analysis

p	q	r	AC (\$)	CO(R) (\$)	CO(M) (\$)	CO(H) (\$)	EMV PROCEED (\$)
0.50	0.50	0.50	20,000,000	3,333,333	1,250,000	0	19,361,111
0.00	0.50	0.50	20,000,000	3,333,333	1,250,000	0	18,750,000
1.00	0.50	0.50	20,000,000	3,333,333	1,250,000	0	19,972,222
0.50	0.00	0.50	20,000,000	3,333,333	1,250,000	0	19,208,333
0.50	1.00	0.50	20,000,000	3,333,333	1,250,000	0	19,513,889
0.50	0.50	0.00	20,000,000	3,333,333	1,250,000	0	19,170,139
0.50	0.50	1.00	20,000,000	3,333,333	1,250,000	0	19,552,083
0.50	0.50	0.50	15,625,000	0	0	0	18,750,000
0.50	0.50	0.50	21,875,000	5,208,333	3,125,000	1,041,667	20,000,000
0.50	0.50	0.50	20,000,000	3,333,333	1,250,000	0	19,322,917
0.50	0.50	0.50	20,000,000	3,333,333	1,250,000	0	19,513,889

RD Delay (months)	DVT (\$/month)		Time Value (\$)	Cost (\$)	EMV Perfect (\$)		EMV(STUDY) (\$)
6	250,000		1,500,000	600,000	18,750,000		20,850,000
0	250,000		0	600,000	18,750,000		19,350,000
12	250,000		3,000,000	600,000	18,750,000		22,350,000
6	0		0	600,000	18,750,000		19,350,000
6	500,000		3,000,000	600,000	18,750,000		22,350,000
6	250,000		1,500,000	250,000	18,750,000		20,500,000
6	250,000		1,500,000	1,000,000	18,750,000		21,250,000

Figure A-1: Sensitivity to Change in p
(Base Values)

Figure A-2: Sensitivity to Change in p

Figure A-3: Sensitivity to Change in p
for Expanded Tree (Base Values)

Figure A-4: Sensitivity to Change in p
for Expanded Tree