A DECISION ANALYSIS METHODOLOGY FOR REMEDIATION OF CONTAMINATED GROUNDWATER UNDER THE INFLUENCE OF TECHNICAL AND ECONOMIC PARAMETERS

By

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NOMENCLATURE

B(t)	benefits in year t
C(t)	remediation cost in year t
$C_f(t)$	failure cost
CORA	Cost of Remediation Alternative software program
DAM	Decision Analysis Model
DATA	decision analysis software by TreeAge
EMV	expected monetary value
f	failure cost fraction
i	interest rate
LNAPL	light non-aqueous phase liquid
MCL	maximum contaminant level
P_f	risk fraction
R(t)	cost associated with risk in year t
SF	sinking fund
t	time unit
WM	waste minimization

CHAPTER I

INTRODUCTION

The subject research involved the development and application of a Decision Analysis Model (DAM) to the problem of defining an optimum approach in addressing environmental concerns at a hypothetical petroleum refinery. The developed model identifies alternative decisions under conditions of uncertainty to define an optimum environmental management approach for given sets of information. The goal of this thesis was to develop a decision-oriented methodology that was conducive to various situations and at various levels of decision making. In addition to the technical information considered in developing the model, such as waste minimization programs, regulatory levels, and technological improvement, the model also incorporated the individual perception to risk by the decision maker. The individual perception to risk was introduced in the tree as a decision variable to assist the decision maker to obtain a clear picture of the influence of risk on the outcome. To minimize the effect of uncertainty in the decision approach, a range of values were considered. This approach represents an evolution from years of research on similar efforts. The next several sections of this thesis outline some of these topics.

For a long time religion, literature, and philosophy focussed on the dilemmas faced by a person when making a choice (Kleindorfer et al., 1993). The evolution of choice has been depicted by many poems and tragedies ranging from just an extension of the will of gods to the realm of willful choice (Kleindorfer et al. et al., 1993). The actions were viewed as something beyond an impulse which made people responsible for their choices. It was many centuries later however, that the process was subjected to systematic analysis (Kleindorfer et al., 1993).

Decision making and choice became areas of immense theoretical and applied interests in many fields. However, it was only during World War II that the fields of management science and operations research developed from an initial emphasis on improving decision making in military and business organizations (Kleindorfer et al., 1993). A number of optimization models have been developed for the purpose of maximizing profits or minimizing costs for a wide array of business or tactical applications. In recent years, these techniques have been extended to many areas of decision making, such as transportation, environment, and energy system planning (Kleindorfer et al., 1993).

Trade-off

Many decisions are made on intuition without analyzing the consequences of such decisions (Sturk et al., 1996). A balance has to be maintained between the objective and the consequences while making decisions in any situation. So trade-offs have to be made in everyday decisions, whether by an individual or an organization. Moreover, trade-offs become essential because of the limited availability of resources and time. This becomes difficult when human lives and environment are involved in the decision process. A consensus exists for a cleaner environment but making a trade-off between the benefits of a cleaner environment and the costs involved in realizing this objective is very difficult. Also, reluctance to make trade-offs between dollars and lives can lead to misguided arguments. Budgetary constraints are sometimes a useful device for forcing people to prioritize their expenditures, but trade-offs between benefits and costs are generally not explicit (Kleindorfer et al., 1993).

The outcome of decisions influences the future. Decisions in the case of an environmental issue have a bearing on the future environment as well as on human lives, apart from the decision maker, and costs can be extreme. The costs can be in the form of an environmental cost, which include human health or environment degradation. A classic example that can be cited for environmental costs is the Bhopal gas tragedy in India. A decision was made to use risk assessment techniques to determine the acceptable standards for operating the plant (Kleindorfer et al., 1993). In general, the procedure was to design processes so that the chances of an accident were at or below an acceptable probability level, instead of an analysis based on the worst outcome scenarios. This resulted in the failure of the plant and eventually loss of human lives and deterioration of the environment. Other examples of environmental failure costs include those resulting from a decision to dump waste at a landfill based on the then existing standards. Often these sites were found to be in violation of the new regulatory standards when the regulatory levels were tightened. To be within the regulatory limit, a large sum of money has to be spent.

Decisions have to be taken in a very rational and structured manner taking time line into account, as the consequences will be apparent only at a later stage. Decision-analysis techniques can be used to evaluate the trade-offs between costs and risks with the help of an objective function and appropriately configured constraints (Freeze et al., 1990).

Uncertainty in Decision Making

Uncertainty is involved in the information used in real world problems. Although uncertainty can be reduced, it cannot be completely eliminated and decisions are typically made based on incomplete knowledge. Probability and utility theory are used to address decision making under uncertainty conditions and are together known as decision theory. The practice of decision theory is known as decision analysis. Decision analysis theory offers a set of procedures (Druzdzel, 1997). These procedures help the decision makers to:

1. structure the problems
2. quantify the uncertainty in the information
3. quantify the preferences of the decision maker towards risk
4. combine the uncertainty in information and preferences of risk to arrive at optimal decisions

The processes involved in engineering designs are usually shown as a sequence of decisions between various alternatives under conditions of uncertainty (Freeze et al., 1990). The various alternatives are subjected to an economic analysis when decisions are made. The economic analysis takes into consideration the costs and benefits of each alternative involved in the decision making. This does not take uncertainty into account. A risk factor can be used to accommodate uncertainty, which also reflects the costs. (Massmann et al., 1991). According to Freeze et al. (1990), "Decision analysis provides the link between the economic framework in which decisions are made and the results of the technical analyses on which decisions are based." This methodology is very much applicable to systems with large uncertainties and high risks and has proven itself in nuclear engineering applications (Freeze et al., 1990). The application of this methodology in hydrogeological projects has the potential to lead to cost savings in remedial projects involving the cleanup of contaminated groundwater (Freeze et al., 1990).

Necessity for Decision Analysis in Oil Refineries

The presence of oil in an aquifer may be viewed as a very serious threat to groundwater resources. Oil refiners frequently encounter questions about environmental compliance. The answers to these questions may however, involve significant amounts of money (Andrews et al., 1996). A typical decision that often confronts these operations is whether to remediate spills immediately or wait for further technological development. Also, the refiners have to address questions relative to establishing often costly waste minimization modifications to their processes while simultaneously initiating remedial measures. Guidance is needed as to which of the many potential approaches would best serve the refiners goals of minimizing the payoff. Under these circumstances the need for optimizing resources and making the right decisions has never been greater. The approach may seem simple but the problem involves numerous decisions that can make solving the problem a very complex and monumental task. Moreover, there are numerous advantages such as evaluating trade-offs between costs and risks using an objective function, reducing the uncertainty of the factors that influence remediation cost while using a decision-analysis approach for groundwater contamination remediation (Massmann et. al., 1991).

Decision Making Environments

Situations under which decisions are made can be broadly classified into 3 categories.

1. Decision making under conditions of certainty

   Here, only one state of nature exists, that is, there is complete certainty about this single state.

2. Decision making under conditions of risk

   In this environment, more than one state of nature exist and there is sufficient information available to assign probabilities to each of these states. The probability values can be collected from historical records or determined analytically.

3. Decision making under conditions of uncertainty

   Here, more than one state of nature exists but there is insufficient knowledge to assign probabilities to the various states of nature (White et al., 1989). Decision making involved in launching a new product can be categorized under this. This means that even though the decision maker does not lack information about the demand for the new product, it may be inadequate to assign probability to the number of units demanded.

Need for Decision Models

As mentioned earlier in the chapter, in most real world situations, decisions are made under conditions of risk and uncertainty. Decision making is problem solving and a certain degree of uncertainty is associated with it (Wang, 1995). As the complexity and uncertainty of a problem increases, the decision maker's ability to keep it in perspective and analyze all the factors is lessened (Wang, 1995). A model incorporating all the variables that affect decision making will help the decision maker to focus their attention on the main problem.

A decision model is a logical abstraction of reality created to help somebody make a decision (Wang, 1995). It consists of quantities and their relationships. With the help of a model a decision maker can respond to subjects of much more complex nature than a person can easily grasp. Moreover, the model can keep track of a large number of details and rapidly perform all the computations. The model helps the decision maker to split the larger problem into smaller ones and analyze them in a rational and structured manner.

Types of Decision Models

Decision models for situations involving risk and uncertainty and where situations suggest criteria for choosing among alternatives are of two types. They are either a matrix or a network or tree model (White et al., 1989). According to White et al. (1989), "A matrix model describes a set of alternatives available where a single alternative is to be selected at the present time". The alternatives are mutually exclusive to each other. There is an outcome for each alternative and the outcomes do not necessitate subsequent decisions (White et al., 1989). A network or tree model is used for situations that involve a sequence of decisions over a time period where the outcomes are uncertain (White et al., 1989). The subject study was over a period time and the outcome for a given alternative resulted in the necessity of subsequent decisions. Hence a network or tree model was used for the analysis.

Decision trees are powerful tools for depicting and facilitating analysis of important problems. A decision tree is a pictorial representation of a sequence of events and the possible outcomes. A typical decision tree is shown in Figure 1. There is no scaling in a decision tree. So the lengths of the branches or the angles between the branches have no meaning. The trees read from left to right and are drawn in the same order as the actual sequence in which the decision choices and events occur in a problem. The point from which two or more branches start is called a node. Decision nodes are points at which the decision maker dictates which branch is followed. Decision nodes are represented by square blocks and are sequential and related to a time line. Chance nodes, which are represented by circles, are points in a decision tree where chance or probability affects the outcome. Any number of decision alternatives or outcomes can branch out from a node. A tree can be drawn with two or more chance nodes or decision nodes in sequence. Branches between decision nodes and random event nodes represent alternative selections or decisions. The ends of a decision tree are called terminal nodes, represented by triangles and are all mutually exclusive points (Newendorp, 1975). Branches between random event nodes and terminal nodes represent the states of nature that are uncontrollable (Ossenbruggen, 1984).

This framework assists the decision maker in determining the best alternative. For decision tree analyses, the easiest way to take into account the timing of money is to use the present worth approach and discount all monetary outcomes to the decision points in consideration (White et al., 1989). Hence, the present worth values of capital cost and the monetary value of loss of property are used as measures of the consequence

(Ossenbruggen, 1984). The consequence will depend upon the alternative chosen and the actual state of nature (Wang, 1995).

The advantages in using a decision tree for the analysis include the following points:

1. The contingencies and decision alternatives are defined and analyzed in a consistent way. The complex decision is broken down into simpler parts and then reassembled to provide a rational basis for the initial decision.
2. The analysis provides a better chance of consistent action in arriving at a decision as each step is analyzed ahead of time.
3. The decision tree can be used to follow the course of events. At any decision node, if the conditions have changed, the remaining alternatives can be re-analyzed to develop a new strategy from that point.

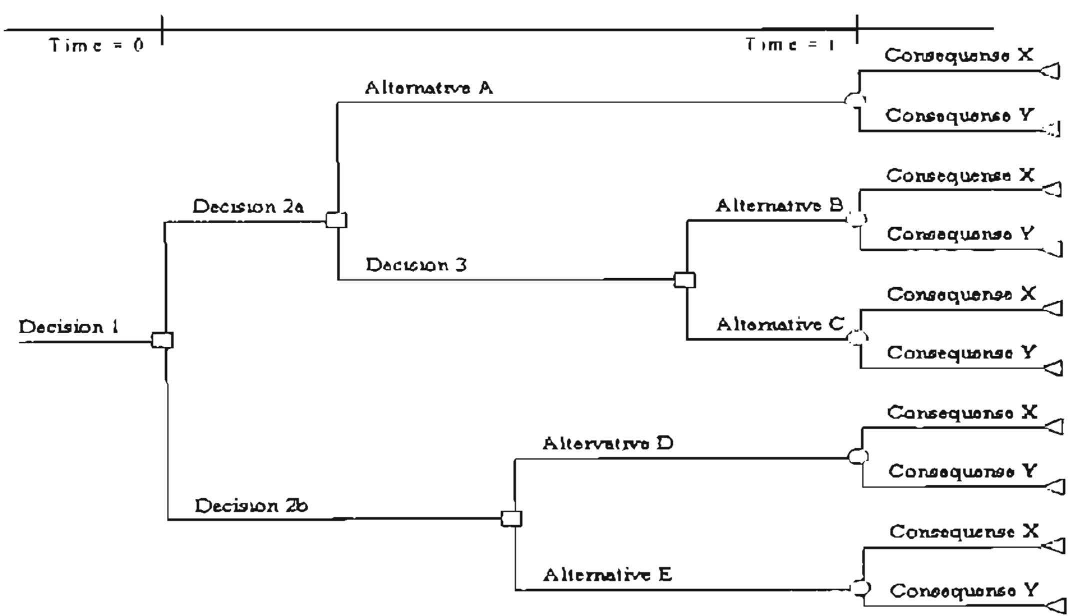


Figure 1. Example decision tree used to select alternatives under uncertain conditions (Source: Wang, 1995).

Development of Methodology Structure

The structure of the Decision Analysis Methodology consisted of five steps, which are illustrated in Figure 2. The first step is defining the objective of the problem, which in this case was to develop an overall scenario for the optimum approach for environmental compliance at a hypothetical petroleum refinery. The next step is listing the available alternatives. The third step is developing screening criteria which include all the constraints and the objective of the decision maker. In the subsequent step, each possible alternative is evaluated in terms of desired outcomes according to the criteria. The final step involves the selection and execution of the best alternative determined from the previous step. This problem-solving process is the same as described by Baird (1978).

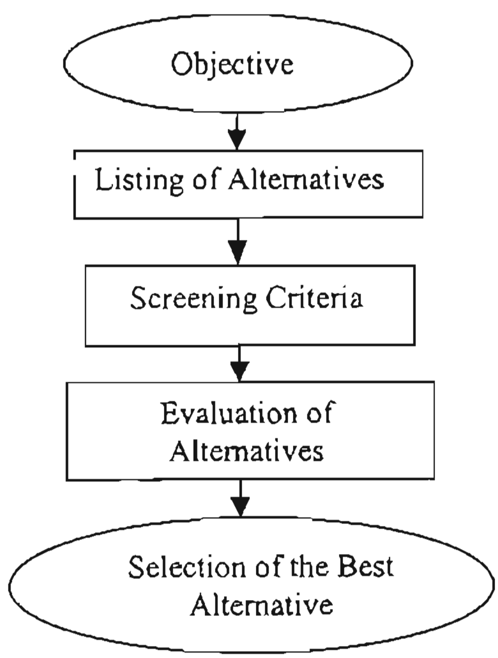


Figure 2. Decision making process flow chart. (Source: Baird, 1978)

CHAPTER II

SCOPE OF WORK

Problem Situation

The Decision Analysis Methodology was applied to a hypothetical oil spill scenario previously developed by Andrews et al. (1996), in their study to compare trade-offs between groundwater remediation and waste minimization for the petroleum refining industry. Andrews et al. used geohydrologic site characteristics (published in reports detailing the Sand Springs Petrochemical Complex Superfund Site in Sand Springs, Oklahoma), together with varying regulatory levels for benzene, remediation methods, and technology considerations incumbent upon petroleum refineries in general, as well as for those refineries located in the riparian Arkansas River or similar locales.

The spill hypothesis developed used a scenario of a 125,000 barrel oil storage tank leaking at a rate of 6.25 barrels per day for a period of 4 years. The total spill used in the basecase scenario was 9003 barrels of oil. In addition, they have considered waste minimization situations where the basecase spill volume was reduced by ten and twenty percent. This could be accomplished by many means including preventive maintenance of equipment, inventory monitoring and an initiation of a spill prevention program.

These spills were hypothetically routed through the alluvium to the top of the water table aquifer with conditions typical of the Arkansas River. At the water table, a benzene plume solubilized from the LNAPL petroleum spilled. As with the LNAPL, this benzene was predicted to have been routed into and through the water table by analytical transport models. Details from the resultant benzene and LNAPL plume were then input into an EPA supported expert system called CORA (Cost of Remediation Action) to define appropriate remediation approaches as well as attendant costs. These were completed for periods of time ranging from 2 to 50 years. Figure 3 presents the Andrews et al. research structure employed in the earlier effort.

To estimate the costs of cleanup at the site, for the trade-off analysis between remediation and waste minimization programs, Andrews et al. considered various factors:

1. Rate of Biological Decay of Benzene

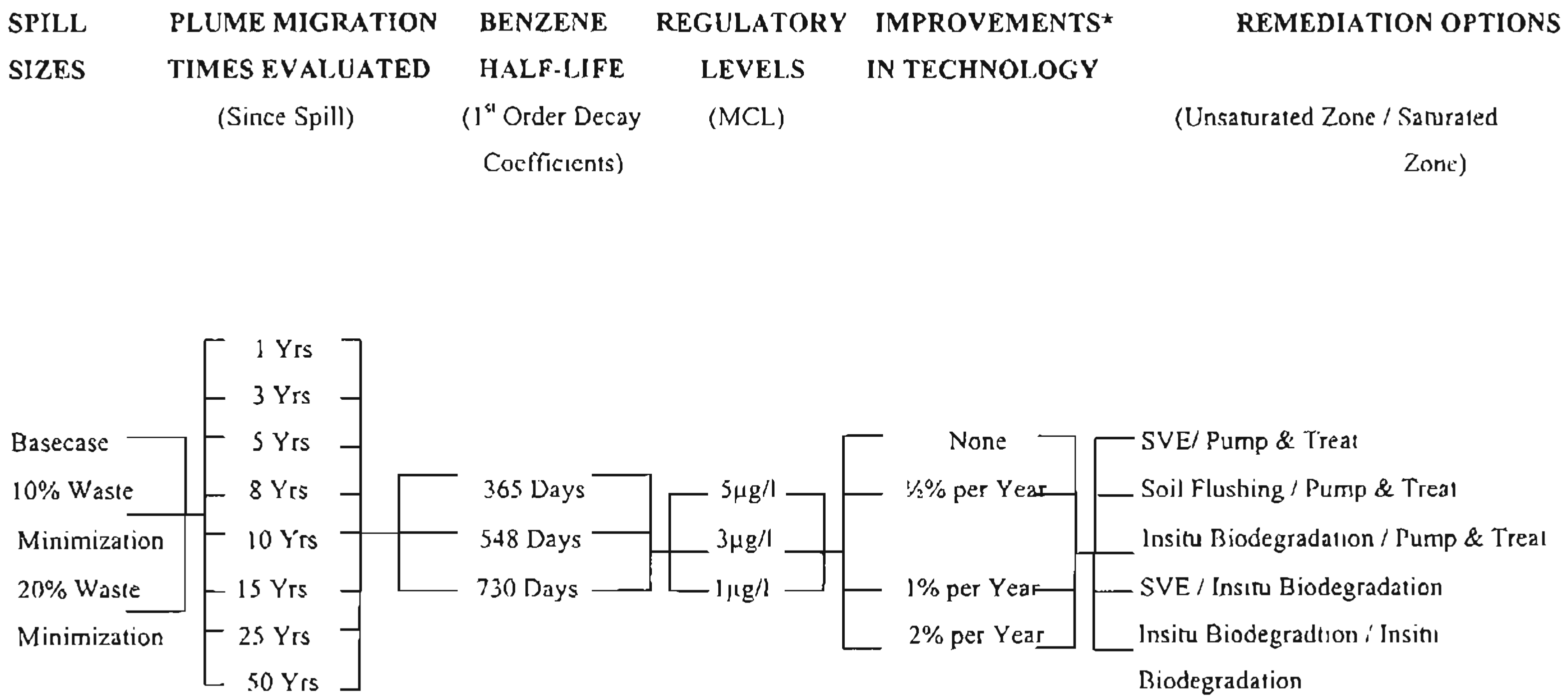
   The effect of biological decay of benzene was evaluated by considering three half-life periods of 365, 548 and 765 days, respectively. These were considered based on climatic factors and are reported to be typical of half-lives from Northern, Central and Southern United States sampling locations. (Andrews et al., 1996).

2. Technology Improvement Rate

   Over the recent past the growth in remediation technologies has resulted in lower costs. These reductions can suggest that postponing remediation could ultimately be economically favored. However, there is an uncertainty in determining the rates at which the technology improves. In order to accommodate such an uncertainty, Andrews et al. considered a series of technology improvement rates ranging from 0% through 0.5% and 1% to 2% on a per annual cost basis. The criterion for considering these rates was to address the effects of the improvement rate on the cost of remediation.

Figure 3

The Research Structure Employed By Andrews et. al.



(Source: Andrews et al. 1996)

3. Regulatory Levels

Andrews et al. also studied the effects of regulatory responsibilities by decreasing the maximum allowable concentration level of benzene in contaminated groundwaters from an initial concentration of 5μg/l to 3 and then to 1μg/l. This served to increase the size of the contaminated aquifer for remediation, which increased costs.

4. Spill Sizes

Andrews et al: also studied the effect of waste minimization on the remediation cost. The minimization was done in terms of spill volume. Two levels of minimization program were considered by reducing the spill volume by 10 and 20 percent of the initial volume.

In order to study the trade-offs between remediation and waste minimization, Andrews et al (1996) considered various treatment methods for the vadose and saturated zones. From a wide set of remediation methods suggested by CORA, five methods were considered to estimate costs for cleanup at the site:

1. Soil vapor extraction and Groundwater extraction.
2. Soil flushing and Groundwater extraction.
3. In-situ biodegradation and Groundwater extraction.
4. Soil vapor extraction and In-situ biodegradation.
5. In-situ biodegradation and In-situ biodegradation.

The time taken for remediation of the oil spill was one year. Figure 4 presents the relative cost comparisons for alternative remediation methods for the basecase situation with the maximum concentration level for benzene as 5μg/l and no technology improvement. This figure is presented for illustrative purposes to show the relationships between technologies, time and costs. Other figures can be generated for other scenarios developed from the research configuration presented in Figure 3 based on the costs generated by Andrews et al. (1996).

From Figure 4, it is evident that method 5 (In-situ biodegradation of the vadose and saturated zones) was the most economical alternative considered. This remediation alternative over the 50-year period was taken as the data set to be applied to the Decision Analysis Methodology developed in this analysis. No other technologies were considered, as in-situ biodegradation in both the saturated and unsaturated vadose zones always had the lowest costs.

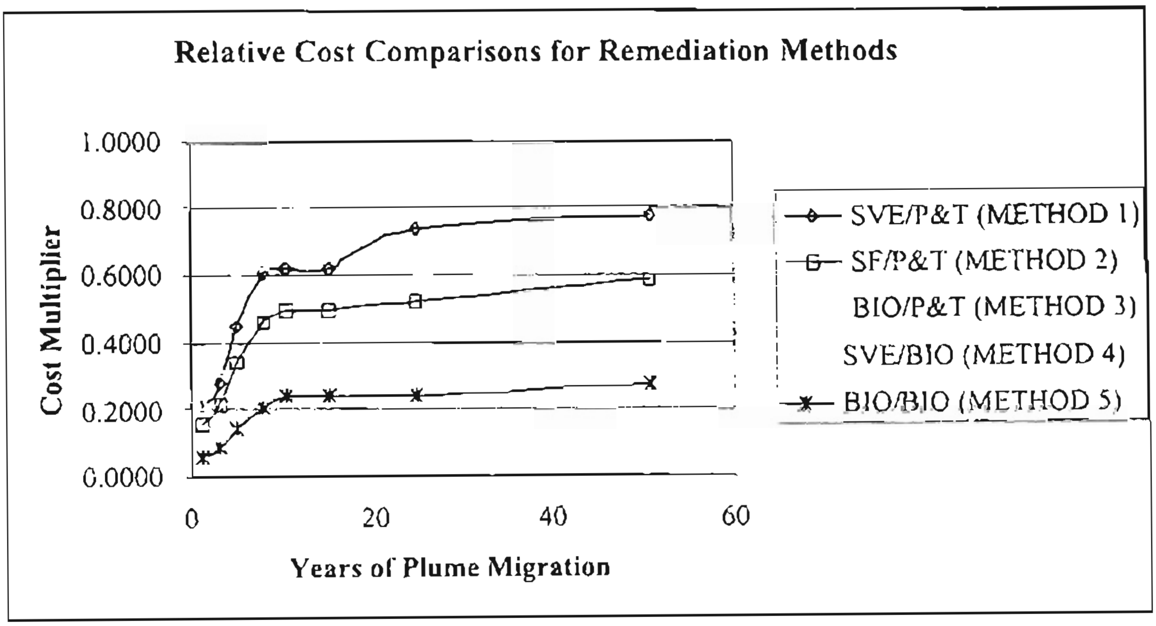


Figure 3. Relative Cost Comparisons for Alternative Remediation Methods for Basecase, MCL - 5μg/l, and No Technology Improvement (Source: Andrews et al., 1996)

<u>Structure of Study</u>

Of the variables mentioned in the previous section, the rate of biological decay of benzene in the aquifer is dependent on natural factors like groundwater temperature

(Andrews et al., 1996). The effect of biological decay would have more significance on the location of a new refinery rather than for an existing refinery. As this decision model was primarily built for existing refineries, the rate of biological decay was not considered as a variable in this decision analysis methodology. Since the half-life period of benzene was not considered as a variable in this research, it did not play a role in the selection of remediation cost. So, the costs based on the half-life period of one year were used in all modeling efforts.

Andrews et al. determined the remediation costs over a period of 50 years. In order to reduce the size of the tree to accommodate some technical constraints like computer processing ability, not all the years considered by Andrews et al. were employed. Since the objective of the thesis was to develop a scenario that would enable the decision maker to make effective decisions, a sample set of values was considered in building the model. The values in the sample set included 1, 5, 10, 15 and 50 years. Tables 1, 2, and 3 present the remediation costs including the operating and maintenance costs, as determined by Andrews et al. (1996). The tables are divided according to the waste minimization levels considered in developing the trade-off analysis by Andrews et al. (1996).

Time has a bearing on the other factors that were considered by Andrews et al. in developing their scenario. For example, the maximum regulatory concentration level for benzene at present is 5μg/l. This may be reduced or relaxed in the future. Since the model was built for a period of 50 years, factors like technology improvement rate and regulatory levels were also included in the decision methodology. Waste minimization programs were also considered when developing the methodology in order to see its effect on the decision scenario. It should be mentioned that though the model was built only for a period of 50 years, it could be extended to any number of years and the only additional information needed would be the remediation costs.

Base Case				
Time (in Years)	0% Tech. Improvement (Cost in $)	0.5% Tech. Improvement (Cost in $)	1% Tech. Improvement (Cost in $)	2% Tech. Improvement (Cost in $)
5ppb				
1	3,419,000	3,398,155	3,377,334	3,335,760
5	8,562,000	8,349,661	8,141,558	7,737,806
10	14,426,000	13,700,097	13,007,338	11,715,869
15	14,426,000	13,385,805	12,415,933	10,669,676
50	16,154,000	12,526,270	9,699,467	9,219,542
3ppb				
1	3,389,000	3,368,338	3,347,699	3,306,491
5	9,862,000	9,617,421	9,377,721	8,912,666
10	16,526,000	15,694,427	14,900,822	13,421,353
15	16,526,000	15,334,384	14,223,327	12,222,866
50	19,554,000	17,289,890	15,278,461	11,907,916
1ppb				
1	3,469,000	3,447,850	3,426,724	3,384,543
5	11,462,000	11,177,740	10,899,152	10,358,647
10	20,626,000	19,588,119	18,597,626	16,751,110
15	20,626,000	19,138,751	17,752,048	15,255,284
50	23,554,000	18,266,331	14,147,566	8,453,785

Table 1: Total Cost of Remediation for Base Case Scenario (No Waste Minimization) (Source: Andrew et al., 1996)

10% Waste Minimization				
Time (in Years)	0% Tech. Improvement (Cost in $)	0.5% Tech. Improvement (Cost in $)	1% Tech. Improvement (Cost in $)	2% Tech. Improvement (Cost in $)
5ppb				
1	3,285,000	3,268,575	3252150	3,219,300
5	7,418,000	7,220,990	7028260	6.655,349
10	9,962,000	9,467,363	8994978	8,113.410
15	11,290,000	10,440,282	9650711	8,236,315
50	13,362,000	10,435,200	8142801	4,937,333
3ppb				
1	3,375,000	3,358,125	3,341,250	3,307,500
5	7,718,000	9,070,529	8,828,434	8,360,008
10	11,562,000	13,743,927	13,058,158	11,778,372
15	11,790,000	13,214,493	12,215,116	10,424.884
50	14,462,000	15.280,398	11,921,081	7,228,268
1ppb				
1	3,375,000	3,358,125	3,341,250	3,307,500

5	9,318,000	9,070,529	8,828,434	8,360,008
10	14,462,000	13,743,927	13,058,158	11,778,372
15	14,290,000	13,214,493	12,215,116	10,424,884
50	19,562,000	15,280,398	11,921,081	7,228,268

Table 2: Total Cost of Remediation for 10% Waste Minimization Scenario (Source: Andrew et al., 1996)

20% Waste Minimization				
Time	0% Tech. Improvement	0.5% Tech. Improvement	1% Tech. Improvement	2% Tech. Improvement
(in Years)	(Cost in $)	(Cost in $)	(Cost in $)	(Cost in $)
5ppb				
1	3,612,000	3,589,439	3,566,906	3,521,926
5	6,380,000	6,228,327	6,079,524	5,790,363
10	8,588,000	8,173,458	7,776,987	7,035,474.
15	9,962,000	9,246,465	8,579,102	7,376,974.
50	11,765,000	9,139,880	7,091,476	4,252,549
3ppb				
1	3,612,000	3,589,439	3,566,906	3,521,926
5	6,680,000	6,521,195	6,365,395	6,062,637
10	9,988,000	9,505,880	9,044,777	8,182,384
15	10,362,000	9,617,734	8,923,576	7,673,179
50	12,065,000	9,372,941	7,272,304	4,360,986
1ppb				
1	3,662,000	3,639,126	3,616,282	3,570,680
5	7,890,000	7,702,430	7,518,408	7,160,810
10	12,288,000	11,694,859	11,127,576	10,066,594
15	14,462,000	13,423,246	12,454,425	10,709,275
50	16,265,000	12,635,797	9,803,898	5,879,108

Table 3: Total Cost of Remediation for 20% Waste Minimization Scenario (Source: Andrew et al., 1996)

The decision methodology also takes into account other factors like failure costs, the impacts of a sinking fund, and the risk tolerance of a decision maker. Failure cost is the cost to be paid in case the constraints of the problem are exceeded. The constraint in this project was the Maximum Concentration Level of Benzene set by EPA. The sinking fund is a fixed amount deposited in an interest bearing account in installments over a period of time. Establishment of a sinking fund allows the decision maker to set aside resources for remediation which can be applied when either regulatory responsibilities, or improvement in pollutant capture and possibly reuse dictate implementation of the optimum remediation approach.

The decision maker's attitude towards risk is defined as risk avoidance and is a mathematical quantity. It is not the amount of money that the decision maker can lose. Rather, people have various risk tolerance levels. With a greater risk avoidance level, the cost of compliance increases and results in a lower chance of failure. These factors are explained in detail in the subsequent chapter on materials and methods.

CHAPTER III

MATERIALS AND METHOD

The primary objective of this thesis was to develop a model showing various possible outcomes for a given set of variables and to enable the decision maker to make decisions in an effective manner. Most projects have a single primary objective and the projects must try to meet the objective within a set of technical and/or economical constraints (Massmann et al., 1991). The decisions are usually made based on economic factors (Massmann et al., 1991). A technical objective, from a refinery manager's perspective, usually involves satisfying a constraint in the form of a regulatory standard. The economic objective must be to meet the technical objective in such a way as to minimize economic loss. The decision model built in this thesis allows for the comparison of alternatives and is an analysis based on a risk-cost-benefit objective function.

The objective function can be defined as the net present value of costs, risks, and benefits taken over a time period. Being a cost minimization model, the objective function's goal was to minimize costs. An objective function was used to calculate the cost of each consequence in a decision tree similar to Figure 1. Equation (1) presents the objective function for this project. The function developed was similar to the one developed by Jardine et al. (1996) who used a decision analysis approach to design an environmental monitoring network at a waste management facility. Their decision model identified the preferred monitoring strategy as the design alternative that minimized the monitoring and expected costs of failure and on-site remediation. The objective function was defined so as to enable the least costly remediation. Since the work involved in this thesis was to develop an optimization model that presented an overall picture for the decision maker, it was decided to use an approach similar to Jardine et al. (1996). The objective function is:

$$\text{Minimize } \$ = [C(t) + R(t) - B(t)] \tag{1}$$

where $ = Cost in dollars

t = Time in years

B(t) = Benefits in year t

C(t) = Remediation Cost in year t

R(t) = Risk Cost in year t

Remediation costs are the costs calculated by Andrews et al. (1996) and include the annual operating and maintenance costs. The remediation costs are all in terms of present worth. As mentioned before, the easiest way to take into account the timing of money is to use the present worth approach and discount all monetary outcomes to the decision points in consideration. So, the values that were not in their present worth were all converted to their present worth.

Risks are defined as the net present worth of the expected cost of failure. The cost associated with failure is represented by the risk term and includes the regulatory costs. Risk cost is obtained for each alternative by multiplying the "risk fraction" (defined below) with the cost of failure, which for this effort was taken to be potential fines imposed if an oil spill occurred. Since it may be difficult to develop firm estimates for failure costs (Freeze et. al, 1991), a range of possible failure costs were used to evaluate the effect of these costs on a decision. In this manner, the Decision Maker is presented with a range of possible alternatives, each a function of a specific risk tolerance level he/she must provide. This approach changes risk from a random to a decision variable.

The cost associated with risk depends on the extent to which the refinery manager can tolerate a risk and on a projected failure cost, which for this effort was taken to be potential fines imposed if an oil spill occurred. Hence, the cost associated with risk is:

$$R(t) = P_f(t) * C_f(t) \qquad (2)$$

Where $R(t)$ = Cost associated with risk in year t

t = Time in years

T = Total time period in years

$P_f(t)$ = Risk fraction

$C_f(t)$ = Failure cost and

The term *risk fraction* denotes the extent to which a decision maker can tolerate risk when weighing the alternatives. Individual perception of risk varies between people. Some people tend to be more risk averse than others. Since the objective was to develop a model that provided an overall picture for the decision maker, a series of risk fractions were considered. The values considered in terms of percentages were 10%, 50%, and 90%. A 10% risk fraction meant that the decision maker wanted to have only a 10% chance of making a correct decision or in other words, had a 90% chance of being incorrect, while a 90% risk fraction has only a 10% chance of being correct and so on.

The three values were chosen arbitrarily, but address a wide range of possibilities. They include cases of highly uncertain information relative to future technology gains and regulatory level. They also include the impact of other unforeseen events that contribute to a highly uncertain decision. The influence of risk fraction in the decision making process was then evaluated.

Estimation of environmental failure costs, i.e. fines imposed for oil spills, may prove to be difficult and were chosen somewhat arbitrarily. To reduce the effect of uncertainty in this effort, a range of values were considered as failure costs and for comparative purposes were taken as a fraction of the remediation cost. The failure cost is determined as shown below.

$$C_f(t) = f * C(t) \tag{3}$$

Where $C_f(t)$ = Failure cost in year t

t = Time in years

f = Failure cost fraction

C (t) = Cost of Remediation

The values chosen for failure cost fraction "f" were 0.1 and 0.3. This means that the failure cost considered for the methodology were 10% and 30% of the total remediation cost. The effects of failure cost on the decision procedure were studied.

The term *benefits* in an objective function usually represents the revenue generated by making a particular decision. However, in this case, benefit represents the sinking fund that goes in at the beginning of the project. As used in this study, a sinking fund is a pool of money allocated for eventual remedial action. If not spent in year t, these funds, plus any accrued interest, are rolled into the next time period where they may be augmented by another principal contribution. Adding a sinking fund to the effort in some ways favored postponement of remediation as the pool of funds increasing each year against minimal annual expenses inherently has many optimal features. In this case too, there was no fixed sum since the amount to be deposited depends on the individual organization. In order to study the effect of sinking fund on the decision, an arbitrary value of $100,000 per annum was used in the decision tree. The benefit cost for 't' years was calculated using the formula:

$$B(t) = \sum_{t=0}^{T} \frac{1}{(1+i_2)^{t_2}} \text{(Sinking Fund)} * [\frac{(1+i_1)^{t_1} - 1}{i}] \qquad (4)$$

Where B(t) = Benefit cost

t_1, t_2 = Time in years and

i_1, i_2 = Interest rate

Interest rate is the rate of gain from an investment. Here the investment is in the form of annual deposit. The uniform deposit over a period of time would generate some interest which was determined by using i_1. The benefit cost is multiplied by a factor, $[\frac{1}{(1+i_2)^{t_2}}]$, to determine the present value of the total amount generated from the sinking fund contributions, where i_2 and t_2 are the interest rate and time (in years), respectively. However, the interest rate was assumed to be the same for all cases. Time, t_1, is the time period in years for which sinking fund was considered and time, t_2, is the time period in years used to determine the present worth of the fund. These were considered separately because various scenarios were developed to study the effect of sinking fund. The scenarios included time periods for which no sinking fund was considered.

The formula calculates the interest generated on the sinking fund, which is a uniform series of amounts, deposited over time. This can be considered as revenue because the amount can be used towards remediation purposes thereby reducing the amount to be put in at the time of remediation.

The variables discussed above and the associated values could be summarized as follows:

- The risk fraction was assumed to be a series of alternative values. The values considered were 10%, 50%, and 90%. As mentioned earlier, a 10% risk means that the decision maker wants to have only a 10% chance of making a correct decision. These values were taken in such a way as to cover a wide range of possibilities as well as highly uncertain information.
- The failure cost was considered as a fraction of the total remediation cost. The fractional values considered were 10 and 30 percent of total remediation costs.
- Sinking fund was included in the *objective function* to optimize resources. A sinking fund of $100,000 was chosen as the amount of money to be deposited. These deposits were made after each "no remediation" alternative was encountered as the "remediation" selection stopped all activity. These deposits compounded for 1, 5, 10, 15 and 50 years depending upon which "no remediation" alternative introduced the "sinking fund" choice. Figure 4 presents this information.

Obviously, only a limited number of sinking fund variations could be considered. The ones selected, however, were considered representative of a decision maker's alternatives and were chosen to illustrate the effects of sinking fund contributions on the ultimate decisions reached.

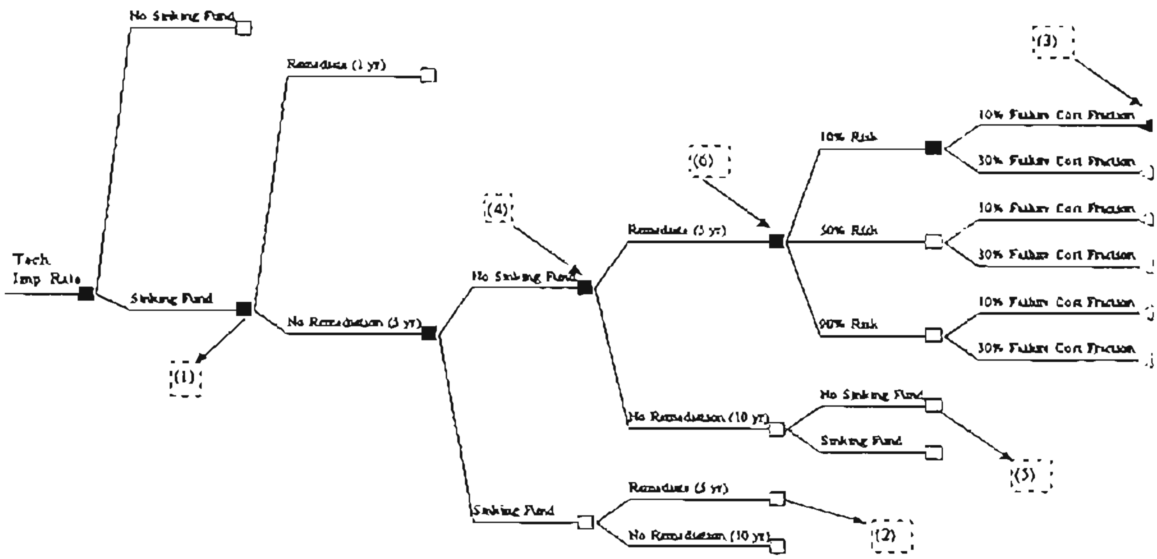


Figure 4. Section of the Decision Tree showing the path for the calculation of Expected Value

- An interest rate of 4% was used to calculate the interest accrued by the sinking fund and also to determine the present value of the total amount generated by the sinking fund.

At this point, the example problem has been introduced. Referring to the decision making process in Figure 2 of Chapter I, the first and the third steps, i.e. the objective definition and screening definition, are both complete. The decision-maker now must develop courses of action and process the data. The next section discusses the methods used within these steps as applied to the example problem.

Model Development

Developing the decision tree framework starts with visualizing the problem and developing a logical flow diagram of the decisions that must be made (Wang, 1995). This process is tedious and usually requires changes or adjustments to the tree.

Decision Tree Construction

Figure 6 is the portion of the total decision tree that compares regulatory levels, waste minimization and technology improvement. This figure is included to show the alternatives available before making a decision on initiating a sinking fund. The construction of the decision tree consisted of the following steps:

1. Identify the points of decisions and alternatives available at each point.

   The decision maker was faced with the problem of finding out the most effective way of remediation. The root decision point of the decision tree shown in Figure 6 defines this. At this point the decision maker faces three alternatives which are based on the maximum concentration level of benzene allowable in affected groundwater. As mentioned in the previous chapter, three allowable concentration levels of benzene were considered. Following each of these regulatory levels, three waste minimization alternatives were evaluated. The three alternatives included "no waste minimization", "10% waste minimization", and "20% waste minimization" programs. These are represented in Figure 6 as Base Case, 10% WM, and 20% WM, respectively. At each waste minimization node, the alternatives on technological improvement rate were evaluated. These are represented in Figure 6 as 0%, 0.5%, 1%, and 2% per annum Technology Improvement, respectively.

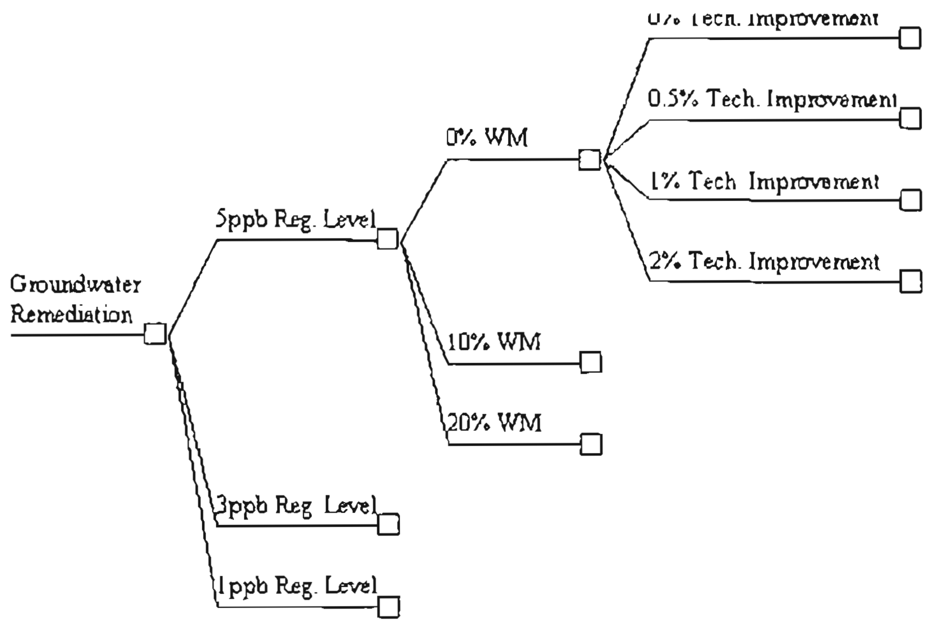


Figure 6. Decision tree in skeletal form, depicting initial decision nodes within the tree. WM – Waste Minimization

Once the initial alternatives which included selection among the regulatory levels, the waste minimization programs, and technology improvement rate were selected, the decision maker was faced with the "sinking fund" or "no sinking fund" alternatives. This is shown in the subtree following the "alternative technology improvement" in Figure 5. Additionally, the figure shows the alternatives "remediation" and "no remediation", that could be followed, at the decision nodes "no sinking fund" and "sinking fund". If decision to remediate was made then subsequent decisions involving risk and failure cost fraction follow in the decision tree. These are shown in Figure 5 following the decision to remediate at the 5th year [point (6)]. In case of a decision to postpone remediation, the decision maker was presented with an option to introduce a sinking fund or not, and so on.

2. Estimate the values needed to make the analysis; the expected monetary outcome for various outcomes and alternative actions.

The objective function developed in the previous section was used to determine the outcome of each alternative in the decision tree. An example is shown here calculating the payoff of an alternative. The alternative considered is a basecase spill scenario with a maximum regulatory concentration level for benzene of 5μg/l and no technological improvement. Ten percent risk and failure cost fractions were utilized in determining the Expected Monetary Value. The decision path followed is highlighted in Figure 5 and the Expected Monetary Value is calculated for point (3). According to Equation (1), the expected monetary value of the alternative was:

Expected monetary value = C(t) + R(t) - B(t)

C(t) = $ 8,562,000 (from Table 1)

R(t) = Risk Fraction * Failure Cost Fraction* Remediation Cost

= 0.1*0.1*8,562,000

= $ 85,620

yielding a total cost of $ 8,647,620.

A sinking fund deposit for the first five years generated a benefit of $541,632 (as calculated by Equation 4).

The *present value* of this amount

= $[1/(1+0.04)^5]*541,632$

= $445,181. Hence, the expected monetary value of the alternative as $8,202,439.

Expected monetary values for all other alternatives were calculated in a similar manner.

3. Analyze the alternatives, starting with the most distant decision point and work back, to choose the best initial decision(s). The calculated expected monetary values for all the alternatives were compared to determine the optimal path, i.e. the path with minimal costs. Two kinds of decision nodes were involved in this tree construction. One set, independent of the decision maker, was controlled by external factors like the maximum allowable concentration level for benzene and/or the technological improvement rate. The other set of decision nodes was those that were dependent on the decision maker. These decision nodes were the waste minimization programs, sinking fund and remediation alternatives, in addition to those that represented the various values of risk and failure cost fractions. Of these nodes, the decision node "risk fraction" was dependent on the decision maker's aversion to risk. Depending on the decision maker, the value of the risk fraction will vary as will the optimum solution. Hence, different values for probabilities of failure as well as the attendant costs were included in the tree so that the decision maker can fully evaluate the significance of the different alternatives. This approach replaces the requirement that significant stochastic analyses be conducted to fully to define the expected probabilities of occurrence with a deterministic risk perception level which directly addresses the managers risk tolerance level and allows that level to be a full participant in the decision.

This method was similar to the one used by Freeze et al. (1990) where an integrated decision process with a set of alternatives was defined in such a way that each alternative covered the entire process. This allowed the decision maker the opportunity to assess the economic tradeoffs between choosing different time periods and risk fractions for remediation.

Tool Used

The Decision Analysis software by TreeAge (DATA) was used to implement the decision tree analysis (DATA, 1994). DATA is capable of performing the analysis quickly and has other options including evaluating intermediate points within the tree and conducting sensitivity analysis on variables. Using a program such as DATA was helpful with its ability to edit large trees quickly.

The disadvantage in using a decision tree approach is that the size of the tree increases in a geometrical proportion. The size of the tree constructed in this effort was very big. A large number of expected monetary values had to be generated. To expedite the process, codes were written in C language to generate the expected monetary values for each alternative and to generate the tree in the form of an outline which is the text format of the tree. DATA has an added feature that helps to convert the text form into the tree format. The program codes written for building the tree are given in Appendix A.

Since the size of the model was very large, the entire tree could not be shown here. However, using DATA the tree could be collapsed to illustrate specific problems and their optima as illustrated in the preceding figures. The collapsed tree (Figure 6) shows the initial set of decision alternatives which includes the most effective remediation, the various regulatory levels considered for benzene, the waste minimization programs, and the different rates of technological improvement.

Objective Function Variable Sensitivity Analysis

Quantities incorporated into the objective function such as risk fraction, failure cost fraction and sinking fund, are inherently uncertain. Any changes to the values of these variables would produce a change in the Expected monetary value. So a sensitivity analysis was done by studying the effect of change for any of the critical variables on the expected monetary value. Bivariant sensitivity plots, as shown in Figures 7 and 8, were utilized to evaluate the sensitivity of the respective variable(s). Since a wide range of user specified alternatives for failure cost and risk were incorporated into the decision analysis, sensitivity analysis for those variables were carried out by plotting histograms showing the Expected Monetary Values for different failure costs and risks. Figure 7 shows the variation of the Expected monetary value for different failure costs. The initial selection of the alternatives included 5μg/l benzene MCL, 0% waste minimization and 0% technology improvement rate. The path of sinking fund deposit until remediation was chosen for illustrative purposes and the Expected Monetary Value calculated. The plot shows an increase in the Expected Monetary Value for a change in the failure cost from 10% to 30% by $288,520 when the risk aversion level of the decision maker was 10%.

Another type of sensitivity analysis was completed for sinking fund effects, using DATA. Figure 7 shows the variation of expected monetary value with a change in sinking fund at the node "sinking fund" at the 5^{th} year. The example plot shows a threshold value of $469,000 per year. Above this value the "no remediate" option is preferable in the example presented. At sinking fund deposits less than $469,000 per year, the "remediate" alternative is optimum.

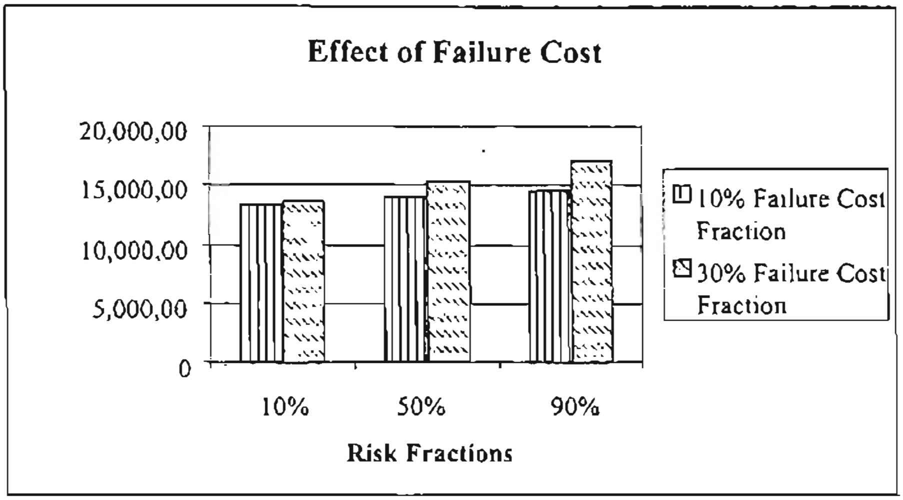


Figure 7. Plot showing the Expected Monetary Values for different Failure Cost values, an objective function variable

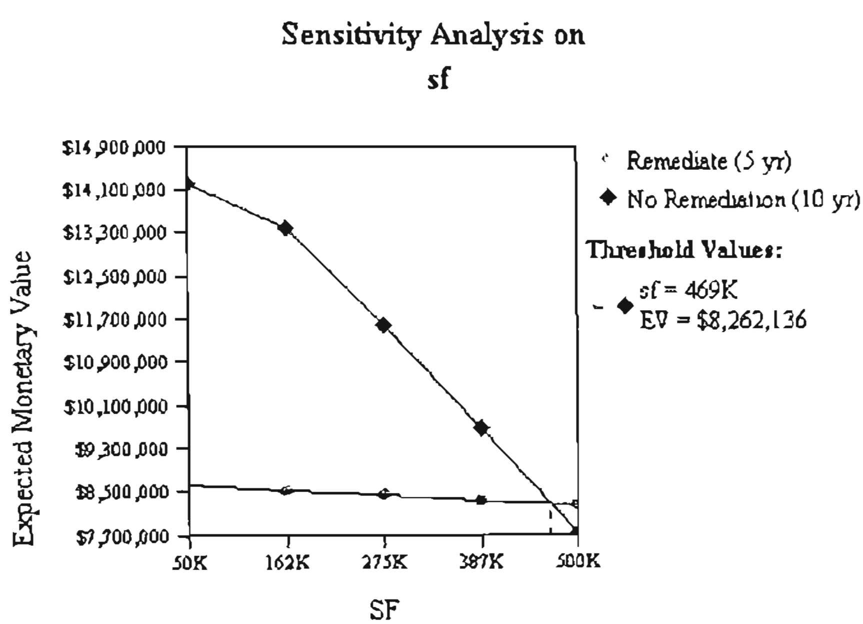


Figure 8. Sensitivity Analysis plot for Sinking Fund, an objective function variable with the Expected monetary value
SF – Sinking Fund

The other variable in the objective function, the remediation costs was influenced by many factors such as the regulatory level of benzene, the waste minimization program and the technology improvement rate. So the effect of change in the remediation was determined by analyzing the effects of variation of the influencing variables. The effects of all the variables in the objective function are dealt with in detail in the following chapters.

CHAPTER IV

RESULTS

The complete decision tree for the analysis with all the scenarios and alternatives is too large to be shown on standard paper. To illustrate the decision tree analysis, Figure 9 presents the entire tree in "rolled back" form showing the expected monetary values (EMV) for each of the decision alternatives, collapsed at the Technology Improvement Rate decision nodes. Similarly, Figure B-1 (see Appendix B) presents the entire tree over a time period of one year. The branches shown are repeated for 5, 10, 15 and 50 years. For the purpose of illustration, the decision tree was fragmented into nine sections. These sections are shown in Figure B-1.

Following the highlighted path in Figure 9, 5μg/l MCL of benzene, 20% waste minimization, 2% technology improvement rate and remediation at the 1st year with sinking fund, gave the overall optimum for the decision tree for a risk and failure cost fraction of 10% each. The latter two variables could not be shown in this figure because the size of the tree precluded them from being shown on standard paper. This finding, while obvious without technical analysis, cannot be said to represent the range of conditions confronting the refinery manager. Rather, the values of these variables are subjected to uncertainty and could vary at any stage of the decision process given alterations in regulatory levels, the manager's risk aversion, waste minimization program,

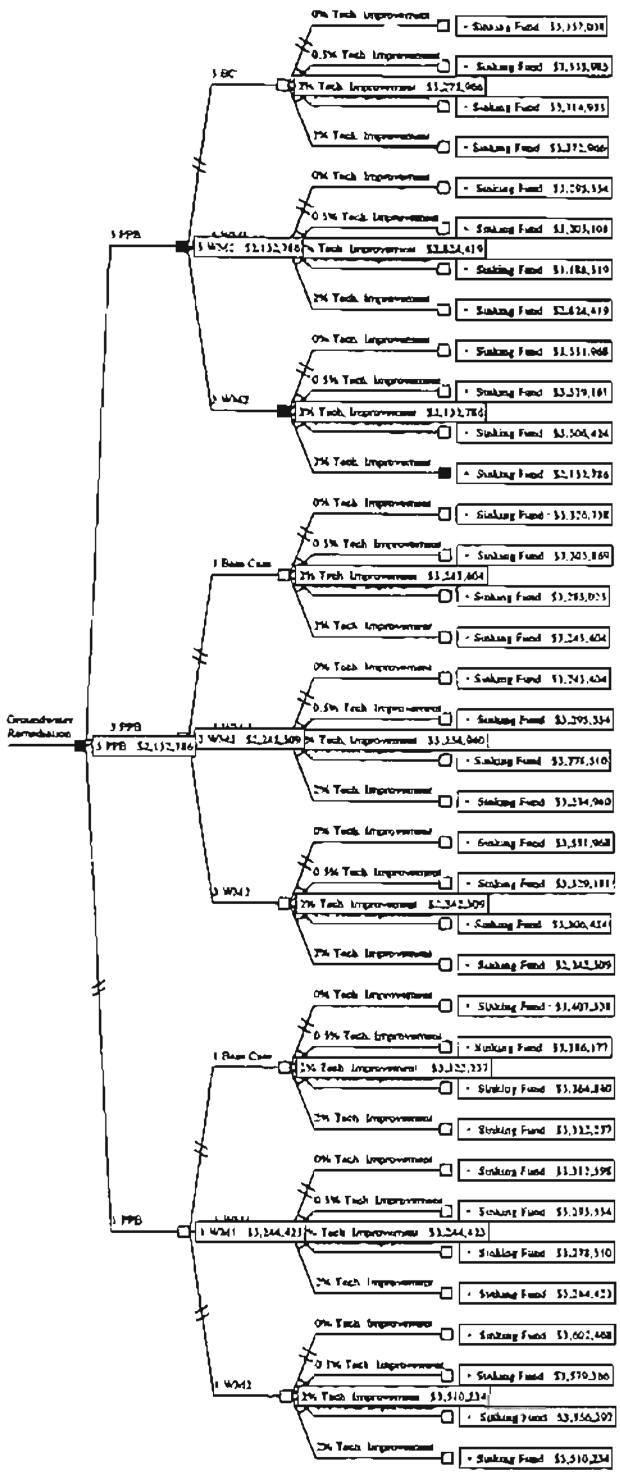


Figure 9. Decision Tree collapsed at the technology improvement rate nodes showing the Expected Monetary Values for the various alternatives considered in the decision tree.

technology improvement rate and failure cost among others. Such a change would lead to a change in the expected monetary value and the optimal path. The research goal, therefore, was to determine the influence of such changes on the expected monetary values and to identify alternate optimum paths for other decision possibilities under conditions of uncertainty. These figures were shown to illustrate the decision tree analysis. As an example, suppose the refinery managers decided to remediate at the end of the 15^{th} year, based on their interpretation of the pertinent conditions at that time. If one of the variables say technology improvement rates changed, then the expected monetary value would change too. Now the question is, for the same amount of available funds are there other more desirable paths? Say for example a path where there is "no sinking fund" input for a certain period of time. This might be desired, if the decision maker foresees a future fund crunch, making sinking fund deposits impossible.

The influence due to different sinking fund duration on the expected monetary value was determined. The remediation for this purpose was assumed to be executed at the 10th and/or the 15th year. The following sections introduce these results.

Influence of sinking fund deposit period on the expected monetary value

The influence of sinking fund deposit period on the expected monetary value was determined by considering two decisions at two years: the 10^{th} and the 15^{th} year. These years were selected arbitrarily, but are illustrative of the flexibility of the process. Two different regulatory levels and three different waste minimization programs were considered to check for the consistency of the optimum path for different cases. These were 5μg/l and 3μg/l MCL's of benzene and a 0, 10, and 20% waste minimization programs. The values of remaining constants were assumed to be: 0% technology improvement rate, 90% risk aversion, and 10% failure cost. Tables 4, 5, 6, and 7 give the expected monetary values and decision paths for these situations.

Expected monetary values along different paths for Remediation at the 10th year for 5 μg/l MCL of Benzene

Table 4 shows the different sinking fund scenarios that could be chosen leading to remediation and the corresponding expected monetary values for the three different waste minimization programs. Figures 10, 11 and 12 are the corresponding decision trees showing the points of decision for 0%, 10%, and 20% waste minimization programs, respectively. The trees are in the collapsed form showing the paths leading only to remediation at the 10th year. The points, 1 through 8, marked in the decision trees indicates the points of remediation, for the different cases of sinking fund deposit, that corresponds to the points 1 to 8 shown in Table 4.

PATH	POSITION IN THE DECISION TREE	EXPECTED MONETARY VALUES (in $)		
		0% WM	10% WM	20% WM
No SF throughout the decision process	1	14,570,260	10,061,620	8,673,880
SF at the10th year	2	14,502,705	9,994,065	8,606,325
SF from the 5th to the 10th year	3	14,204,354	9,695,714	8,307,974
SF from the 5th to the 10th year + SF at the 10th year before remediation	4	14,136,797	9,628,157	8,240,417
SF for the 1st 5 years	5	14,125,080	9,616,440	8,228,700
SF for the 1st 5 years and SF at the 10th year before remediation	6	14,057,523	9,548,883	8,161,143
SF for 10 years	7	13,759,172	9,250,532	7,862,792
SF for the 1st 10 years + SF at the 10th year before remediation	8	13,691,615	9,182,975	7,795,235

TABLE 4. Alternate paths of sinking fund in the decision tree, following the Technology Improvement node, for remediation at 10 years for MCL of benzene as 5μg/l.

* SF - Sinking Fund
- WM - Waste Minimization

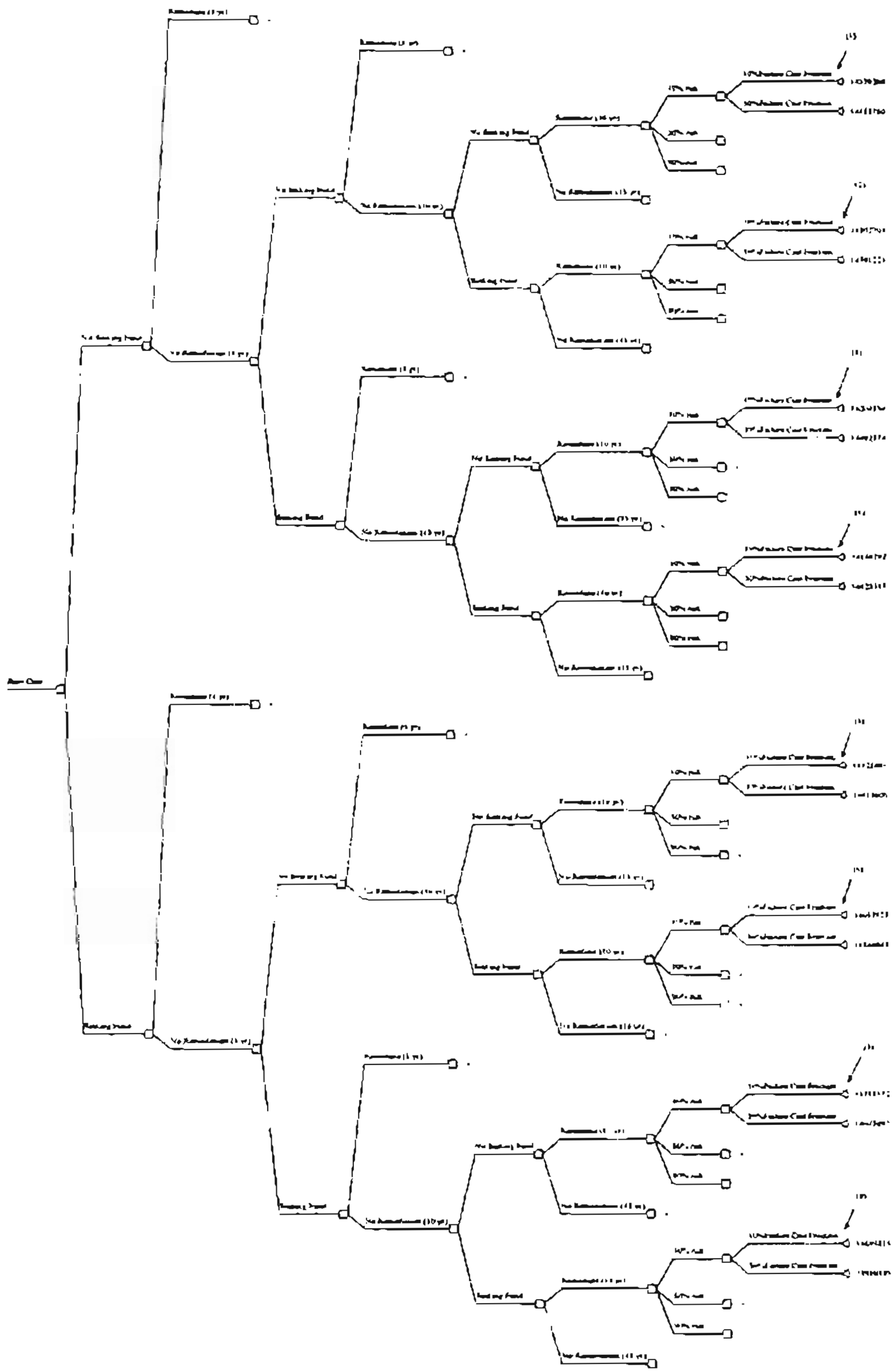


Figure 10. Collapsed decision tree showing different sinking fund alternatives for remediation at the 10th year for a 5ppb MCL of benzene and 0% waste minimization

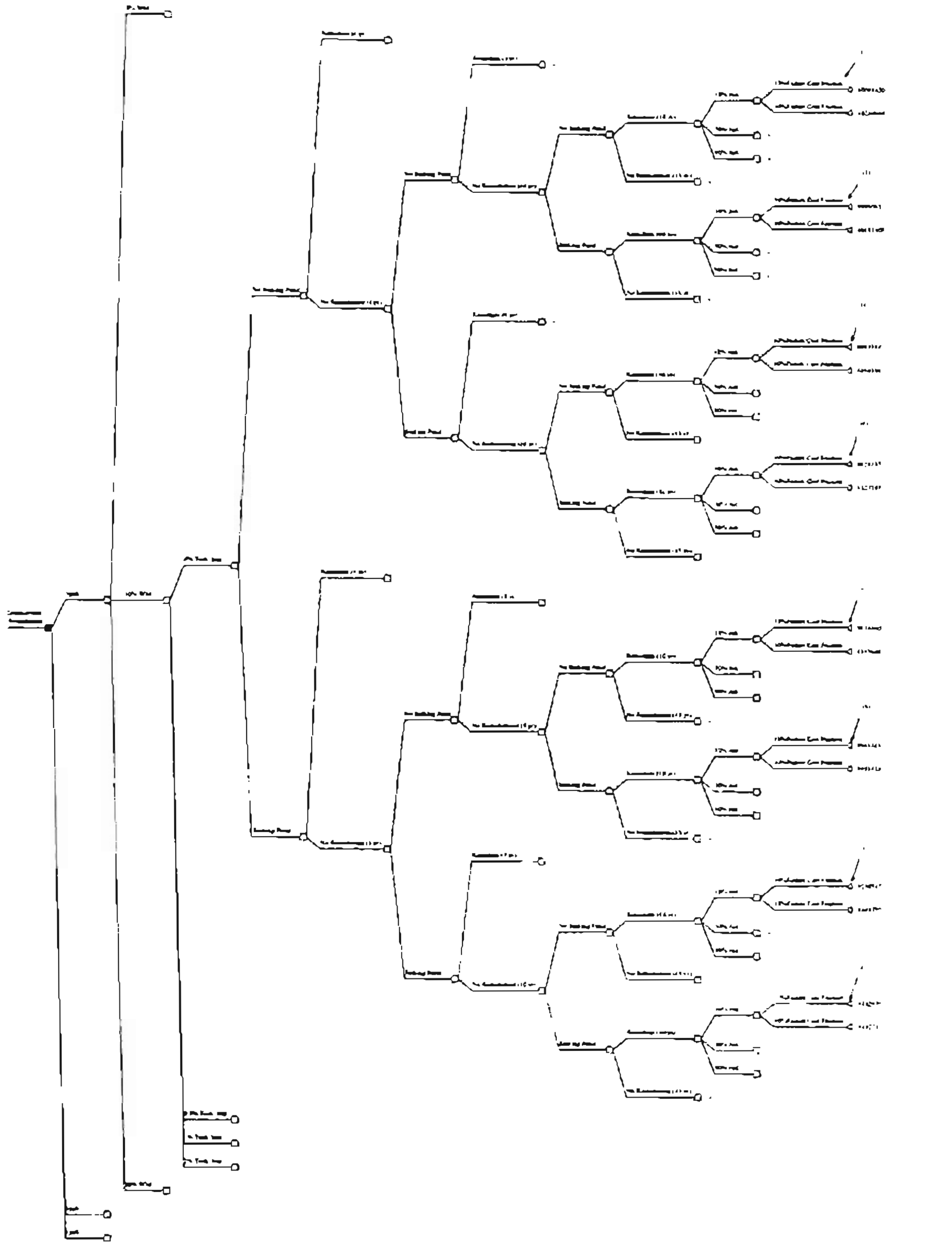


Figure 11. Collapsed decision tree showing different sinking fund alternatives for remediation at the 10^{th} year for a 5ppb MCL of benzene and 10% waste minimization

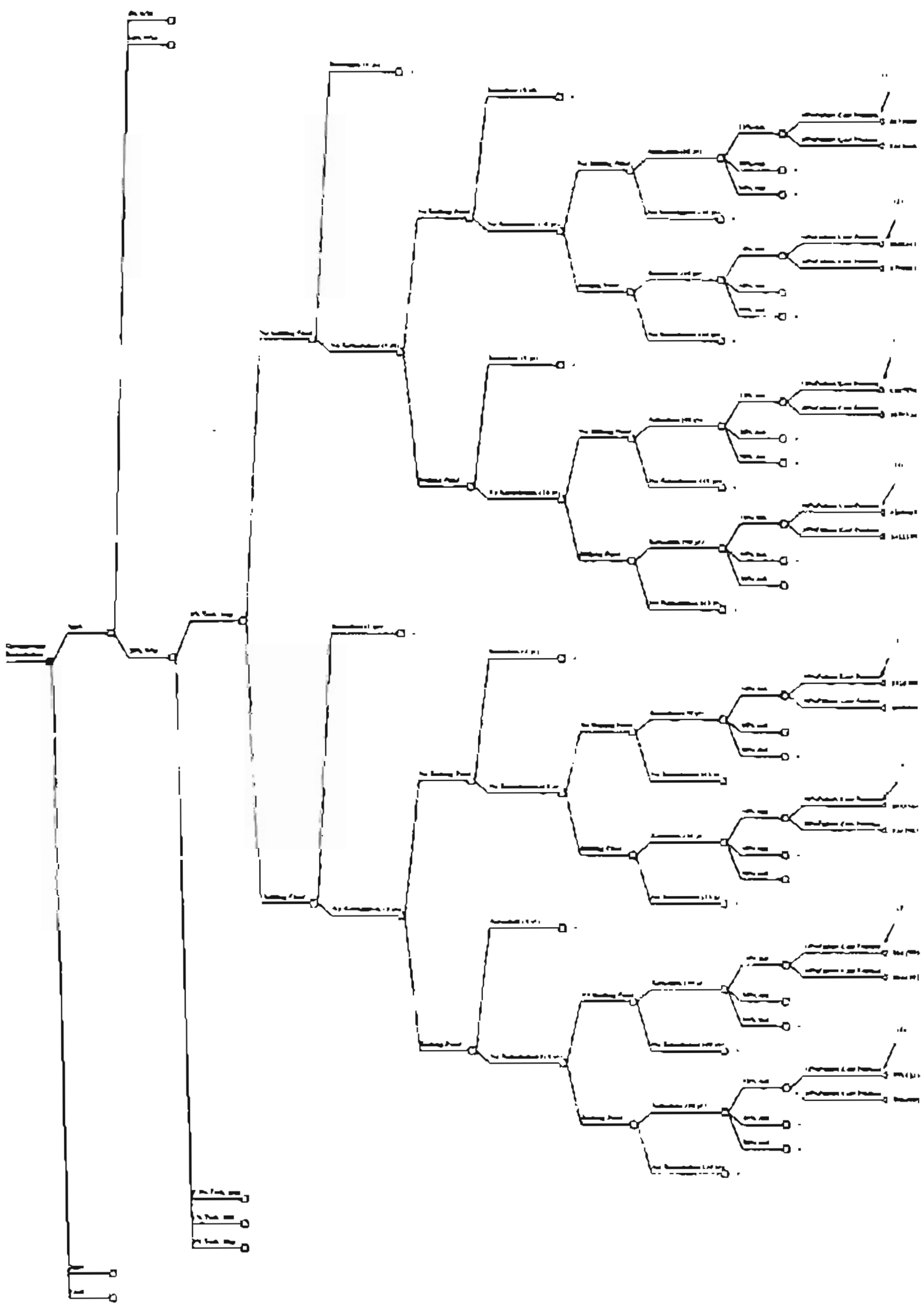


Figure 12. Collapsed decision tree showing different sinking fund alternatives for remediation at the 10th year for a 5ppb MCL of benzene and 20% waste minimization

In Table 4, for a change in the path from "No Sinking Fund" deposit throughout the decision process [point 1] to "Sinking Fund" deposit until remediation [point 8], the expected monetary value decreased by $878,645 for each of the two minimization programs. Similarly, the decrease in expected monetary value between the "No Sinking Fund" path for 0% WM (basecase) and the "Sinking Fund" path for 20% WM was about $6,775,025 or about 46.5% of the expected monetary value of the base case ($14,570,260). In certain situations, in the decision tree, deposits would be considered for the same number of years but the expected monetary values would be different. For instance, for the two cases where the sinking fund deposit was continued for 5 years [points 3 and 6 of Table 4], the only difference was in the year at which the fund was initiated. In one case, [point 3], the deposit was initiated at the 5th year and continued until the 10th year, while in the second case, [point 6], the deposit was initiated in the 1st year for a period of 5 years. The difference in the expected monetary value between these two cases was about $79,274, which represents the different interest accrued until remediation for the deposit already made in the second case.

Expected monetary values along different paths for Remediation at the 10th year for 3μg/l MCL of Benzene

Table 5 is similar to Table 4 and presents similar information when the regulatory level was reduced to 3μg/l of benzene. The table gives the different sinking fund paths that could be chosen leading to remediation at the 10th year and the corresponding expected monetary values for the three waste minimization programs. Figures 13, 14 and 15 are the corresponding decision trees showing the points of decision for 0%, 10%, and 20% waste minimization programs, respectively. The trees are in the collapsed form showing the paths leading to remediation at the 10th year. The points, 1 through 8, marked in the decision trees indicates the points of remediation, for the different paths of sinking fund deposit, that corresponds to the points 1 to 8 shown in Table 5.

OPTIMAL PATH	POSITION IN THE DECISION TREE	EXPECTED MONETARY VALUES ($)		
		0% WM	10% WM	20% WM
No SF throughout the decision process	1	16,691,260	11,677,620	10,087,880
SF at the10th year	2	16,623,705	11,610,065	10,020,325
SF from the 5th to the 10th year	3	16,325,354	11,311,714	9,721,974
SF from the 5th to the 10th year + SF at the 10th year before remediation	4	16,257,797	11,244,157	9,654,417
SF for the 1st 5 years	5	16,246,080	11,232,440	9,642,700
SF for the 1st 5 years and SF at the 10th year before remediation	6	16,178,523	11,164,883	9,575,143
SF for the 10 years	7	15,880,172	10,866,532	9,276,792
SF for 10 years + SF at the 10th year before remediation	8	15,812,615	10,798,975	9,209,235

TABLE 5. Alternate paths of sinking fund in the decision tree, following Technology Improvement Rate node, for remediation at 10 years for MCL of benzene as 3μg/l.
* SF – Sinking Fund
* WM - Waste Minimization

In the table, for a change in the path from "No Sinking Fund" deposit until remediation [point 1] to "Sinking Fund" deposit until remediation [point 8], the expected monetary value decreased by $878,645 for each of the two minimization programs. This amount is the interest accrued on the sinking fund deposit for a period of 10 years. The difference in expected monetary value between the "No Sinking Fund" [point 1] path for 0% WM and "Sinking Fund" [point 8] path for 20% WM was about $7,482,025 or 45% of the expected monetary value of basecase. As in the previous case, in certain situations

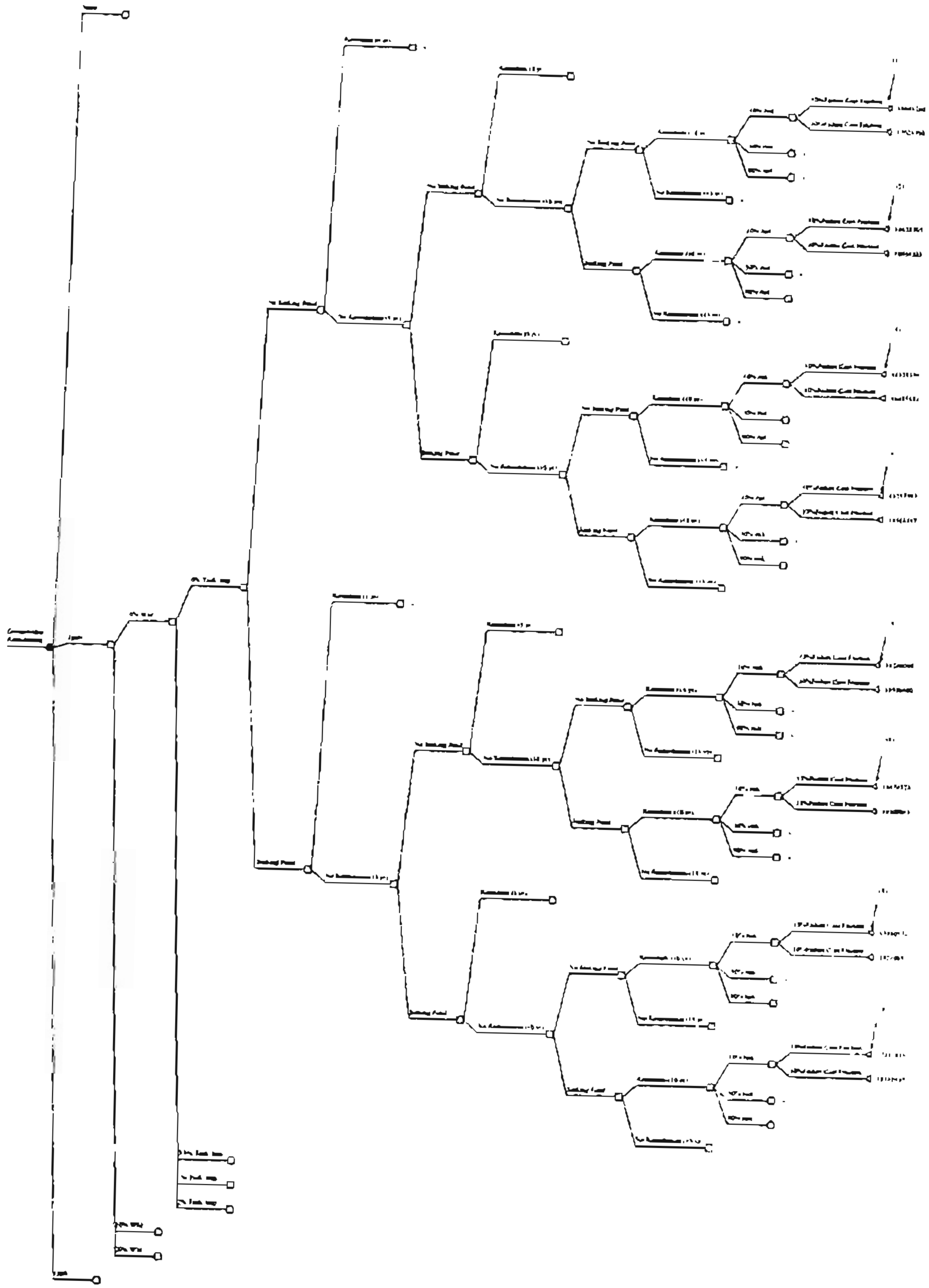


Figure 13. Collapsed decision tree showing different sinking fund alternatives for remediation at the 10^{th} year for a 3ppb MCL of benzene and 0% waste minimization

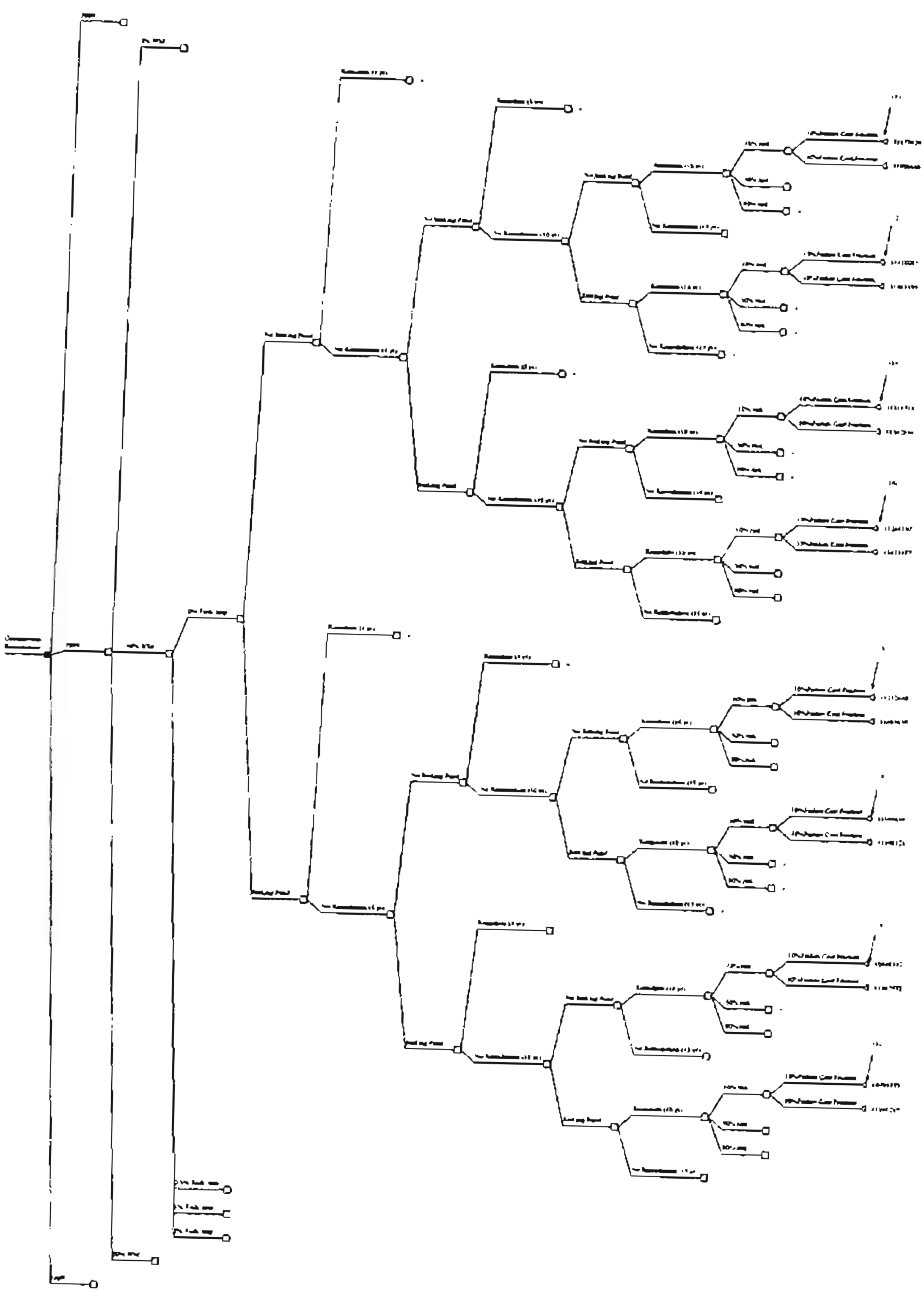


Figure 14. Collapsed decision tree showing different sinking fund alternatives for remediation at the 10th year for a 3ppb MCL of benzene and 10% waste minimization

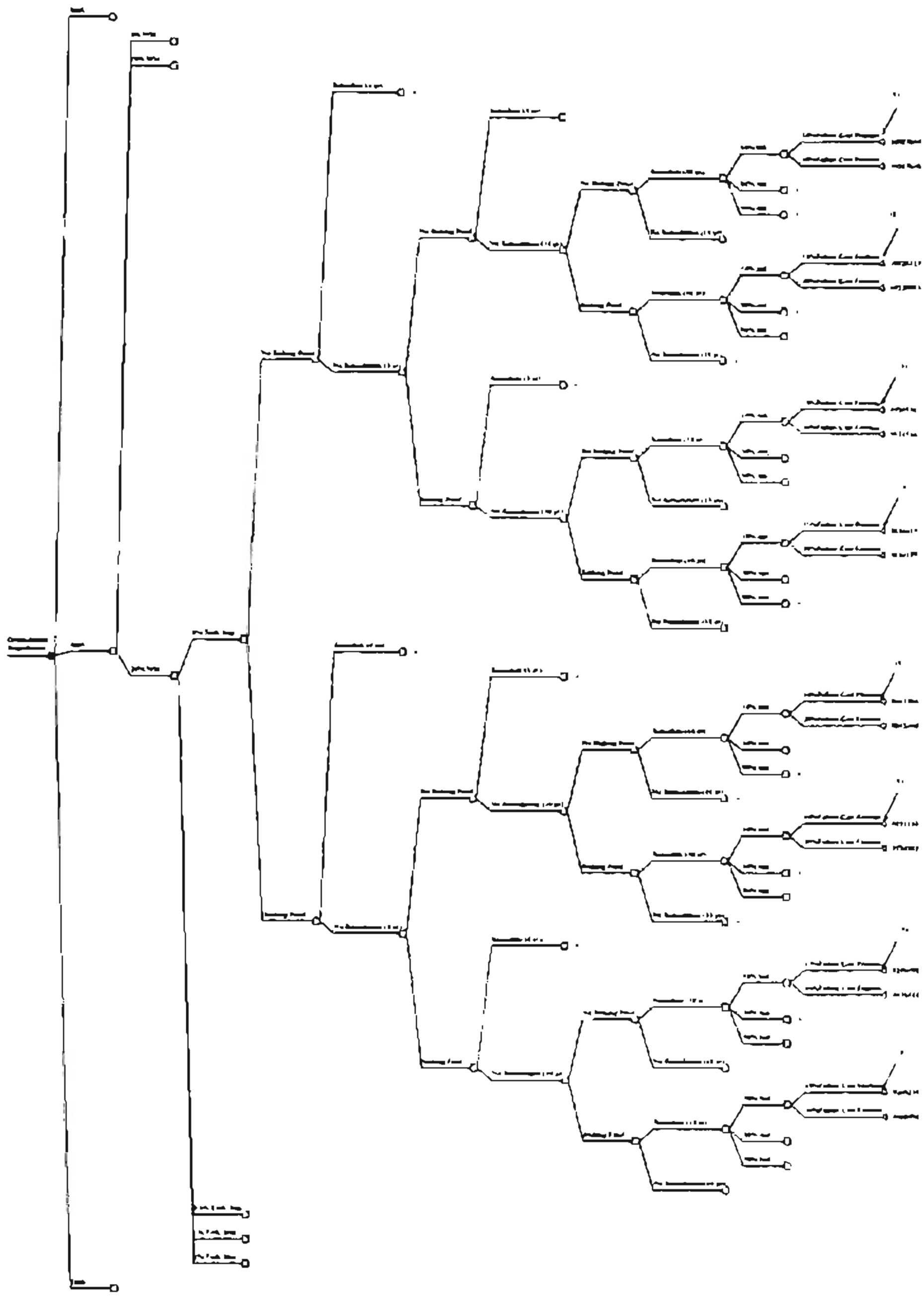


Figure 15. Collapsed decision tree showing different sinking fund alternatives for remediation at the 10th year for a 3ppb MCL of benzene and 20% waste minimization

in the decision tree sinking fund deposits would be considered for the same number of years, but the expected monetary values would be different.

For a change in the regulatory level of benzene from 5μg/l to 3μg/l and for 0% WM, the expected monetary value increased by $2,121,000, from $13,691,615 for 5μg/l of benzene [Table 4] to $15,812,615 3μg/l of benzene [Table 5]. Sinking fund was considered throughout the decision process until remediation in both conditions. In case a sinking fund deposit was not considered for a regulatory level of benzene as 5μg/l but was considered for 3μg/l then the increase in the expected monetary value was about $1,242,355, from $14,570,260 [Table 4] to $15,812,615 [Table 5] or $878,645 less than when sinking fund deposits were utilized for both regulatory levels.

Expected monetary values along different paths for Remediation at the 15th year for 5μg/l MCL of Benzene

The different paths of sinking fund scenarios that could be chosen leading to remediation in the 15th year was evaluated and when the regulatory level of benzene was 5μg/l, are given in Table 6. The table also gives the expected monetary values associated with the three waste minimization programs. Figures 16, 17 and 18 are the corresponding decision trees showing the points of decision for the 0%, 10%, and 20% waste minimization programs, respectively. As before, the trees are in the collapsed form showing the paths leading only to remediation at the 15th year. The points, 1 through 16, marked in the trees indicates the points of remediation, for the different paths of sinking fund, that corresponds to the points 1 to 16, shown in Table 6.

PATH	POINT IN THE TREE	EXPECTED MONETARY VALUES ($)		
		0% WM	10% WM	20% WM
No SF throughout the decision process	1	14,570,260	11,402,900	10,061,620
SF at the 15th year	2	14,514,735	11,347,375	10,006,095
SF from the 10th to the 15th year	3	14,269,512	11,102,152	9,760,872
SF from the 10th to the 15th year + SF at the 15th year before remediation	4	14,213,985	11,046,625	9,705,345
SF from the 5th to the 10th year	5	14,204,354	11,036,994	9,695,714
SF from the 5th to the 10th year + SF at the 15th year before remediation	6	14,148,828	10,981,468	9,640,188
SF from the 5th to the 15th year	7	13,903,604	10,736,244	9,394,964
SF from the 5th to the 15th year + SF at the 15th year before remediation	8	13,848,078	10,680,718	9,339.438
SF for the 1st 5 years	9	14,125,080	10,957,720	9,616,440
SF for the 1st 5 years + SF at the 15th year before remediation	10	14,069,553	10,902,193	9,560,913
SF for the 1st 5 years + SF from the 10th to the 15th year	11	13,824,328	10,656,969	9,315,689
SF for the 1st 5 years + SF from the 10th to the 15th year + SF at the 15th year before remediation	12	13,768,805	10,601,445	9,260,165
SF from the 1st to the 10th year	13	13,759,172	10,591,812	9,250,532
SF from the 1st to the 10th year + SF before at the 15th year before remediation	14	13,703,645	10,536,285	9,195,005
SF from the 1st to the 15th year	15	13,458,423	10,291,063	8,949,783
SF from the 1st to the 15th year + SF before remediation	16	13,402,897	10,235,537	8,894,257

TABLE 6. Alternate paths of sinking fund deposit in the decision tree, following the Technology Improvement Rate node, for remediation at 15 years for MCL of benzene as 5μg/l.

* SF – Sinking Fund
* WM - Waste Minimization

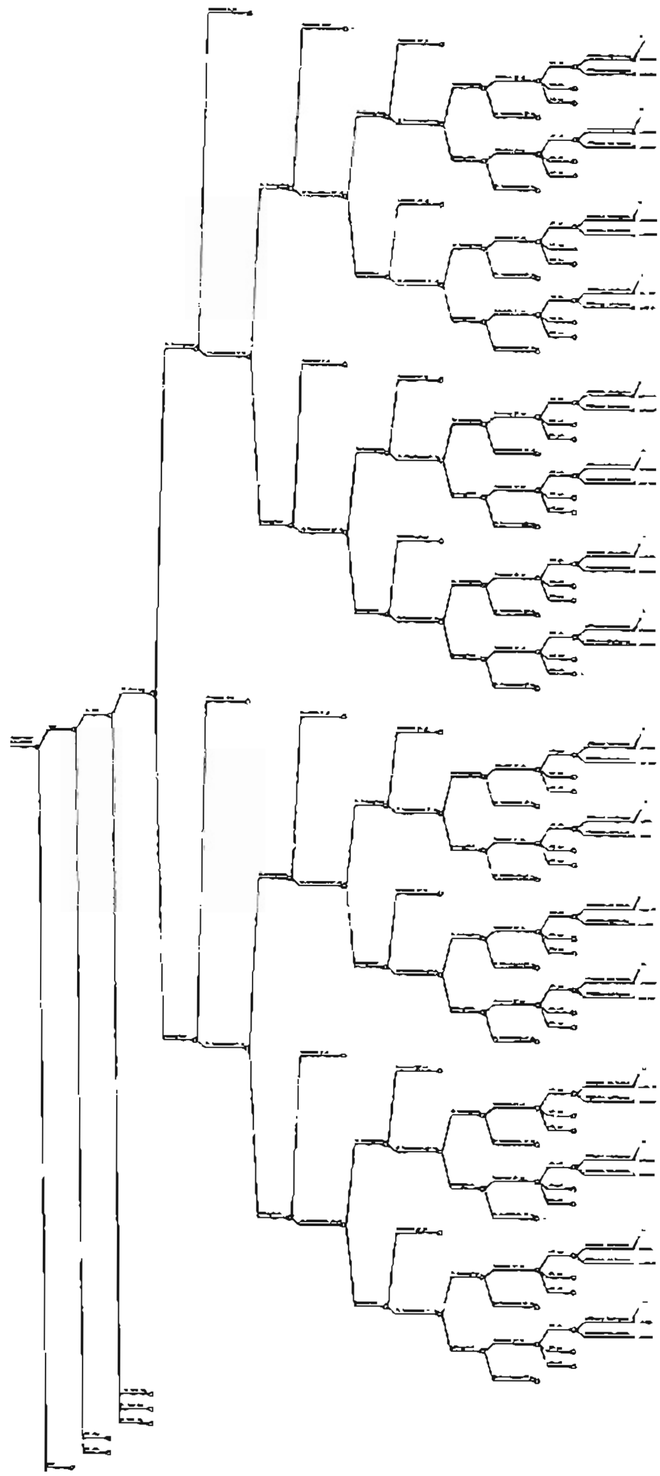


Figure 16. Collapsed decision tree showing different sinking fund alternatives for remediation at the 15th year for a 5ppb MCL of benzene and 0% waste minimization

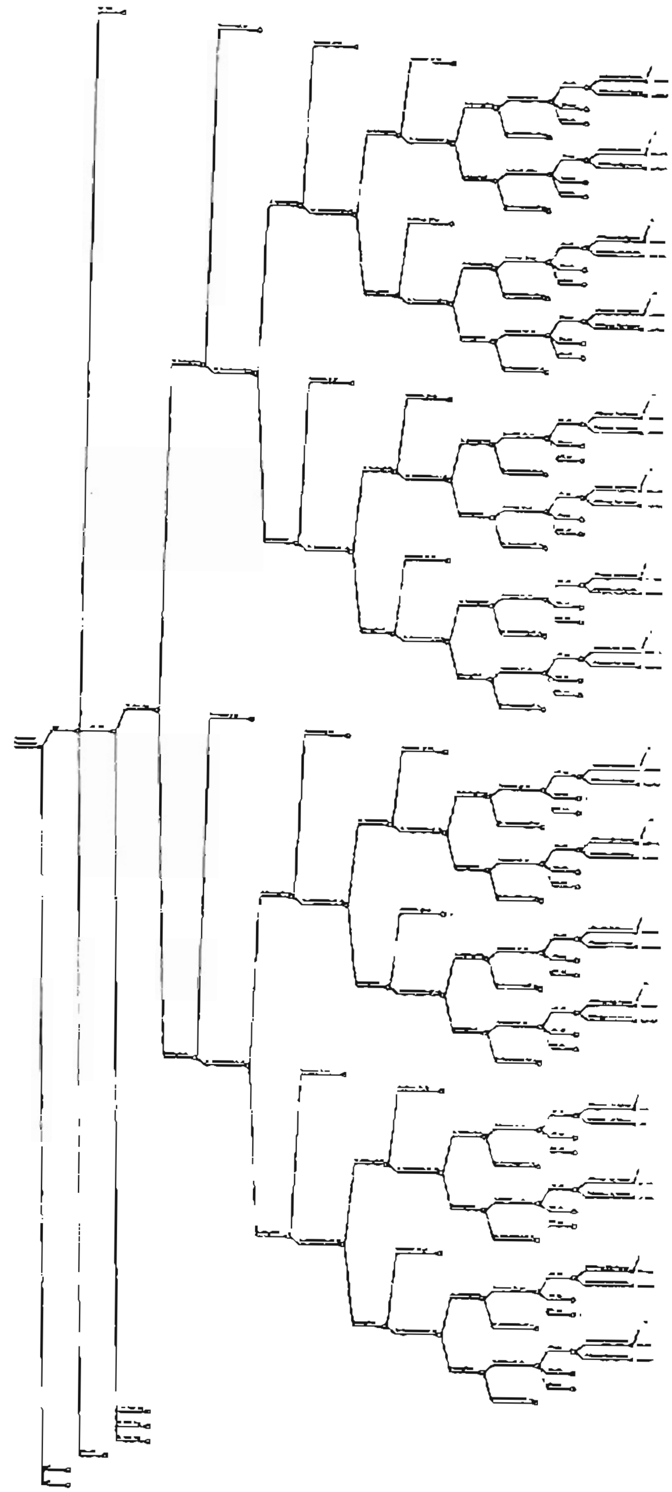


Figure 17. Collapsed decision tree showing different sinking fund alternatives for remediation at the 15th year for a 5ppb MCL of benzene and 10% waste minimization

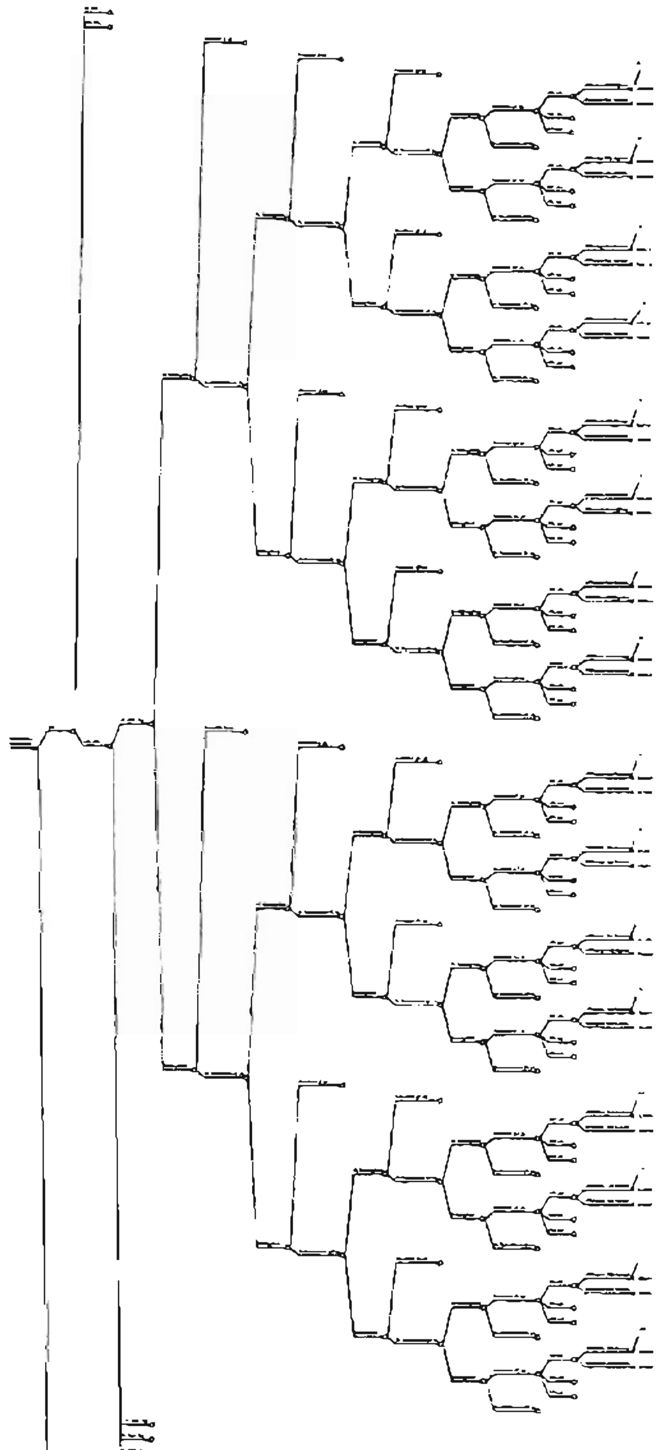


Figure 18. Collapsed decision tree showing different sinking fund alternatives for remediation at the 15th year for a 5ppb MCL of benzene and 20% waste minimization

For a change in the path from "No Sinking Fund" deposit until remediation [point 1] to "Sinking Fund" deposit throughout [point 16], the expected monetary value decreased by $1,167,363 for each of the three cases of minimization programs. This is more than that for the corresponding case of remediation at the 10th year and results from the increase in the number of sinking fund deposit years from 10 to 15 years. The difference in expected monetary value between the "No Sinking Fund" path for 0% WM and "Sinking Fund" path for 20% WM was about $5,676,003 or 39% of the expected monetary value of base case. As with the previous two cases, where remediation was initiated at the 10th year, there were situations in the decision tree that considered sinking fund deposits for the same number of years but resulted with different expected monetary values.

Expected monetary values along different paths for Remediation at the 15th year for 3μg/l MCL of Benzene

The different paths of sinking fund scenarios that could be chosen leading to remediation at the 15th year when the regulatory level of benzene was 3μg/l, are given in Table 7. The table also gives the expected monetary values for the three waste minimization programs for the corresponding sinking fund paths. Figures 19, 20 and 21 are the corresponding decision trees showing the points of decision for 0%, 10%, and 20% waste minimization programs, respectively. The trees are in the collapsed form showing the paths leading only to remediation at the 15th year. The points, 1 through 16, marked in the trees indicate the points of remediation, for the different paths of sinking fund, that correspond to the points 1 to 16 shown in Table 7.

PATH	POINT IN THE TREE	EXPECTED MONETARY VALUES ($)		
		BASE CASE	10% WM	20% WM
No SF throughout the decision process	1	16,691,260	11,852,375	10,410,095
SF at the 15th year	2	16,635,735	11,607,152	10,465,620
SF from the 10th to the 15th year	3	16,390,512	11,551,625	10,164,872
SF from the 10th to the 15th year + SF at the 15th year before remediation	4	16,334,985	11,541,994	10,109,345
SF from the 5th to the 10th year	5	16,325,354	11,486,468	10,099,714
SF from the 5th to the 10th year + SF at the 15th year before remediation	6	16,269,828	11,241,244	10,044,188
SF from the 5th to the 15th year	7	16,024,604	11,185,718	9,798,964
SF from the 5th to the 15th year + SF at the 15th year before remediation	8	15,969,078	11,120,324	9,743,438
SF for the 1st 5 years	9	16,246,080	11,462,720	10,020,440
SF for the 1st 5 years + SF at the 15th year before remediation	10	16,190,553	11,407,193	9,964,913
SF for the 1st 5 years + SF from the 10th to the 15th year	11	15,945,329	11,106,445	9,664,165
SF for the 1st 5 years + SF from the 10th to the 15th year + SF at the 15th year before remediation	12	15,889,805	11,050,917	9,608,637
SF from the 1st to the 10th year	13	15,880,172	11,041,285	9,599,005
SF from the 1st to the 10th year + SF before at the 15th year before remediation	14	15,824,665	10,985,759	9,543,479
SF from the 1st to the 15th year	15	15,579,423	10,740,337	9,298,257
SF from the 1st to the 15th year + SF before remediation	16	15,523,897	10,685,010	9,242,730

TABLE 7. Alternate paths of sinking fund deposit in the decision tree, following the Technology Improvement Rate node, for remediation at 15 years for MCL of benzene as 3μg/l.

* SF – Sinking Fund
* WM - Waste Minimization

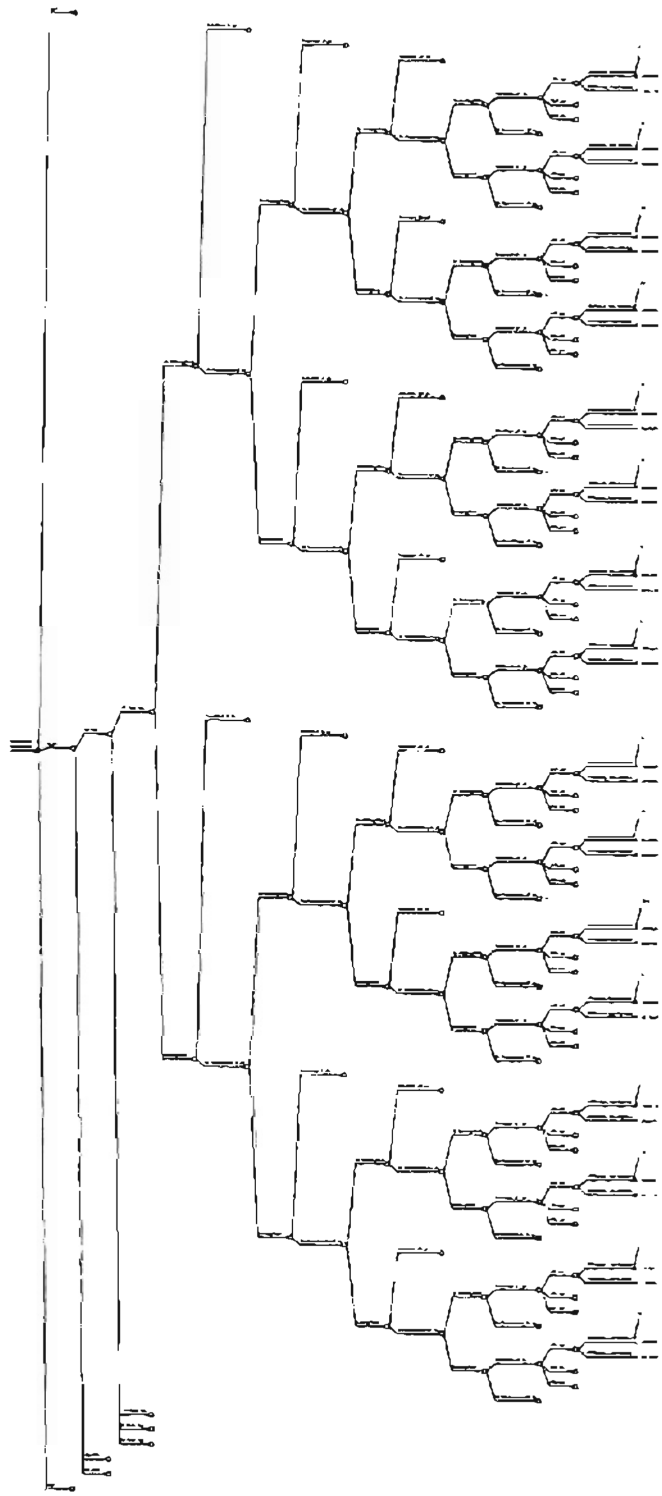


Figure 19. Collapsed decision tree showing different sinking fund alternatives for remediation at the 15th year for a 3ppb MCL of benzene and 0% waste minimization

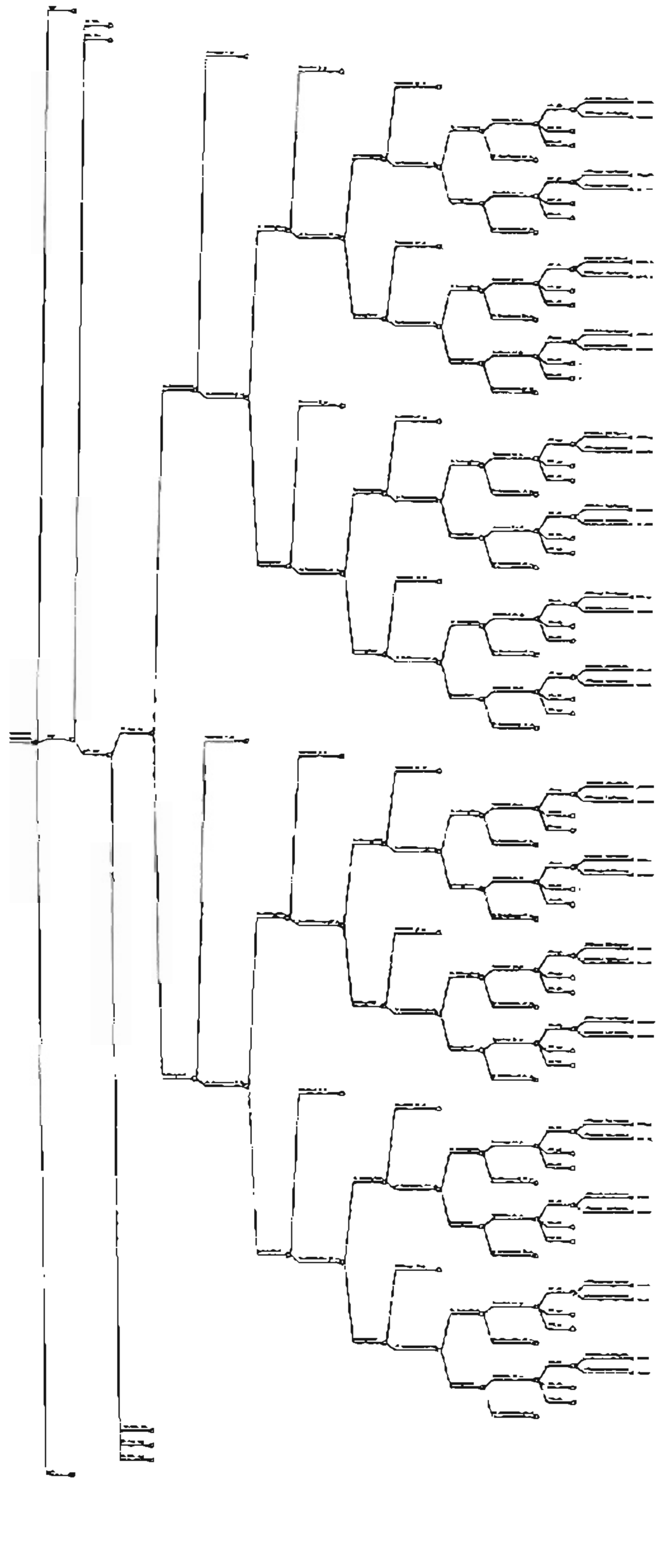


Figure 21. Collapsed decision tree showing different sinking fund alternatives for remediation at the 15th year for a 3ppb MCL of benzene and 20% waste minimization

For a change in the path from "No Sinking Fund" deposit until remediation [point 1] to "Sinking Fund" deposit throughout [point 16], the expected monetary value decreased by $1,167,363 for each of the two minimization programs. The difference in expected monetary value between the "No Sinking Fund" path for 0% WM (basecase) and "Sinking Fund" path for 20% WM was about $7,448,530 or 44.6% of the expected monetary value of base case. As with the previous cases, alternative paths in the decision tree considered sinking fund deposits for the same number of years but resulted with different expected monetary values. In the above tables, for paths where "no sinking fund" deposits followed an earlier "sinking fund" designation, interest was accrued on the amount already deposited.

The objective, as mentioned earlier, was to evaluate different realistic scenarios, which could confront the environmental decision maker. The following section deals with defining the optimal paths for these various scenarios achieved by changing the values of the critical variables. The results are divided into two sections. Section I deals with determining the effects of changing the technical variables, such as the regulatory levels of benzene, waste minimization programs, technology improvement rate and failure cost, used in the methodology. A total of thirteen cases are presented. Section II deals with the determination of the effect of varying the sinking fund on the expected monetary value over a time period.

SECTION I: Impact of Changing the Values of Technical Variables on the Resultant Decision

The effect due to the change in the technical variables like regulatory levels, technology improvement rate, waste minimization programs and failure cost were determined by changing the variables, first one at a time, then two and three simultaneously. In order to be consistent it was assumed that the remediation was initiated on sinking fund paths, at 15 years, with alterations in the technical variables occurring in the 5th year of the decision process. The tables for each case show the expected monetary values for the basecase, i.e. for the initial set of values for the critical variables in the decision tree, and for the changed scenario which resulted due to the change in the variables. The expected monetary values after the change in the variables are the amounts needed for remediation in the changed scenario if the same sinking fund path as that of the basecase was followed. In each case, the expected monetary values for the basecase and changed scenario were determined for the three different risk fractions, namely 10%, 50% and 90% to reduce the uncertainty in selection of a particular risk fraction. Each table is followed by a plot of the expected monetary values for the basecase and the changed condition. The expected monetary values in the plots are grouped together for each risk fraction. A decision tree showing the points where the expected monetary values are calculated in the basecase as well as in the changed scenario is shown for each case. Point 1 in the decision tree corresponds to the basecase scenario where the expected monetary value is calculated before any change in the critical variables. Point 2 in the decision tree corresponds to the changed scenario where the expected monetary value is calculated after a change in the critical variables. The decision trees are in the collapsed form showing only the path of the alternatives under consideration.

Effect of varying one variable

The following cases were considered by assuming that only one technical parameter was varied during the entire decision process.

determined by changing the variables, first one at a time, then two and three simultaneously. In order to be consistent it was assumed that the remediation was initiated on sinking fund paths, at 15 years, with alterations in the technical variables occurring in the 5^{th} year of the decision process. The tables for each case show the expected monetary values for the basecase, i.e. for the initial set of values for the critical variables in the decision tree, and for the changed scenario which resulted due to the change in the variables. The expected monetary values after the change in the variables are the amounts needed for remediation in the changed scenario if the same sinking fund path as that of the basecase was followed. In each case, the expected monetary values for the basecase and changed scenario were determined for the three different risk fractions, namely 10%, 50% and 90% to reduce the uncertainty in selection of a particular risk fraction. Each table is followed by a plot of the expected monetary values for the basecase and the changed condition. The expected monetary values in the plots are grouped together for each risk fraction. A decision tree showing the points where the expected monetary values are calculated in the basecase as well as in the changed scenario is shown for each case. Point 1 in the decision tree corresponds to the basecase scenario where the expected monetary value is calculated before any change in the critical variables. Point 2 in the decision tree corresponds to the changed scenario where the expected monetary value is calculated after a change in the critical variables. The decision trees are in the collapsed form showing only the path of the alternatives under consideration.

Effect of varying one variable

The following cases were considered by assuming that only one technical parameter was varied during the entire decision process.

CASE 1: Effect of varying Regulatory Levels over variation in Risk Aversion Level

The effect due to a change in the regulatory levels on the decision was determined after fixing the rate in the improvement of the technology, the waste minimization programs, and the failure cost fraction at constant values: 0% technology improvement rate, 0% waste minimization program, and 10% failure cost fraction. Table 8 gives the expected monetary values for the different risk fractions due to changes in the regulatory levels from 5μg/l to 3μg/l. Figure 22 is the corresponding plot for the expected monetary values and shows the variation of expected monetary values due to changes in the regulatory levels of benzene from 5μg/l to 3μg/l for different risk fractions. The decision tree showing the corresponding paths for different regulatory levels is shown in Figure 23. Points 1 and 2 in the decision tree show the points where the alternatives were evaluated for the different regulatory levels. The expected monetary values for the points 1 and 2 in the decision tree corresponds to the expected monetary values shown in Table 8 for different risk fractions.

Regulatory Levels	**Position in the Decision Tree**	**Expected monetary values (in $)**		
		Risk Fractions 10%	Risk Fractions 50%	Risk Fractions 90%
5ppb	1	13,402,897	13,979,937	14,556,977
3ppb	2	15,523,897	16,184,937	16,845,977

Table 8. Expected monetary values for different regulatory levels and risk fractions

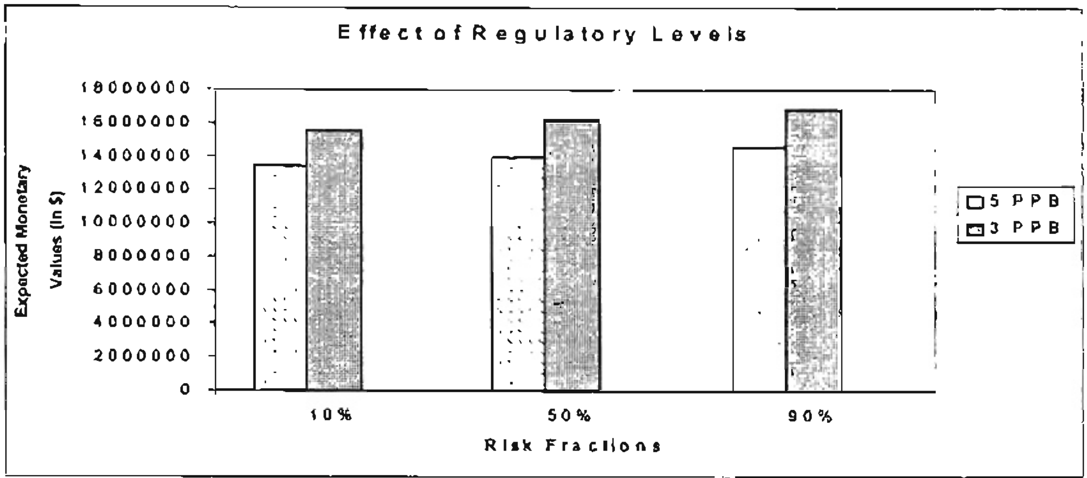


Figure 22. Figure showing the expected monetary values for different regulatory levels and risk fractions

The table and the figure show an increase of about \$2,121,000 in the expected monetary values for a risk aversion level of 10% due to a change in the regulatory levels of benzene from 5 to 3μg/l. For the same change in regulatory level, the risk increased to 90% from 10%, the expected monetary value increased by \$3,443,080 from the basecase amount of \$13,402,897.

<u>CASE 2: Effect of variation of Rate of Technology Improvement over variation in Risk Aversion Level</u>

The effect of changes in the rate of technology improvement on the decision was determined by holding the regulatory level, the waste minimization programs and the failure cost fraction constant at 5ppb MCL of benzene and 0%, and 10%, respectively. Table 9 gives the expected monetary values for the various risk fractions with a change in the technology improvement rate from 0% to 1% while Figure 24 is the corresponding plot. The decision tree showing the corresponding paths is shown in Figure 25. Points 1 and 2 in the decision tree shows the points in the tree where the alternatives were evaluated for the 0% and 1% technology improvement rates, respectively, which correspond to the information presented in Table 9.

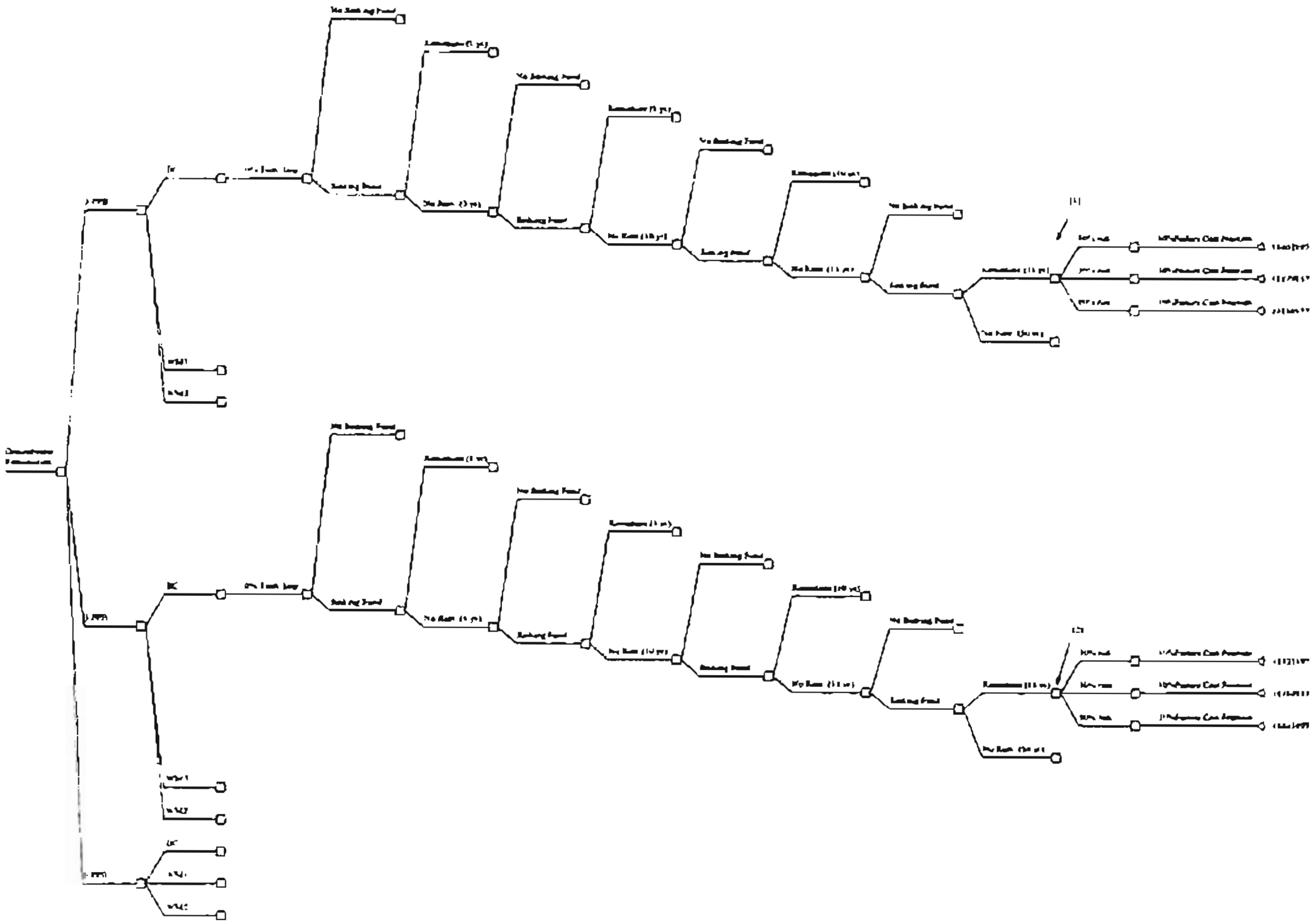


Figure 23. Collapsed decision tree showing the paths and the point where expected monetary values were calculated for a change in regulatory level from 5ppb to 3ppb

Technology Improvement Rate	Position in the Decision Tree	Expected monetary values (in $)		
		Risk Fractions 10%	Risk Fractions 50%	Risk Fractions 90%
0%	1	13,402,897	13,979,937	14,556,977
1%	2	11,372,729	11,869,366	12,366,004

Table 9. Expected monetary values for different rates of technology improvement and different risk fractions

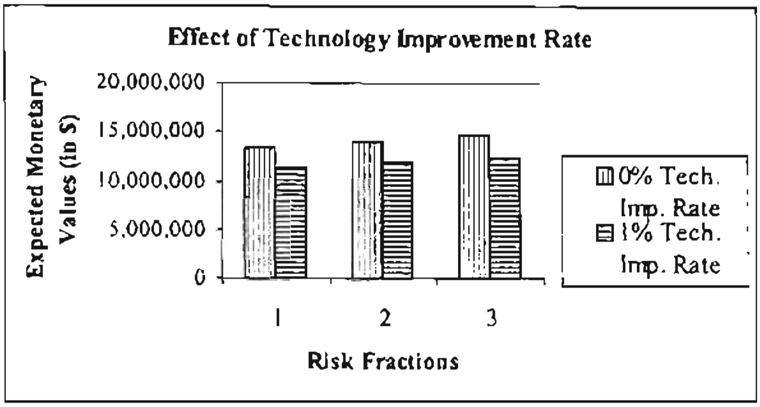


Figure 24. Figure showing the Expected monetary values for different rates of technology improvement and different risk fractions

The table and the figure show a decrease in the expected monetary values due to increase in the rate of technology improvement from 0% to 1%. The decrease in the expected monetary value was due to a decrease in the remediation cost due to technology improvement. For the change in the rate of technology development from 0% to 1%, the corresponding decrease in the expected monetary value was about $2,030,168 for a risk aversion level of 10%. For the same change in the technology improvement rate, an increase in risk aversion level from 10% to 90% resulted in the expected monetary value decreasing by $1,036,893 from the basecase value of $13,402,897.

CASE 3: Effect of Waste Minimization Programs over variation in Risk Aversion Level

The effect of introducing a waste minimization program on the decision was determined by holding the regulatory level of benzene, the increase in technology

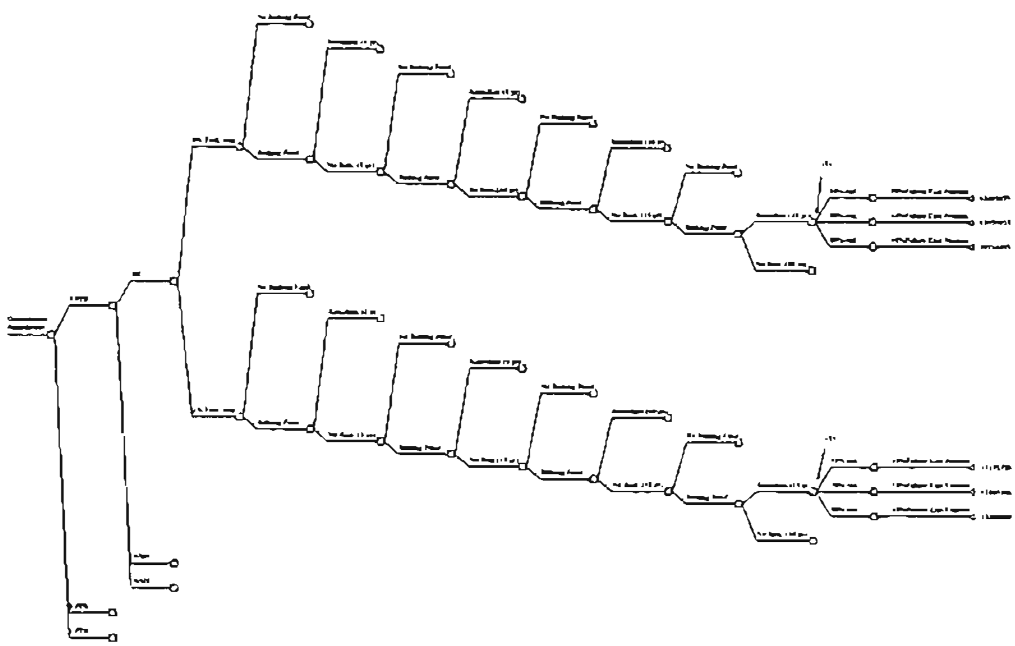


Figure 25. Collapsed decision tree showing the path and the points where expected monetary values were calculated for a change in the technology improvement rate from 0% to 1%.

improvement rate, and the failure cost fraction constant at 5ppb MCL, 0%, and 10%, respectively. Table 10 gives the expected monetary values for the various risk fractions with a change in the waste minimization programs from 0% to 10%. Figure 26 is the corresponding plot for the values and shows the variation of the expected monetary values. The corresponding decision tree is shown in Figure 27 where the expected monetary values for points 1 and 2 in the tree correspond to the expected monetary values shown in Table 10.

Waste Min.	Position in the Decision Tree	Expected monetary values (in $)		
		Risk Fractions 10%	Risk Fractions 50%	Risk Fractions 90%
0%	1	13,402,897	13,979,937	14,556,977
10%	2	10,235,537	10,687,137	11,138,737

Table 10. Expected monetary values for different waste minimization programs and risk fractions

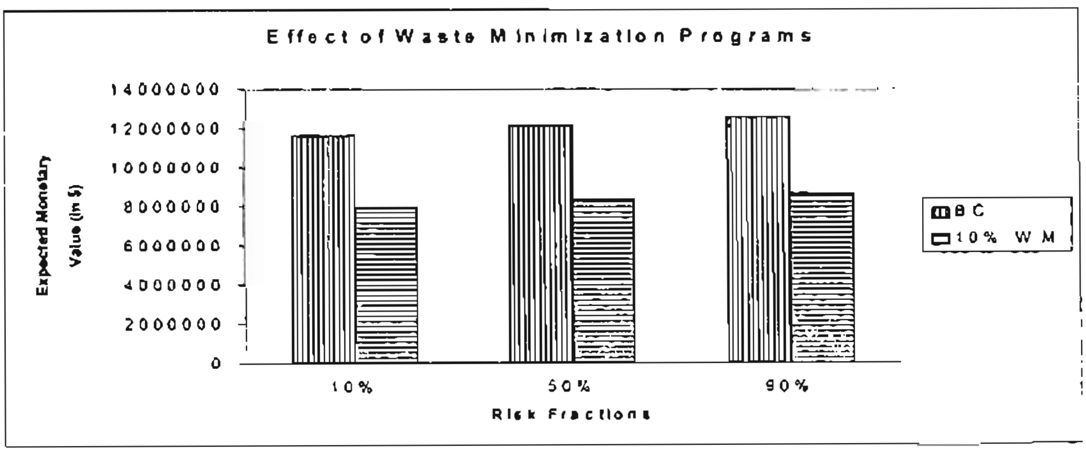


Figure 26. Expected monetary values for different waste minimization programs and risk fractions

The table and the figure show a decrease in the expected monetary value due to change in the waste minimization from 0% to 10%. A 10% waste minimization at 10% risk before and after minimization, reduced the expected monetary value by $3,167,360 from the base case. For a risk fraction of 90%, the alternative reduced the expected monetary value by $2,264,160 from the base case amount of $13,402,897.

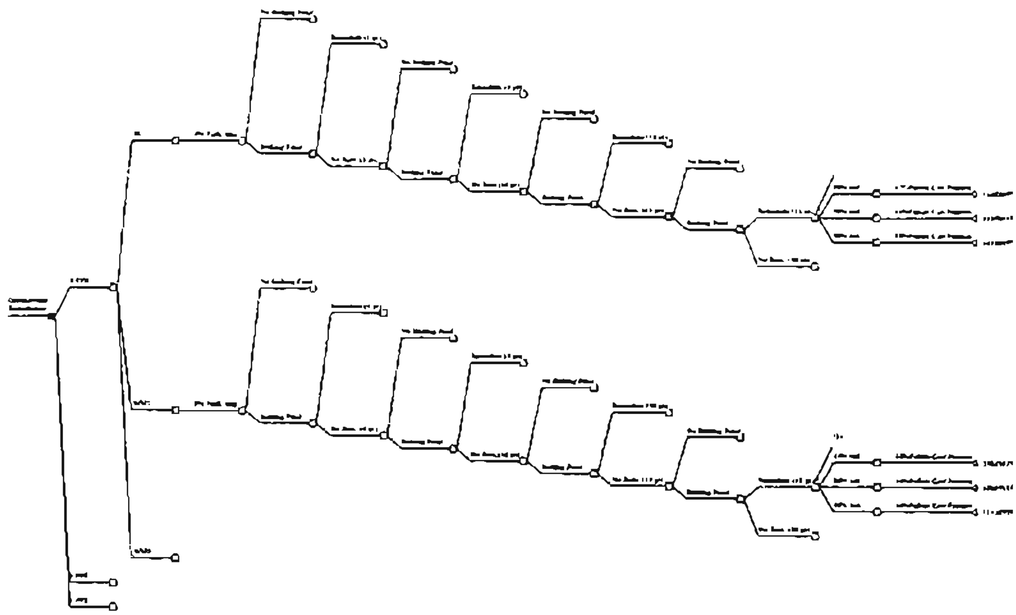


Figure 27. Collapsed decision tree showing the path and the points where expected monetary values were calculated for a change in the waste minimization program from 0% to 10%.

CASE 4: Effect of Failure Cost over variation in Risk Aversion Level

The effect of change in the failure cost on the decision was determined by holding the regulatory level of benzene, the waste minimization programs, and the increase in technology improvement rate constant at 5ppb MCL, 0%, and 0%, respectively. Table 11 gives the expected monetary values for the different risk fractions with a change in the failure cost from 10% to 30% of the total remediation cost. Figures 28 and 29 are the corresponding plot and decision tree for the respective variables. Points 1 and 2 in the decision tree show where the alternatives are evaluated before and after the change in the variables given in Table 11.

Failure Cost Fraction	Position in the Decision Tree	Expected monetary values (in $)		
		Risk Fractions 10%	Risk Fractions 50%	Risk Fractions 90%
10%	1	13,402,897	13,979,937	14,556,977
30%	2	13,691,417	15,422,537	17,153,657

Table 11. Expected monetary values for different failure cost and risk fractions

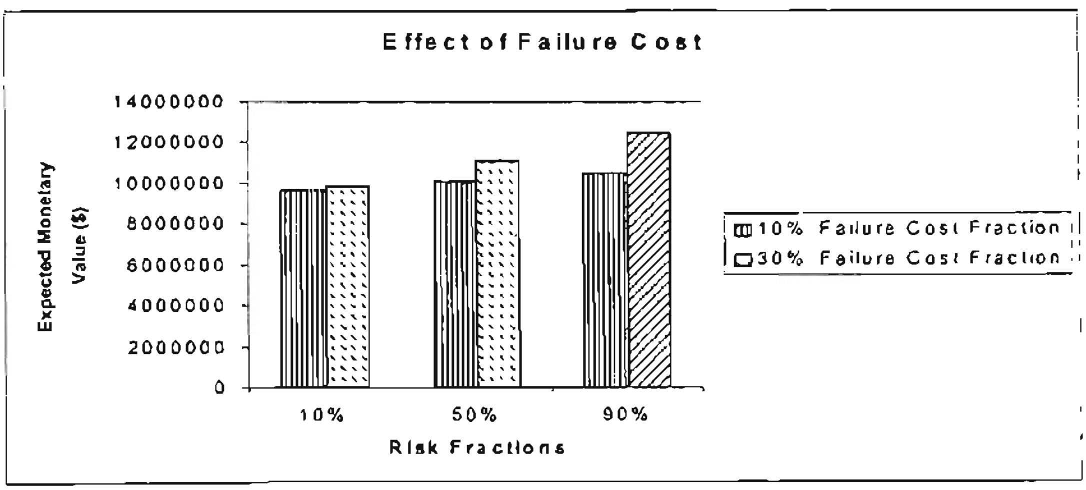


Figure 28. Figure showing the expected monetary values for different failure costs and risk fractions

The table and figure show that with an increase in failure cost, the expected monetary value increases. The expected monetary value for a 10% risk in both the

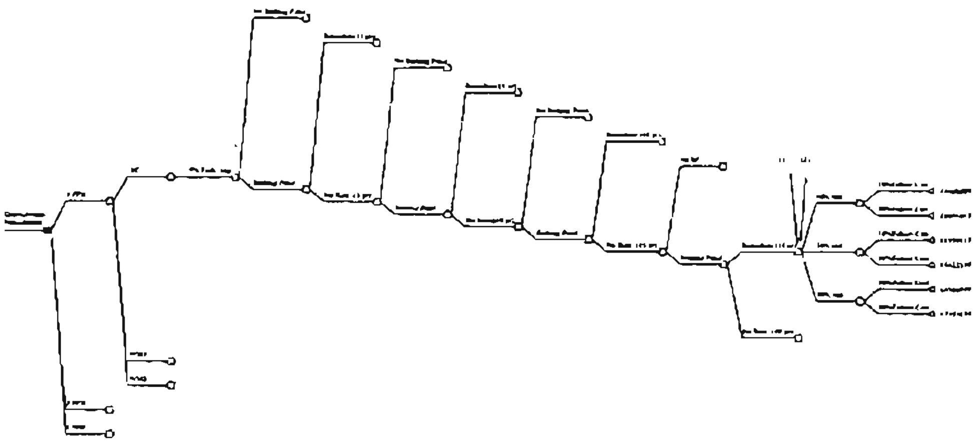


Figure 29. Collapsed decision tree showing the path and the points where expected monetary values were calculated for a change in the failure cost fraction from 10% to 30%.

basecase and the changed condition increased by $288,520 from $13,402,897 to $13,691,417. The increase in the expected monetary value for a 90% risk aversion level was $3,750,760 from $13,402,897 to $17,153,657.

Effect of changing the values of two variables on the decision situation

This section describes the cases where two variables are changed. The changes in the variables was assumed to have occurred simultaneously.

CASE 5: Variation of Regulatory Levels and Technology Improvement Rate over variation in Risk Aversion Level

The effect of varying two variables, regulatory level and technology improvement rate, was completed by holding constant the waste minimization level and the failure cost fraction at 0% and 10%, respectively. Table 12 gives the expected monetary values when the regulatory levels and the technology improvement rate changed from 5μg/l to 3μg/l and 0% to 1%, respectively. Figures 30 and 31 present the corresponding plot and decision tree for the conditions evaluated. Points 1 and 2 in the decision tree show the points where the alternatives were evaluated for the basecase and the changed situation. The expected monetary values at these two points in the tree are given in Table 12.

Reg. Levels	Tech. Imp. Rate	Position in the Decision Tree	Expected monetary values (in $)		
			Risk Fractions 10%	Risk Fractions 50%	Risk Fractions 90%
5ppb	0%	1	13,402,897	13,979,937	14,556,977
3ppb	1%	2	13,198,197	13,767,130	14,336,063

Table 12. Expected monetary values for different regulatory levels, technology improvement rate and risk fractions

Table 12 and Figure 30 show that the change in the regulatory level and technology improvement rate are dependent on the risk fractions evaluated. There was a reduction in the expected monetary value by about $20,700 from the basecase value of $13,402,897, for a 10% risk aversion level. For the same condition, an increase in the risk from 10% to 90% increased the expected monetary value by $933,166 from 13,402,897 to 14,336,063. The combined effect of stringent regulatory level and increase in risk resulted in the increase in the expected monetary value.

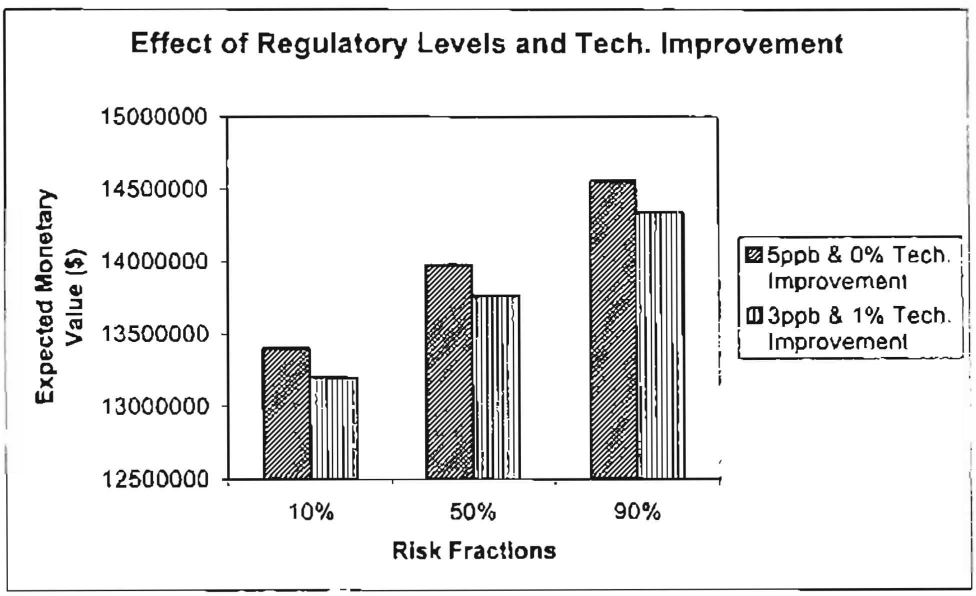


Figure 30. Figure showing the expected monetary values for different regulatory levels, technology improvement rate and risk fractions

<u>*CASE 6: Variation of Regulatory Levels and Waste Minimization Programs over variation in Risk Aversion Level*</u>

The effect of varying two other variables, regulatory level and waste minimization was considered by holding constant the increase in technology improvement rate and the failure cost fraction at 0% and 10%, respectively. Table 13 gives the expected monetary values for the different risk fractions for these conditions while Figures 32 and 33 are the respective plot and decision tree.

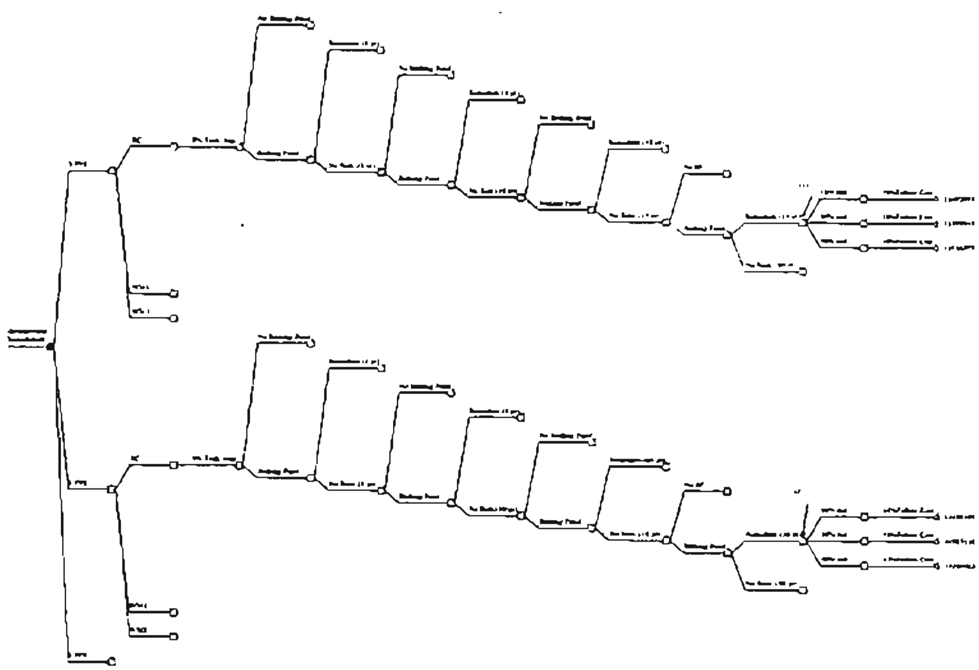


Figure 31. Collapsed decision tree showing the path and the points where expected monetary values were calculated for a change in the regulatory level from 5ppb to 3ppb and technology improvement rate from 0% to 1%.

The expected monetary values at points 1 and 2 in the tree correspond to the expected monetary values shown in Table 13 for the two conditions.

Reg. Levels	Waste Min	Position in the Decision Tree	Expected monetary values (in $)		
			Risk Fractions 10%	Risk Fractions 50%	Risk Fractions 90%
5ppb	0%	1	13,402,897	13,979,937	14,556,977
3ppb	10%	2	10,685,010	11,154,413	11,623,814

Table 13. Expected monetary values for different regulatory levels, waste minimization and risk fractions

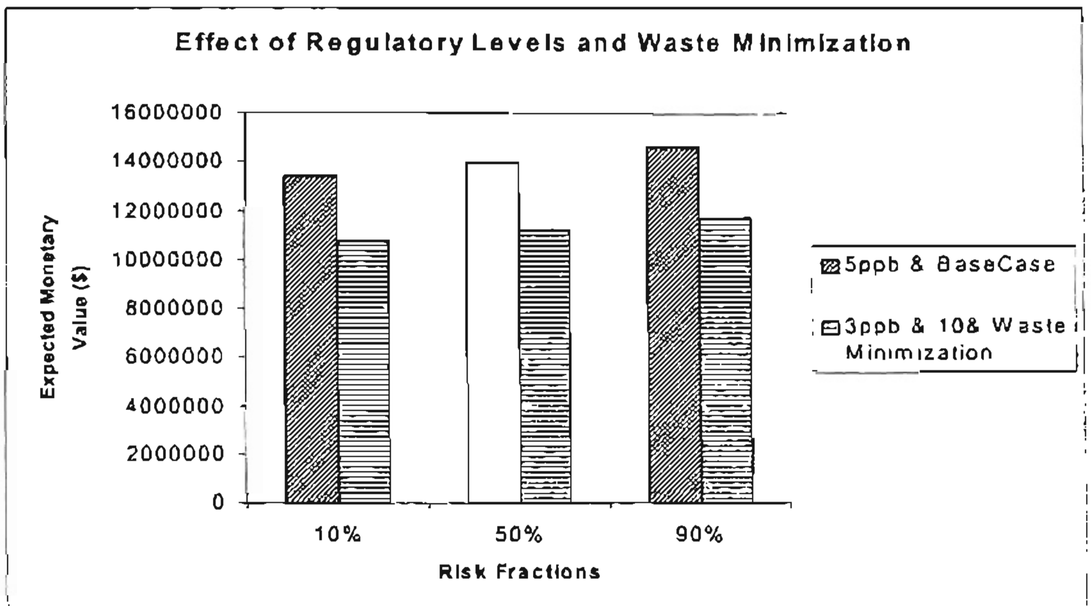


Figure 32. Figure showing the Expected monetary values for different regulatory levels, waste minimization programs and risk fractions

The table and the figure show that with a variation in the regulatory level and waste minimization, the expected monetary value decreased. The difference in expected monetary value for a 10% risk in both the cases was $2,717,887 of the basecase amount of $13,402,897. For a 90% risk in the new situation, the difference in the expected monetary value was $1,779,083, from $13,402,897 to $11,623,814. The negative effect

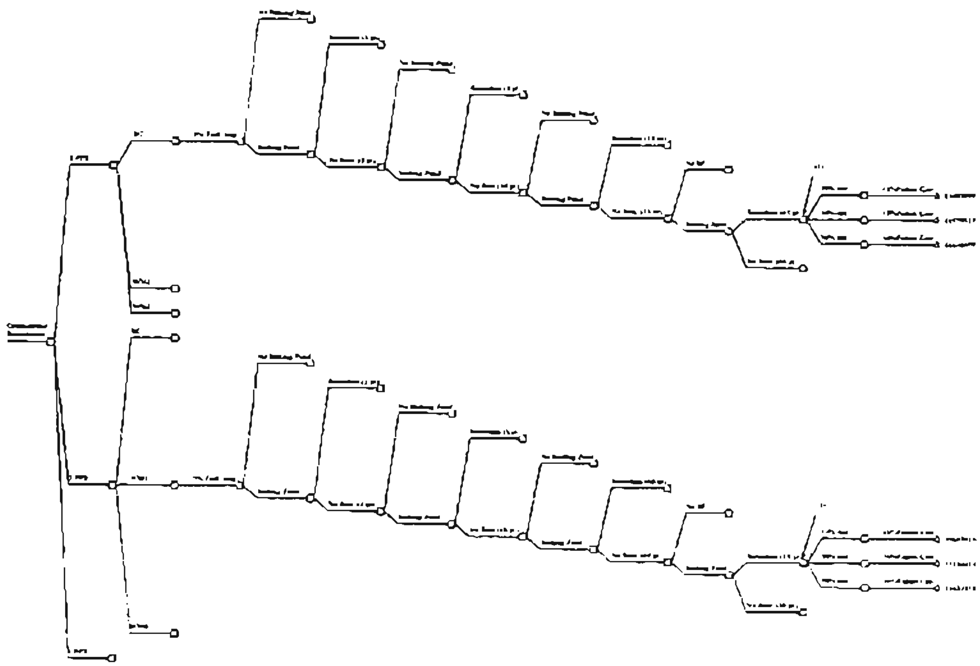


Figure 33. Collapsed decision tree showing the path and the points where expected monetary values were calculated for a change in the regulatory level from 5ppb to 3ppb and waste minimization from 0% to 10%.

due to the increase in risk and regulatory levels was diluted by the waste minimization programs.

CASE 7: Variation of Regulatory levels and Failure Cost over variation in Risk Aversion Level

The effect of changing two different variables simultaneously, regulatory level and failure cost was considered by holding constant the technology improvement rate and the waste minimization levels at 0% each. Table 14 gives the expected monetary values for the different risk fractions when the regulatory levels changed from 5μg/l to 3μg/l and the failure cost changed from 10% to 30% of the remediation cost. Figure 34 plots the resultant cost for the different risk fractions. The decision tree showing the corresponding paths is shown in Figure 35. Points 1 and 2 in the decision tree show the point where the alternatives are evaluated for the basecase and the changed scenario. The expected monetary values at these points in the tree correspond to the expected monetary values shown in Table 14.

Reg Levels	**Failure Cost**	**Position in the Decision Tree**	**Expected monetary values (in $)**		
			Risk Fractions 10%	Risk Fractions 50%	Risk Fractions 90%
5ppb	10%	1	13,402,897	13,979,937	14,556,977
3ppb	30%	2	15,854,417	17,837,537	19,820,657

Table 14. Expected monetary values for different regulatory levels, failure cost and risk fractions

The combined effect of changing regulatory levels and the failure costs increased the expected monetary value by $2,451,520, from $13,402,897 to $15,854,417 for a 10% risk aversion level. The expected monetary value was increased by $6,417,760, from $13,402,897 to $19,820,657 when the risk fraction varied from 10% in the base case to

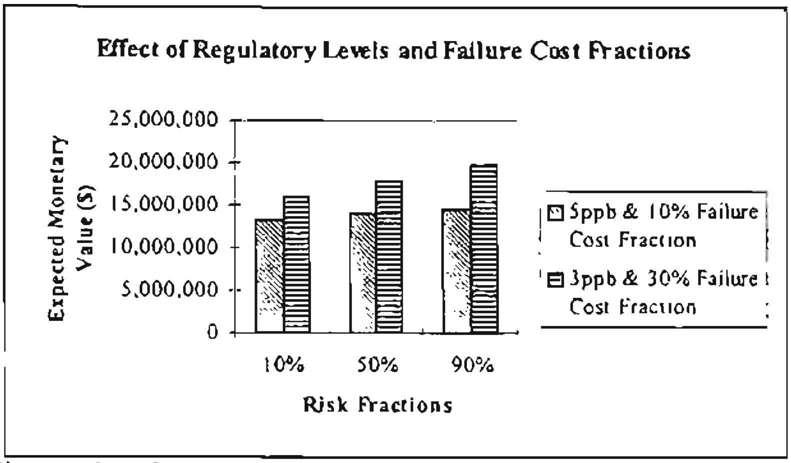


Figure 34. Figure showing the expected monetary values for different regulatory levels, failure cost and risk fractions

90% in the revised alternative. This increase was the biggest change in the expected monetary value for change in variables in all the cases.

CASE 8: Variation of Technology Improvement Rate and Waste Minimization Programs over variation in Risk Aversion Level

The effect of two variables, technology improvement rate and waste minimization programs, was considered by holding constant the regulatory level of benzene and failure cost fraction at 5μg/l and 10%, respectively. Table 15 gives the expected monetary values of this analysis when the technology improvement rate and waste minimization programs were changed from 0% to 1% and 0% to 10%, respectively. Figure 36 is the corresponding plot for these data while the decision tree showing the corresponding paths

is shown in Figure 37. Point 1 in the decision tree presents the location where the expected monetary value was determined for 0% technology improvement rate and waste minimization. Point 2 in the decision tree occurs where the expected monetary value was

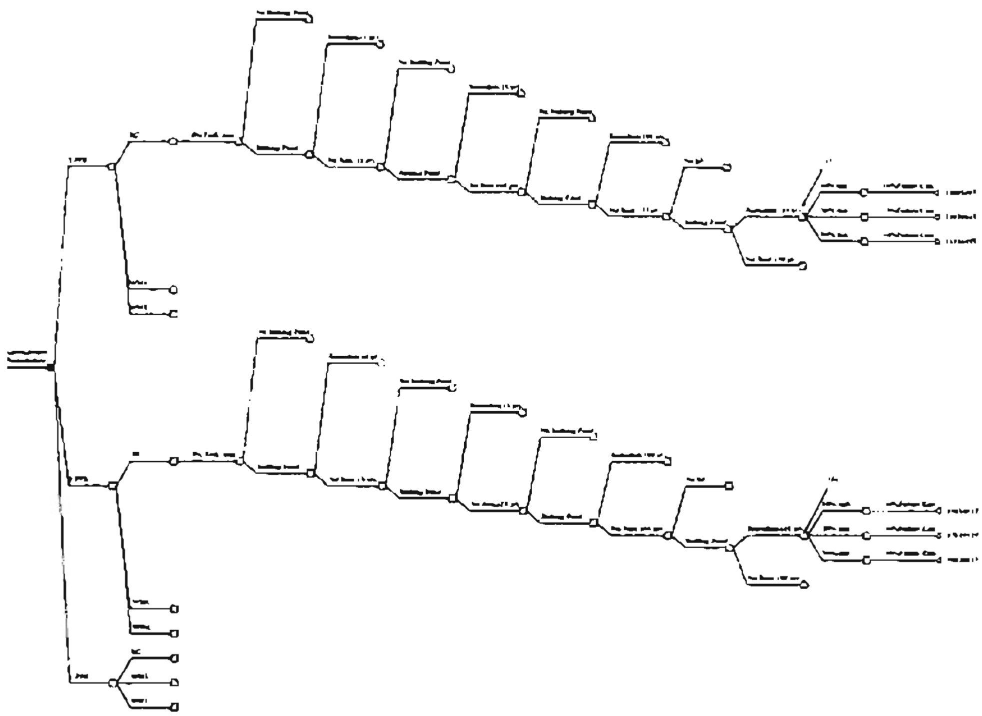


Figure 35. Collapsed decision tree showing the path and the points where expected monetary values were calculated for a change in the regulatory level from 5ppb to 3ppb and failure cost fraction from 10% to 30%.

evaluated for a 1% technology improvement rate and a 10% waste minimization. The expected monetary values at these points correspond to the data presented in Table 15.

CASE 9: Variation of Technology Improvement Rate and Failure Cost over variation in Risk Aversion Level

The effect of varying technology improvement rate and failure cost was considered by holding constant the regulatory level of benzene and waste minimization program at 5 µg/l and 0% respectively. Table 16 gives the expected monetary values for different risk fractions with a change in the technology improvement rate and failure cost from

Tech Imp Rate	Waste Min.	Position in the Decision Tree	Expected monetary values (in $)		
			Risk Fractions 10%	Risk Fractions 50%	Risk Fractions 90%
0%	0%	1	13,402,897	13,979,937	14,556,977
1%	10%	2	8,579,855	8,965,884	9,351,912

Table 15. Expected monetary values for different technology improvement rates, waste minimization programs and risk fractions

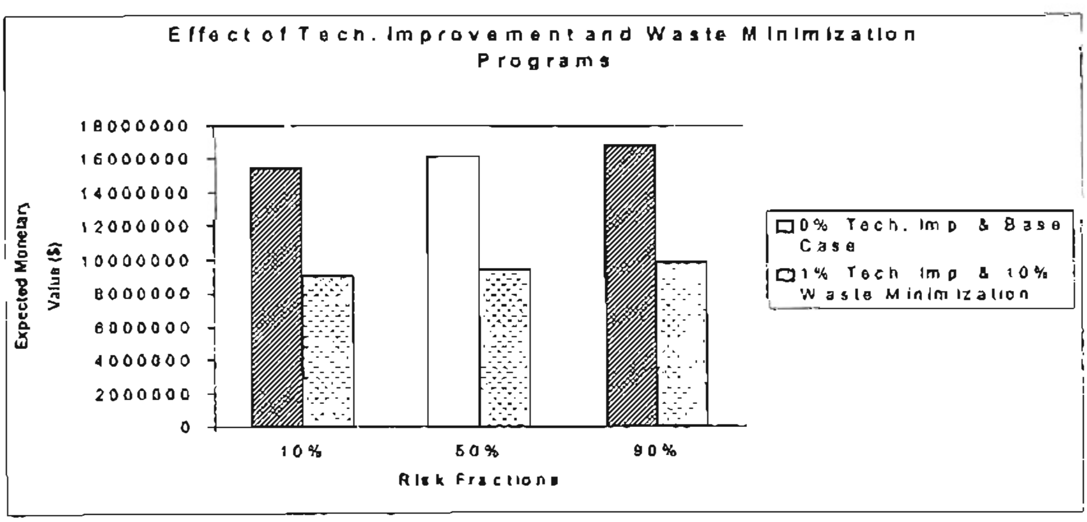


Figure 36. Figure showing the Expected monetary values for different technology improvement rates, waste minimization programs and risk fractions

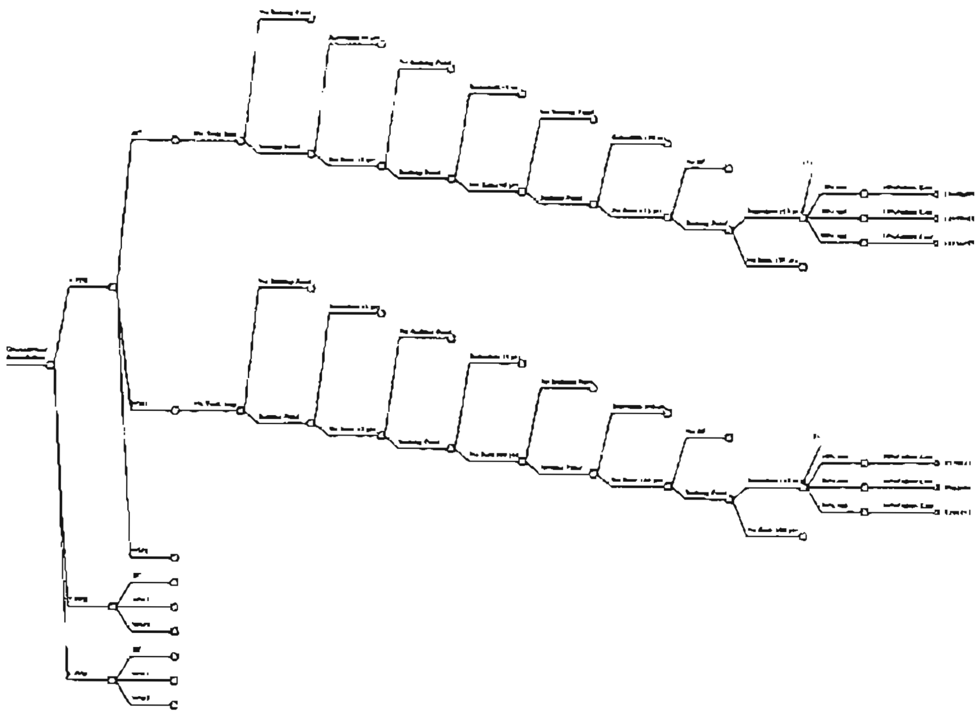


Figure 37. Collapsed decision tree showing the path and the points where expected monetary values were calculated for a change in the technology improvement rate from 0% to 1% and waste minimization from 0% to 10%.

The table and figure show that with an increase in the technology improvement rate and implementation of a waste minimization program, the expected monetary value was reduced for all cases of risk. The reduction in the expected monetary value for a 10% risk between the two data sets was $4,823,042 of $13,402,897. Similarly, for an increase in risk from 10% to 90% in the alternative, the expected monetary value was reduced by $4,050,985.0% to 1% and 10% to 30% respectively. Figure 38 is the corresponding plot for these data while the decision tree showing the corresponding paths is presented in Figure 39. The expected monetary values at points 1 and 2 in the tree correspond to the expected monetary values shown in Table 16.

Tech Imp Rate	**Failure Cost**	**Position in the Decision Tree**	**Expected monetary values (in $)**		
			Risk Fractions 10%	**Risk Fractions** 50%	**Risk Fractions** 90%
0%	10%	1	13,402,897	13,979,937	14,556,977
1%	30%	2	11,621,048	13,110,960	14,600,872

Table 16. Expected monetary values for different technology improvement rates, failure costs and risk fractions

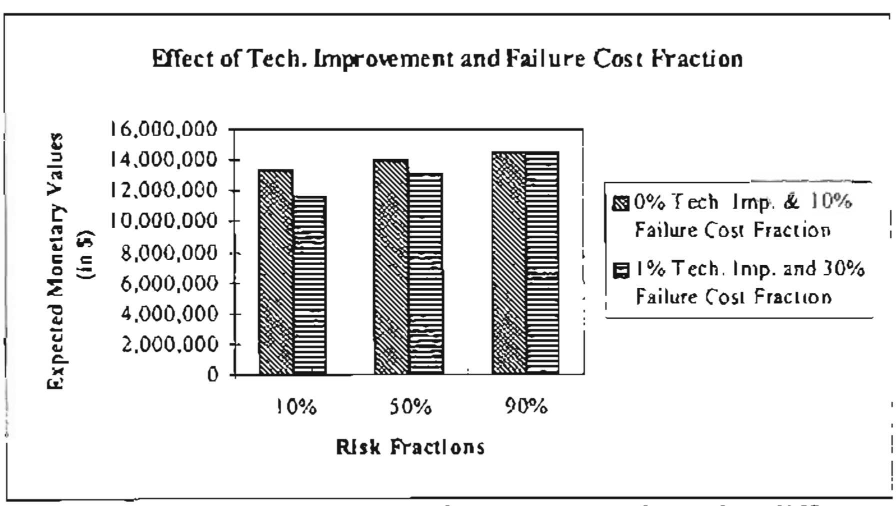


Figure 38. Figure showing the expected monetary values for different technology improvement rates, failure cost and risk fractions

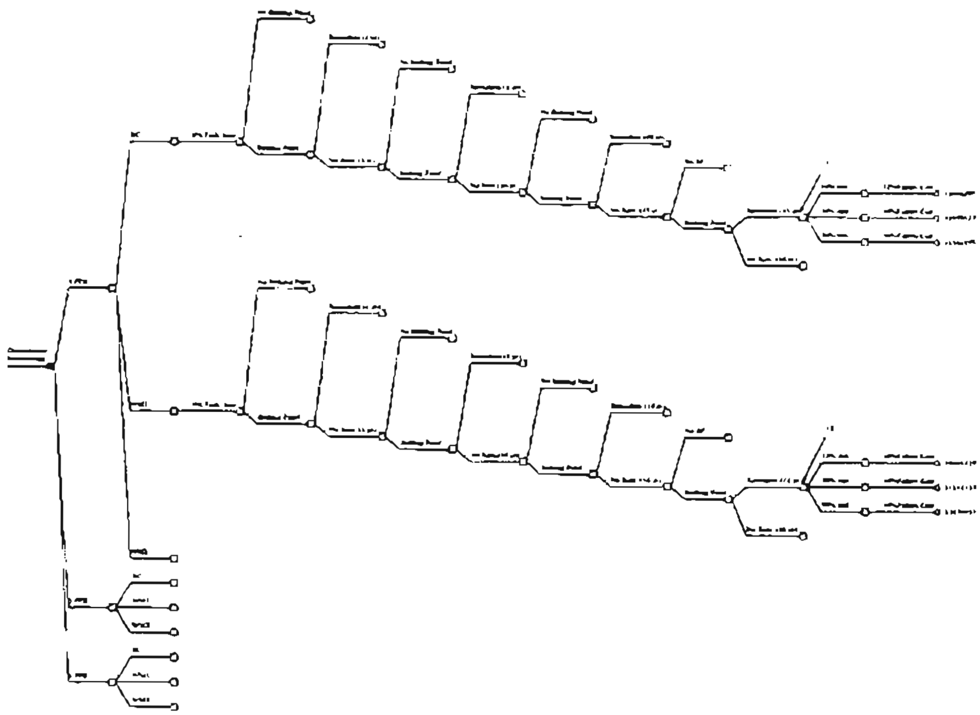


Figure 39. Collapsed decision tree showing the path and the points where expected monetary values were calculated for a change in the technology improvement rate from 0% to 1% and failure cost fraction from 10% to 30%.

Table 16 and Figure 40 shows that with an increase in technology improvement rate and failure cost, the expected monetary value decreased over the two lowest risk aversion levels but increased when risk avoidance went to 90%. The expected monetary value, for a 10% risk aversion level, decreased by about $1,781,849, (from $13,402,897 to $11,621,048) while increasing by $1,197,975 (from $13,402,897 to $14,600,872) at the 90% risk aversion level illustrating the significance of the risk fraction on the case specific optimum.

CASE 10: Variation of Waste Minimization and Failure Cost over variation in Risk Aversion Level

The effect of varying waste minimization programs and failure cost was considered by holding constant the regulatory level of benzene and increase in technology improvement rate at 5μg/l and 0%, respectively. Table 17 gives the expected monetary values for the various risk fractions with a change in the waste minimization program and failure cost from 0% to 10% and 10% to 30%, respectively. Figure 40 is the corresponding plot of the expected monetary values while Figure 41 is the decision tree showing the corresponding paths. The expected monetary values at points 1 and 2 in the decision tree correspond to the expected monetary values shown in Table 17.

Waste Min	**Failure Cost**	**Position in the Decision Tree**	**Expected monetary values (in $)**		
			Risk Fractions 10%	**Risk Fractions** 50%	**Risk Fractions** 90%
0%	10%	1	13,402,897	13,979,937	14,556,977
10%	30%	2	10,461,337	11,816,137	13,170,937

Table 17. Expected monetary values for different waste minimization programs, failure costs and risk fractions

From Table 17 and Figure 40, it is clear that the effects of waste minimization at the levels evaluated overcome negative cost impacts associated with increases in failure cost.

The decrease in the expected monetary value was about $2,941,560 from the basecase value of $13,402,897. The reduction in the expected monetary value for a change in the risk aversion level from 10% in the basecase to 90% when a change in the variables occurred was $231,960 (from the basecase value of $13,402,897).

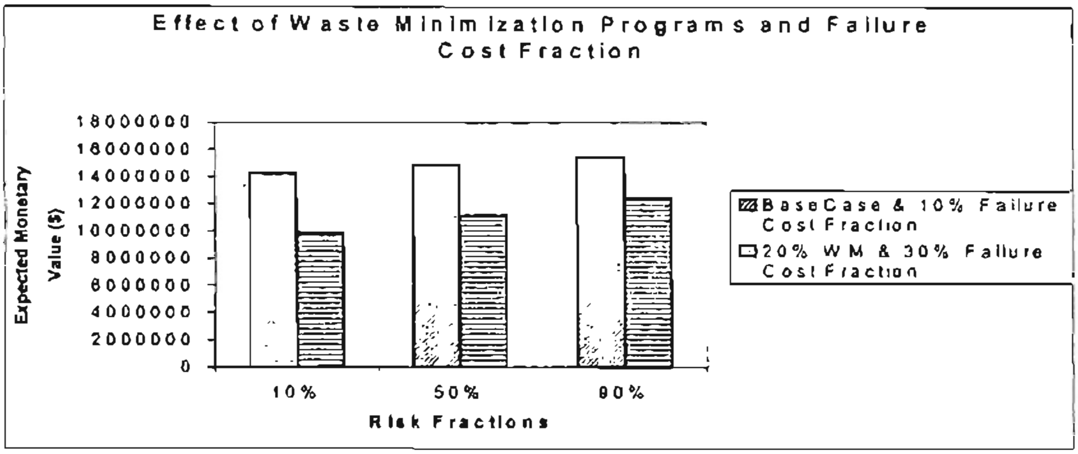


Figure 40. Figure showing the Expected monetary values for different waste minimization programs, failure cost and risk fractions

Effect of changing the values of Three Variables on the decision situation

The following cases were considered to demonstrate the effect of changing three variables on the outcome of decisions. Again, it was assumed that the changes in the variables occurred simultaneously.

CASE 11: Variation of Regulatory Levels, Technology Improvement Rate and Waste Minimization Programs over variation in Risk Aversion Level

The effect of varying regulatory levels, technology improvement rate, and waste minimization programs was considered by holding the failure cost constant at 10% of the total cost. Table 18 gives the expected monetary values for the various risk fractions with

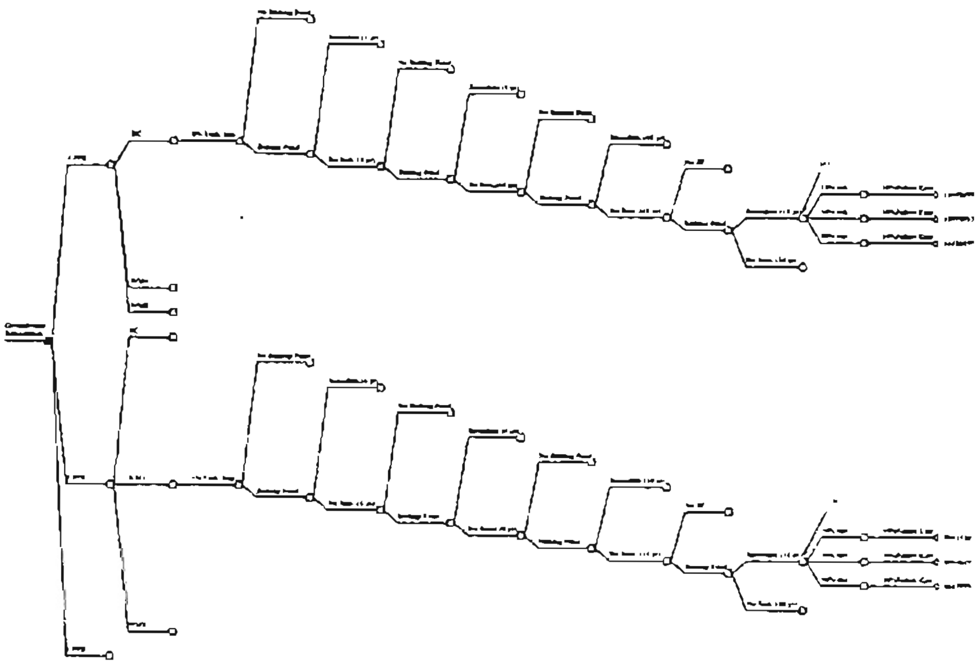


Figure 41. Collapsed decision tree showing the path and the points where expected monetary values were calculated for a change in the waste minimization from 0% to 10% and failure cost fraction from 10% to 30%.

a change in the regulatory levels, waste minimization program and technology improvement rate from 5ppb to 3ppb, 0% to 10%, and 0% to 1%, respectively. Figure 42 is the corresponding plot for these conditions, while the decision tree showing the corresponding paths is shown in Figure 43. The expected monetary values at points 1 and 2 correspond to the expected monetary values shown in Table 18.

Reg. Levels	**Tech Imp Rate**	**Waste Min.**	**Position in the Decision Tree**	**Expected monetary values (in $)**		
				Risk Fractions 10%	Risk Fractions 50%	Risk Fractions 90%
5ppb	0%	0%	1	13,402,897	13,979,937	14,556,977
3ppb	1%	10%	2	9,011,530	9,414,655	9,817,779

Table 18. Expected monetary values for different regulatory levels, technology improvement rates, and waste minimization programs for different risk fractions

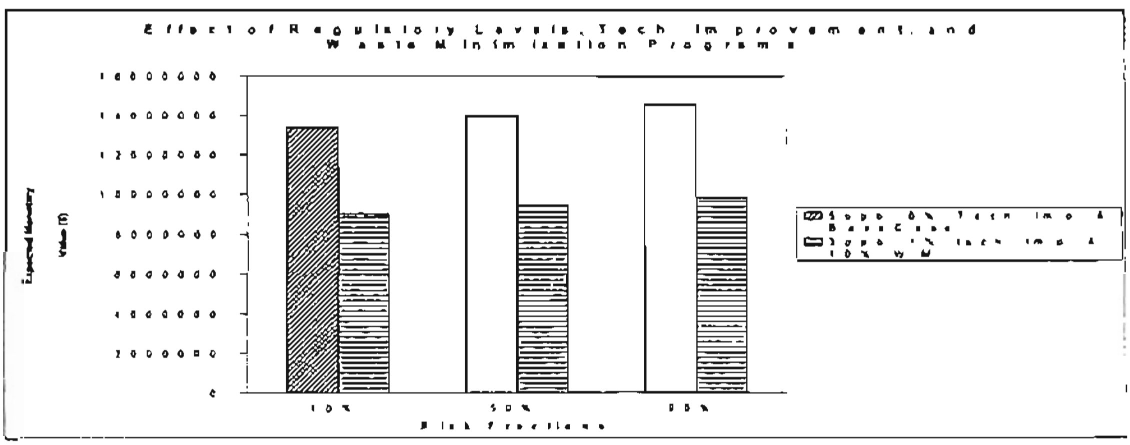


Figure 42. Figure showing the Expected monetary values for different regulatory levels, technology improvement rates, and waste minimization programs for different risk fractions

The table and figure show that, changes in regulatory levels, technology improvement rate, and waste minimization resulted in reductions in the expected monetary value. There was a reduction in the expected monetary value by about $4,391,367 from the basecase projected cost of $13,402,897 when the risk was 10% and by $3,585,118 at 90% risk fraction.

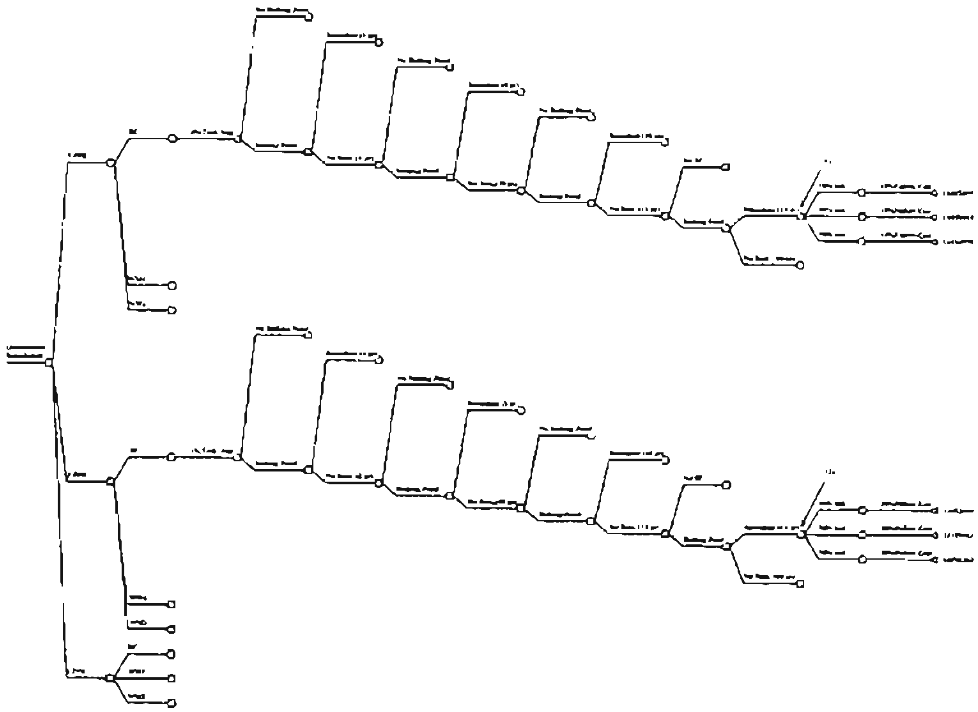


Figure 43. Collapsed decision tree showing the path and the points where expected monetary values were calculated for a change in the regulatory level from 5ppb to 3ppb, technology improvement rate from 0% to 1% and waste minimization from 0% to 10%.

CASE 12: Variation of Regulatory Levels, Technology Improvement Rate and Failure Cost over variation in Risk Aversion Level

The effect of varying regulatory levels of benzene, increases in technology improvement rate, and failure cost was considered by holding waste minimization programs constant at 0%. Table 19 gives the expected monetary values for the various risk fractions with a change in the regulatory levels, technology improvement rate, and failure cost from 5ppb to 3ppb, 0% to 1% and 10% to 30% of the total cost, respectively. Figure 44 is the corresponding plot for the values before and after the changes in the variables and for different risk fractions. The decision tree showing the corresponding paths is shown in Figure 45. The expected monetary values at points 1 and 2 in the tree correspond to the expected monetary values shown in Table 19.

Reg. Levels	**Tech. Imp. Rate**	**Failure Cost**	**Position in the Decision Tree**	**Expected monetary values (in $)**		
				Risk Fractions 10%	Risk Fractions 50%	Risk Fractions 90%
5ppb	0%	10%	1	13,402,897	13,979,937	14,556,977
3ppb	1%	30%	2	13,482,664	15,189,463	16,896,263

Table 19. Expected monetary values for different regulatory levels, technology improvement rates, failure costs and risk fractions

In these kinds of changes, the positive effect due to rate of technology improvement was dominated by the combined effect of regulatory levels and failure cost at high risk aversion levels (50% or 90%). The effect was not predominant for a risk of 10% with the expected monetary value increasing by $79,767 of the basecase projected cost of

$13,402,897 but increased by $3,493,366 from the basecase when the risk increased to 90%, again illustrating the cost associating with risk avoidance.

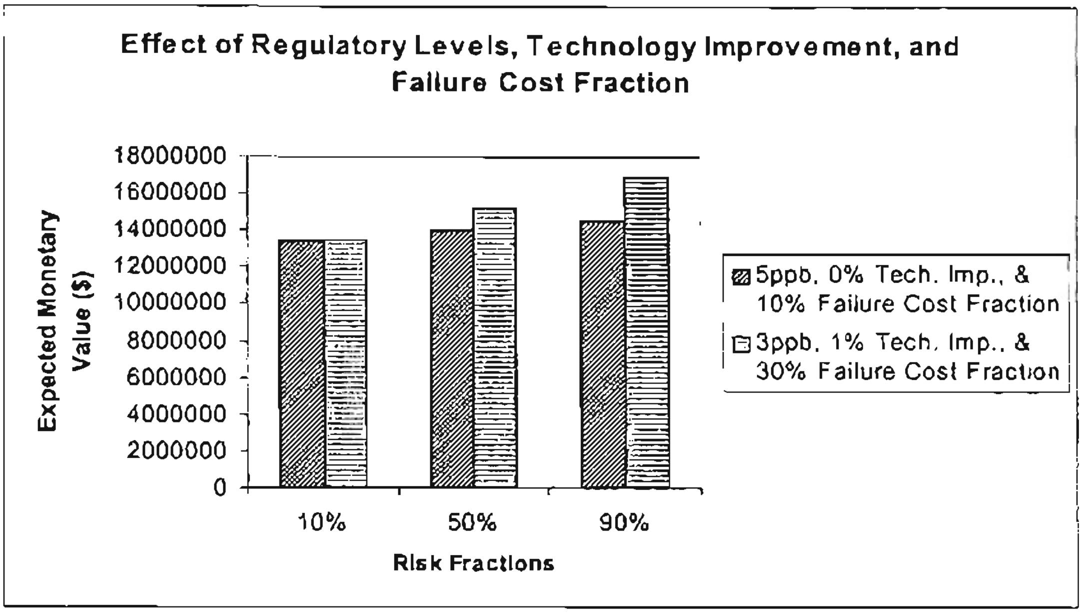


Figure 44. Figure showing the Expected monetary values for different regulatory levels, technology improvement rates, failure costs and risk fractions

CASE 13: Variation of Technology Improvement Rate, Waste Minimization Program, and Failure Cost over variation in Risk Aversion Level

The effect of varying technology improvement rate, waste minimization programs, and failure cost was considered by holding regulatory levels of benzene constant at 5ppb. Table 20 gives the expected monetary values for the various risk fractions with a change in the technology improvement rate, waste minimization program, and failure cost from 0% to 1%, 0% to 10%, and 10% to 30% of the total cost respectively. Figure 46 is the corresponding plot for the expected monetary values before

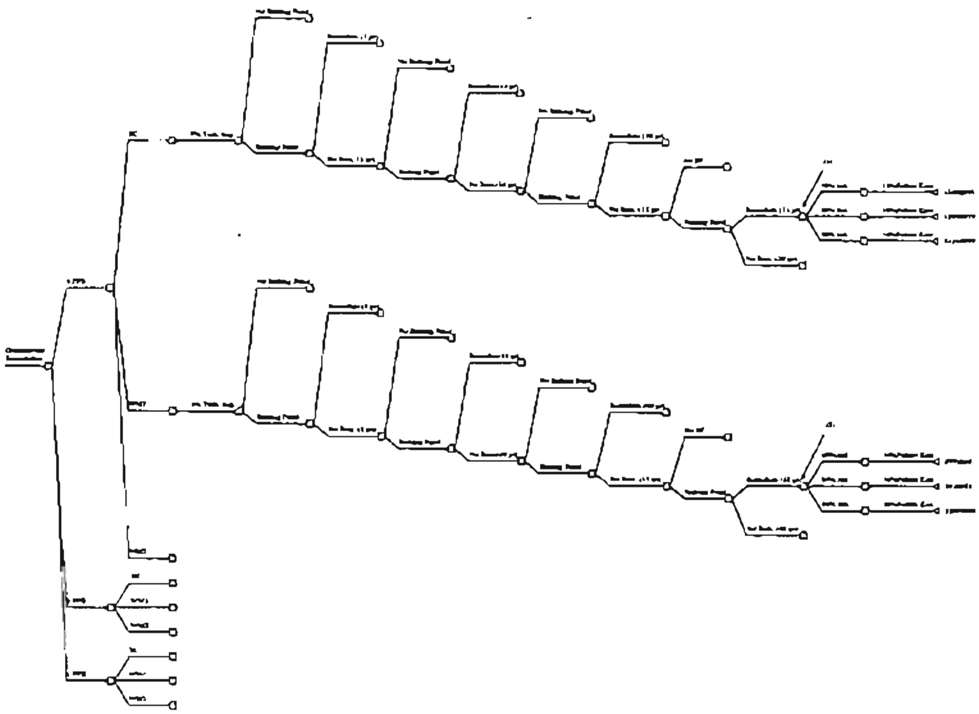


Figure 45. Collapsed decision tree showing the path and the points where expected monetary values were calculated for a change in the regulatory level from 5ppb to 3ppb, technology improvement rate from 0% to 1% and failure cost fraction from 10% to 30%.

and after the changes in the variables under consideration and for different risk fractions. The decision tree showing the corresponding paths is shown in Figure 47. The expected monetary values at points 1 and 2 correspond to the expected monetary values shown in Table 20.

Tech. Imp. Rate	**Waste Min.**	**Failure Cost**	**Position in the Decision Tree**	**Expected monetary values (in $)**		
				Risk Fractions	Risk Fractions	Risk Fractions
				10%	50%	90%
0%	0%	10%	1	13,402,897	13,979,937	14,556,977
1%	10%	30%	2	8,772,869	9,930,955	11,089,040

Table 20. Expected monetary values for different technology improvement rates, waste minimization programs, failure costs and risk fractions

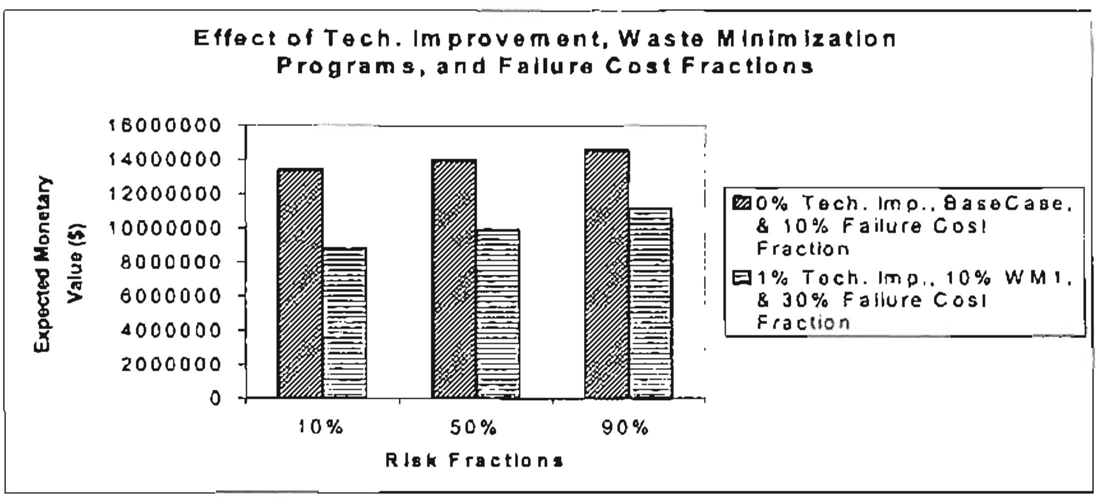


Figure 46. Figure showing the expected monetary values for different technology improvement rates, waste minimization programs, failure costs and risk fractions

The data presented in the table and figures indicate a reduction in the expected monetary value in this case where three variables were altered. The reduction in the expected monetary value of $4,630,028 or 34.5% from the basecase for a risk of 10% was reduced to $2,313,857 when the risk increased to 90%.

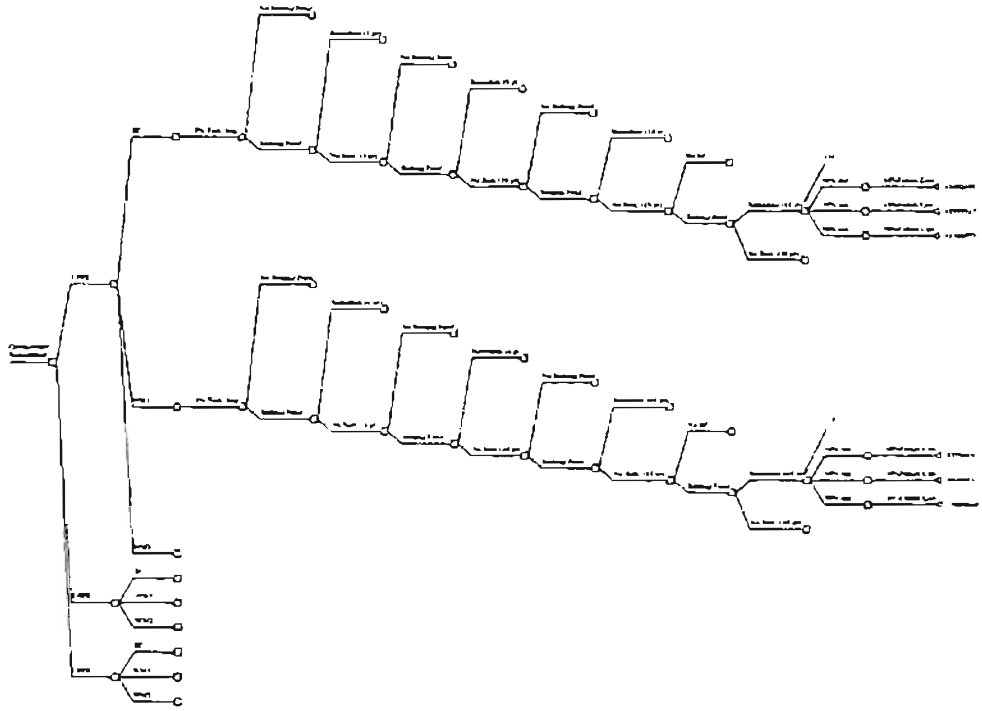


Figure 47. Collapsed decision tree showing the path and the points where expected monetary values were calculated for a change in the technology improvement rate from 0% to 1%, waste minimization from 0% to 10% and failure cost fraction from 10% to 30%

SECTION II: Effect of Sinking Fund on the Expected Monetary Value

This section deals with determining the effect of a sinking fund on the expected monetary value using sensitivity analysis. All other variables in the decision tree were held constant and the analysis was performed. The regulatory level for benzene was considered as 5ppb, 0% technology improvement rate, 0% waste minimization, and 10% failure cost fraction. The decision maker's risk aversion level was maintained at 10% for the analysis. A sinking fund range of $50,000 to $500,000 per year was considered for the analysis. This range was considered arbitrarily and was decided in such a way that the sinking amount of $100,000 chosen in the analysis of the tree was covered in the range. The analysis was done for the "sinking fund" and "no sinking fund" nodes in the decision tree. Different time periods were considered because a sinking fund is a function of time. Sample plots are shown in Figures 48 and 49.

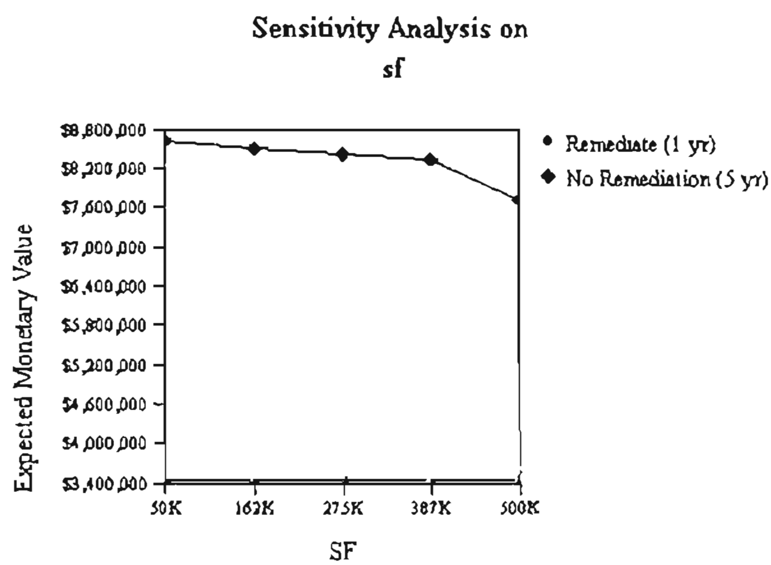


Figure 48. Sensitivity analysis plot on sinking fund at the "No Sinking Fund" node, at the 1st year, following the 0% technology improvement rate, for a regulatory level of 5ppb and 0% waste minimization
* SF – Sinking Fund

Figure 48 shows the variation of the expected monetary value over sinking fund . "No sinking fund" node, for a regulatory level of 5ppb and 0% waste minimization. The analysis was done on the alternatives "remediate at 1st year without sinking fund" and "no remediation". The plot shows that, at the 1st year, remediation was recommended over the "no remediation" alternative.

Similarly, Figure 49 is a sensitivity plot at the "sinking fund" node at the 5th year following the "No Remediation without sinking fund" alternative. The analysis was done on the alternatives, "remediate with sinking fund at the 5th year" and "no remediation until the 10th year" and gave a threshold sinking fund value of $469,000 per year. A threshold value occurs at the point where the optima would change. That is, if the sinking fund deposit equals or exceeded $469,000 the "no remediation" alternative would be preferred. The expected monetary value for the outcome at the threshold point is $8,262,136. Figures 48 and 49 are for illustrative purposes to show the sensitivity analysis on a sinking fund. In a similar manner sensitivity analysis was done at different "sinking fund" and "no sinking fund" nodes for a time period of one and five years. The results of the analyses for different time periods are presented in Table 21.

The table shows the alternate sinking fund paths that were considered for the sensitivity analysis and the corresponding threshold values (if any). The table also gives the optimum in each case. The analyses yielded a sinking fund threshold value of $469,000 per year at the nodes where the alternatives were to "remediate" at the 5th year or to "postpone remediation" to the 10th year. Analyses on the "remediate" and "no remediation" at the 10-year sinking fund nodes indicated that, for the sinking fund range

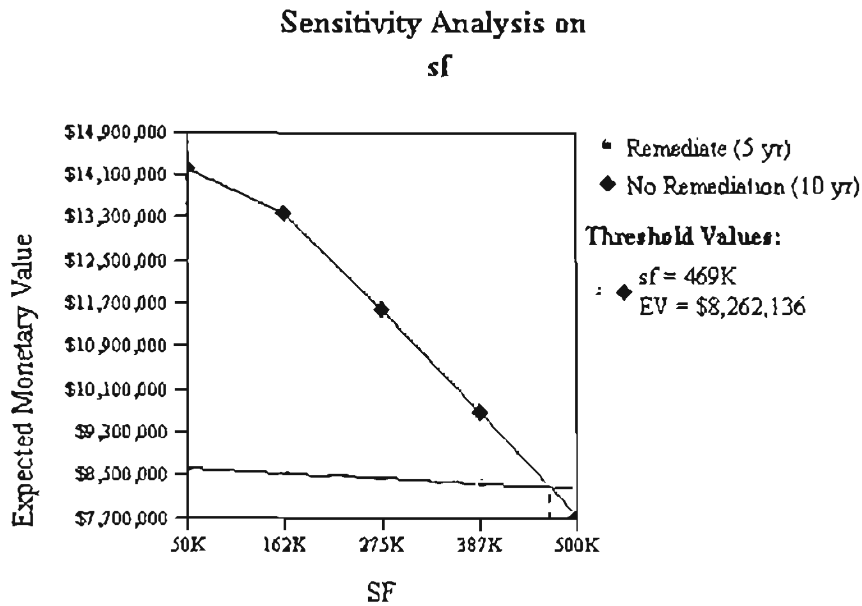


Figure 49. Sensitivity analysis plot on sinking fund at the "Sinking Fund" node, at the 5th year, following the 0% technology improvement rate, for a regulatory level of 5ppb and 0% waste minimization.

- SF – Sinking Fund

Time Period in the tree (years)	Analysis on Node (path in the Decision Tree)	Threshold		Optima
		Sinking fund ($)	Expected monetary value ($)	
1	No SF for the 1st year	-	-	Remediate
1	SF for the 1st year	-	-	Remediate
5	No SF until the 5th year	-	-	Remediate*
5	SF at the 5th year following No SF until the 5th year	469,000	8,262,136	
5	No SF following SF for the 1st year	-	-	Remediate*
5	SF for the 1st 5 years	469,000	8,262,136	
10	No SF for the 10th year	-	-	No Remediation

Table 21. Table showing the Sinking Fund and the corresponding threshold values for different time periods.

* These two paths have a threshold value for a sinking fund amount of $567,000 per year resulting in an expected monetary value of $8,647,620.

- SF - Sinking Fund

of $50,000 to $500,000 per year, postponing remediation was favored to remediation at the 10th year.

Further analysis on the 1st year "sinking fund" node was done to determine the increase in the sinking fund deposit needed that would change the optima from "remediate" at the 1st year to postponing remediation to the 5th year. The sinking fund range was increased to $700,000 from $500,000 for the analysis. It was found that the optimum changed from remediation at 1st year to postponing remediation to the 5th year when an annual deposit of $623,000 was made.

of $50,000 to $500,000 per year, postponing remediation was favored to remediation at the 10th year.

Further analysis on the 1st year "sinking fund" node was done to determine the increase in the sinking fund deposit needed that would change the optima from "remediate" at the 1st year to postponing remediation to the 5th year. The sinking fund range was increased to $700,000 from $500,000 for the analysis. It was found that the optimum changed from remediation at 1st year to postponing remediation to the 5th year when an annual deposit of $623,000 was made.

CHAPTER V

DISCUSSION OF RESULTS

The decision tree shown in Figure 9 (Chapter IV) is in rolled-back form, where the expected monetary values for each of the decision alternatives were evaluated and the optimal alternative highlighted. In this tree the two variables, namely, the MCL for benzene and the technology improvement rate, are both independent of the decision maker. As mentioned in Chapter II, either the United States Environmental Protection Agency (EPA) or an equivalent state agency decides the regulatory level of benzene while the technology improvement rate depends on on-going market conditions. Once the levels for these variables were set, then the decision maker had to decide whether to initiate a sinking fund. Following this, the decision maker evaluates the alternatives of whether to remediate immediately or postpone action. From the figure, it is clear that remediation in the first year, for the values assumed in generating this tree, is preferred over the "no remediation" alternative. Given the availability of sufficient funds and perfect knowledge, however, it would be more economical to remediate in the first year following contamination. This shows that it would be better to perform an immediate clean up on a small oil spill rather than postpone it.

To illustrate some of the alternative conditions this research evaluated the decision to postpone remediation until the end of either the 10^{th} or the 15^{th} year. While for each set of concerns an optimal path exists, the objective of this thesis, however is to present to the decision maker an evaluation and comparison of some example alternatives that could arise due to different values that the variables in the tree could assume. For example, the regulatory levels of acceptable benzene may change over the years, or the situation may warrant the decision maker to assume a different risk factor. The influence of such changes, when occurring alone or together, on the decision making process is discussed below on a case by case basis. In each case the results are discussed in the context of site conditions. The discussions are summarized at the end of each section.

Optimal path considerations

To determine the influence of sinking fund deposit time periods on the expected monetary value, two cases were considered: one in which remediation could be carried out only at the 10th and the other at the 15th year. Tables 4, 5, 6, and 7 of Chapter IV give the expected monetary values for each remediation alternative for regulatory levels of 5 and 3ppb combined with 0% increase in technology improvement rate for 10 and 15 years, respectively.

The values indicate that the time in the decision process at which the sinking fund is initiated affects the expected monetary value. For instance, sinking fund deposits were made from the 5th to the 10th years [point 3, Table 4 of Chapter IV]. This deposit scenario considers an additional deposit to the sinking fund pool, immediately before remediation. Conversely sinking fund deposits made only for the 1st five years of the decision process [point 5, Table 4 of Chapter IV] generated increased returns even though the deposits' were for the same length of time. This was possible due to the interest generated by the second type of deposits. Comparisons of the expected monetary values along each path in both the cases showed that it would be economical to select the path along which sinking fund was initiated in the first year of oil spill and continued until remediation was initiated and completed.

Not surprisingly, the overall optimum occurred when a benzene MCL of 5ppb, a 2% technology improvement rate, a 10% risk aversion level and a 10% failure cost fraction in conjunction with a 20% waste minimization program occurred. This, however, while obvious without technical analysis is often a "nonsensical" solution as conditions external to the decision maker such as regulatory levels and technology improvement rates can combine with internal variables such as risk avoidance levels and waste minimization practices to identify problem settings not defined within the overall optimum. This approach was therefore also used in evaluating decision alternatives under situations when a change in the value of the critical variable occurs. As in Chapter IV, the cases are considered in two sections. Section I discusses the effect of varying the technical variables like the regulatory levels, waste minimization programs, technology improvement rate, and failure cost. Section II discusses the effect of varying the economic variable, sinking fund, on the resultant decision. In Section I, the variables were altered initially one at a time, then two and three simultaneously. Section II deals with the variation of sinking fund over time at the decision nodes, "Sinking Fund" and "No Sinking Fund".

<u>SECTION I: Effect of Changing the Technical Variable Values on the Optimum Decision</u>

In the following tables, a negative percentage difference between the basecase and the alternative indicates an increase in the projected costs of the prospective action while a positive percentage difference indicates a decrease in the projected cost. Alternate paths, with different sinking fund deposit time periods, were not considered when a change in the critical variables resulted in an increase in the projected cost as only the path of the sinking fund deposit from the time of the spill until remediation was considered. Any change from this path would result in a reduction in the amount generated from the sinking fund deposit and hence would increase the expected monetary value. On the other hand, with a reduction in the expected monetary value, alternate paths of sinking fund deposit were evaluated. This was done to determine whether a change in the deposit pattern still resulted in a reduction in the expected monetary value as compared to the basecase. This was done to give the decision maker a flexibility in making decisions. The expected monetary values for the alternative paths of sinking fund deposit were taken from the decision tree based on the new values of the critical variables. The change in the critical variable can occur at any time in the decision process. Here, it was assumed to occur in the 5th year of the decision process.

It should be mentioned that the tables for all the cases in this section compare the expected monetary values between all the risk fractions considered in the methodology. That is, for each risk fraction in the base case, the difference in the expected monetary value between the basecase and the alternative were determined. For example if a risk fraction of 10% was considered in the basecase, then the differences in the expected monetary values between the basecase and the alternative were determined for all the three risk aversion levels of 10%, 50%, and 90% in the alternative. This comparison was made due to the uncertainty involved in selecting any one particular risk fraction.

Effect of Varying One Variable

<u>*CASE 1: Effect of varying Regulatory Levels over variations in Risk Aversion Level*</u>

The expected monetary values for different regulatory levels were given in Table 8 of Chapter IV for different risk fractions. The percentage differences in expected monetary values for changes in regulatory levels from a basecase level of 5μg/l to 3μg/l and for different risk fractions are shown in Table 22. A regulatory level of 5μg/l with a risk aversion level of 10% was considered as the basecase scenario.

Variation in Regulatory Levels	Percentage difference in expected monetary values for different risk fractions								
	10%			50%			90%		
	10%	50%	90%	10%	50%	90%	10%	50%	90%
5 to 3ppb	-16%	-21%	-26%	-11%	-16%	-21%	-7%	-11%	-16%

Table 22. Percentage difference in expected monetary values for different Risk Fractions for variation in Regulatory Levels, from a basecase level of 5ppb to 3ppb.
Base Case: Regulatory level of benzene as 5μg/l and 10% risk aversion level

This table shows that at an initial risk aversion level of 10%, a 16% penalty is expected when an increase in the regulatory level from 5ppb to 3ppb occurs. If the risk aversion level is simultaneously increased to 50% or 90% these penalties go to 21% and 26%, respectively. If the initial risk aversion level is 50% the respective penalties associated with the regulatory change are 11%, 165, and 21% when risk aversion is also altered. Each of the subsequent tables presenting similar information is read accordingly. The percentage differences in expected monetary values were found to be negative, since stricter regulation leads to greater cost of remediation. The percentage increase in the projected cost, with nó change in the initially assumed risk fraction, was about 16% of basecase cost of $13,402,897 [Table 8, Chapter IV] when the regulatory level of benzene changed from 5ppb to 3ppb. If the decision maker perceived an initial risk of 90%, but later reduced it to 50% when the new regulations were enforced, then the increase in expected monetary value would be just 11% of the basecase amount of $13,402,897 rather than 16% had the same risk been maintained. The loss was further reduced to 7% if the decision maker accepted a risk of 10% with increasing regulatory level. A change in the regulatory level caused an increase in the remediation cost even when there was a decrease in the risk tolerance level.

CASE 2: Effect of variation of Rate of Technology Improvement over variations in Risk Aversion Level

The expected monetary values for different rates of technology improvement were given in Table 9 of Chapter IV for different risk fractions. The percentage differences in expected monetary values for increase in technology improvement rates from 0% to 1% are shown in Table 23. A 0% technology improvement rate and a 10% risk aversion level with an expected monetary value of $13,402,897 (Table 9, Chapter IV), was considered as the basecase situation.

Variation in Tech. Improvement Rate from	Percentage difference in expected monetary values for different risk fractions								
	10%			50%			90%		
	10%	50%	90%	10%	50%	90%	10%	50%	90%
0% to 1%	15%	11%	7%	18%	15%	11%	21%	18%	15%

Table 23. Percentage difference in expected monetary values for different Risk Fractions for variation in technology improvement rate, from a basecase level of 0% to 1%.
Base Case: 0% Technology Improvement Rate and 10% risk aversion level

The increase in technology improvement rate had a positive effect on the outcome in general and reduced the projected costs. If the rate of technological improvement is great enough, the decision maker can theoretically consider postponing remediation, stop sinking fund investments or accept a lower risk aversion level. As an example, if an initial risk fraction of 90% was reduced to only 10% with a 1% increase in technological improvement rate, the projected costs were reduced by 21% of the basecase value of $14,556,977 to an expected monetary value of $11,869,366 [Table 9, Chapter IV].

Alternate Path: Since change in technology improvement rate reduced expected monetary value, alternate paths of sinking fund deposit were considered. A few of them are illustrated below. For a change in the technology improvement rate at the 5th year, the alternate path of "No Sinking Fund" deposit at the 5th year could be followed until remediation at the 15th year and still save $1,482,494 (11% of the basecase) by the 15th year. That is, an initial cost of $13,402,897 reduced to $11,920,403 if a 1% technology improvement rate was experienced. The decision maker could even postpone the decision to remediate until the 50th year with a risk avoidance level of 90% if a 1% technology improvement rate was realized and save $680,617 (5%) over the basecase ($13,402,897), [Table 9, Chapter IV], as the expected monetary value reduced to $12,722,280. Figure 50 presents a skeletal tree showing the alternate paths of sinking fund deposit considered. It is immediately apparent, however, that a 1% per year technology improvement rate is probably unsustainable for any extended period of time and the decision maker should look elsewhere to achieve cost savings.

CASE 3: Effect of Waste Minimization Programs over variations in Risk Aversion Level

The expected monetary values for different minimization programs were given in Table 10 in Chapter IV for the various risk fractions. The percentage difference in expected monetary values for a change in waste minimization program from 0% to 10% are shown in Table 24. A 0% waste minimization program and a 10% risk aversion level

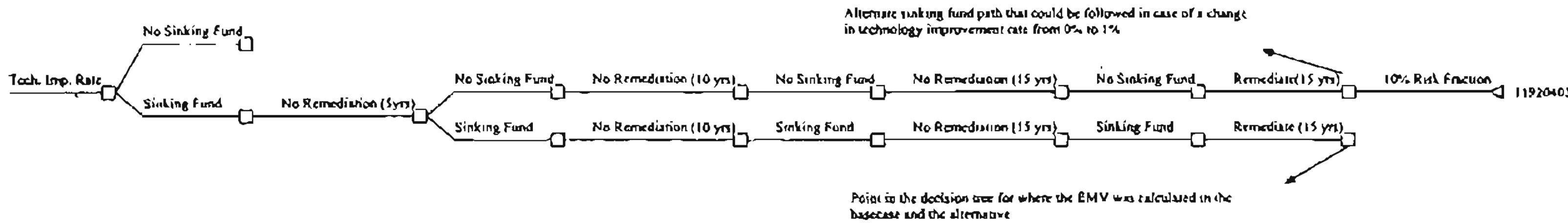


Figure 50. Skeletal tree showing the path followed for the basecase and the alternatives for a change in the technology improvement rate from 0% to 1%.

with an expected monetary value of $13,402,897 (Table 10, Chapter IV) was considered as the basecase situation.

Variation in Waste Minimization Programs from	Percentage Difference in expected monetary values for different risk fractions								
	10%			50%			90%		
	10%	50%	90%	10%	50%	90%	10%	50%	90%
0% to 10%	24%	20%	17%	27%	24%	20%	30%	27%	24%

Table 24. Percentage difference in expected monetary values for different risk fractions for variation in waste minimization programs.
Base Case: 0% Waste Minimization Program and 10% risk aversion level

As expected, the initiation of waste minimization programs had a positive effect on the outcome. For example, an initial risk avoidance fraction of 10%, could be increased to 50% in conjunction with a 10% minimization program and still result the reduction in the projected costs of 20% from the basecase amount of $13,402,897 [Table 10, Chapter IV] or $2,715,760. With the initiation of waste minimization program, the decision maker could either postpone the decision to remediate at the 15th year or stop making sinking fund investment entirely.

Alternate Paths: As mentioned in the beginning of the section, when there was a reduction in the expected monetary values associated with particular combination of variables, alternate paths of sinking fund deposit pattern were analyzed and an example is illustrated. The decision maker can eliminate the sinking fund deposit from the 5th to the 15th year and still realize a reduction in the expected monetary value by 19% ($2,546,550) over the basecase amount of $13,402,897 [Table 10, Chapter IV]. Figure 51 presents a tree illustrating this alternate path which could be followed for remediation when waste minimization programs were initiated. So with an increase in waste

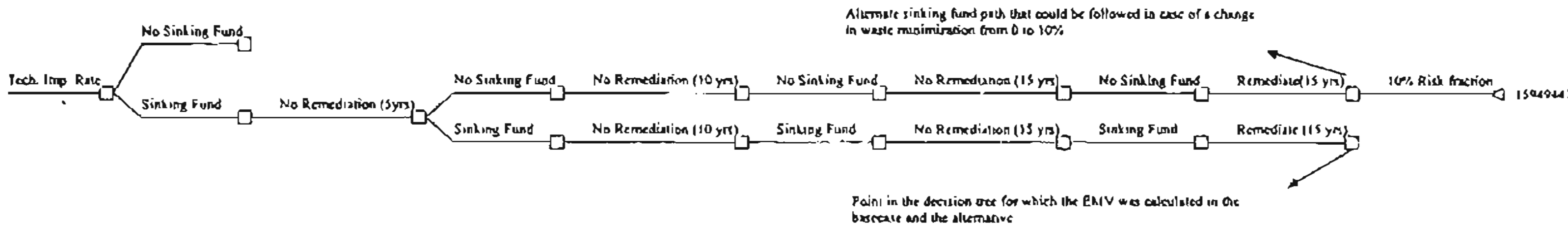


Figure 51. Skeletal tree showing the path followed for the basecase and the alternatives for a change in the waste minimization program from 0% to 10%

minimization programs, no sinking fund alternatives can prove equally or more advantageous in terms of saving remediation funds.

CASE 4: Effect of Failure Cost over variations in Risk Aversion Level

The projected cost for different failure penalties were given in Table 11 of Chapter IV for different risk fractions. The percentage differences in expected monetary values for increase in failure cost fraction from 10% to 30% are shown in Table 25. A 10% failure cost fraction with 10% risk aversion level was considered as the basecase situation with an expected monetary value of $13,402,897 (Table 11, Chapter IV).

Variation in Failure Cost form 10% to 30%	Percentage difference in expected monetary values for different risk fractions								
	10%			50%			90%		
	10%	50%	90%	10%	50%	90%	10%	50%	90%
	-2%	-15%	-28%	2%	-10%	-23%	6%	-6%	-18%

Table 25. Percentage difference in expected monetary values for different Risk Fractions for variation in Failure Cost.
Base Case: 10% Failure Cost Fraction and 10% risk aversion level

This table shows that, as expected, an increase in projected failure cost increased the total expected monetary value due to an increase in the total cost, according to Equation (1) in Chapter III. This could be seen in cases where the risk fractions remained the same in the basecase and the alternative. For instance, for a 50% risk fraction in the basecase and changed scenario, the variation in failure cost fraction from 10% to 30% increased the expected monetary value by 10% of the basecase amount of $13,402,897 [Table 11, Chapter IV] to $14,743,187 [Table 11, Chapter IV]. With a change in the risk fractions along with failure cost, the effect was cumulative. For example, where the failure cost changes from 10% to 30% of the total remediation cost and the risk fraction was 50% before and 90% after, the additional expense on the remediation plan would be

$3,173,720 or 23.7% more than for the basecase scenario amounting to $16,576,617. Since the change in the failure cost fraction resulted in an increase in the expected monetary value, alternate paths of sinking fund deposit were not considered.

Effect of varying two variables

The following section discusses the effects of varying two variables where there is a possibility that an increase in remediation cost due to one variable could be offset by a decrease due to a change in the other variable. Similarly, the effects of two variables could be additive resulting in a net increase in the projected cost.

CASE 5: Variation of Regulatory Levels and Technology Improvement Rate over variations in Risk Aversion Level

The expected monetary values for different regulatory levels and increase in rate of technology improvement were given in Table 12 of Chapter IV for different risk fractions. The percentage differences in expected monetary values when regulatory levels and technology improvement rates changes from 5μg/l to 3μg/l and 0% to 1%, respectively are shown in Table 26. A 5ppb MCL of benzene, 0% technology improvement at a 10% risk aversion level with an expected monetary value of $13,402,897 (Table 12, Chapter IV) was considered as the basecase situation.

Variation in Reg. Levels from 5 to 3ppb and Tech. Imp. Rate from 0 to 1%	Percentage difference in expected monetary values for different risk fractions								
	10%			50%			90%		
	10%	50%	90%	10%	50%	90%	10%	50%	90%
	2%	-3%	-7%	6%	2%	-3%	9%	5%	2%

Table 26. Percentage difference in expected monetary values for different risk fractions for variation in regulatory levels and technology improvement rate.
Base Case: 5μg/l MCL of benzene, 0% technology improvement rate and 10% risk aversion level

The regulatory level change resulted in an increase in the expected monetary value [Case 1] whereas an increase in the technological improvement rate reduced the expected monetary value [Case 2]. When the two variables were varied simultaneously it was found that the effect of technological improvement rates selected dominated the change in the regulatory level for conditions when the risk fraction for the alternative was lesser than for the basecase. This resulted in a net reduction in the amount projected to be needed for remediation. Similarly, the risk aversion level of the decision maker, effected the optima in various manners. At the levels tested, the increase due to very high risk when coupled with the increases due to stringent regulatory level dominated the effects in expected monetary value due to the technology improvement rates. For instance, a change in the risk aversion level from 10% in the basecase, to 90% in the changed scenario increased the expected monetary value by 7% over the basecase value of $13,402,897 to $14,341,080. In such situations the path which includes sinking fund deposits from the time of spill until remediation results in the least increase in expected monetary value.

CASE 6: Variation of Regulatory Levels and Waste Minimization Programs over variations in Risk Aversion Level

The expected monetary values for different regulatory levels and waste minimization programs were given in Table 13 of Chapter IV for different risk fractions. The percentage differences in expected monetary values for change in the regulatory levels and waste minimization from 5µg/l to 3µg/l and 0% to 10% are shown in Table 27. A 5ppb MCL of benzene, 0% waste minimization at a 10% risk aversion level was considered with an expected monetary value of $13,402,897 (Table 13, Chapter IV) as the basecase situation.

Variation in Regulatory Levels from 5 to 3ppb and 0 to 10% WM	Percentage difference in expected monetary values for different risk fractions								
	10%			50%			90%		
	10%	50%	90%	10%	50%	90%	10%	50%	90%
	20%	17%	13%	24%	20%	17%	27%	24%	20%

Table 27. Percentage difference in expected monetary values for different risk fractions for variation in regulatory levels and waste minimization programs.
Base Case: 5μg/l MCL of benzene, 0% waste minimization program and 10% risk aversion level

The change in regulatory levels in waste generation had an effect similar to that of a change in regulatory level and technological improvement rate. That is, the 16% increase observed when regulatory level alone changed (Table 22) was offset completely by the 24% decrease associated with a 10% waste minimization from $13,402,897 to $10,235,537 efforts. The change in both the variables resulted in a combined 20% decrease from $13,402,897 to $10,685,010 when these alternatives were evaluated jointly. In the scenario where the risk fraction was 90% in both analyses, the reduction in the expected monetary value reduced from a basecase cost of $14,556,977 (Table 13, Chapter IV) to $11,623,814 [Table 13], a decrease of about 20% or $2,933,163.

Alternate Path: An alternative path of "no sinking fund" at the 5th year until the 15th year resulted in a decrease in the expected monetary value by $2,306,085 from $13,402,897 in the base case to $11,096,812 in the new case with a 10% risk fraction. The decision maker could also postpone remediation to the 50th year by considering the path of "no sinking fund" from the 5th to the 15th year and again starting sinking fund deposits at the 15th year until the 50th year at a 50% risk fraction. This resulted in the reduction of expected monetary value by $65,265 over the projected basecase costs ($13,402,897). Figure 52, presents a skeletal tree showing the initial and alternate sinking fund deposit paths evaluated in the case. For a change in both the regulatory level and waste minimization, the change in the waste minimization program dominated the change in the regulatory level thereby opening up the possibility of selecting an alternate sinking fund deposit path that is more viable for the decision maker.

CASE 7: Variation of Regulatory Levels and Failure Cost ***over variations in Risk Aversion Level***

The expected monetary values for different regulatory levels and failure cost were given in Table 14 of Chapter IV for different risk fractions. The percentage differences in expected monetary values for change in regulatory levels and failure cost from 5μg/l to 3μg/l and 10% to 30%, respectively are shown in Table 28. A 5ppb MCL of benzene, 10% failure cost fraction at a 10% risk aversion level was considered as the basecase situation.

Variation in Reg. Levels from 5ppb to 3ppb and Failure Cost from 10 to 30%	Percentage difference in expected monetary values for different risk fractions								
	10%			50%			90%		
	10%	50%	90%	10%	50%	90%	10%	50%	90%
	-18%	-33%	-48%	-13%	-28%	-42%	-9%	-23%	-36%

Table 28. Percentage difference in expected monetary values for different risk fractions for variation in regulatory levels and failure cost.
Base Case: 5μg/l MCL of benzene, 10% failure cost fraction and 10% risk aversion level

As expected, an increase in failure cost further increased the expected monetary value when a stricter regulatory level was also initiated. An increase in the expected

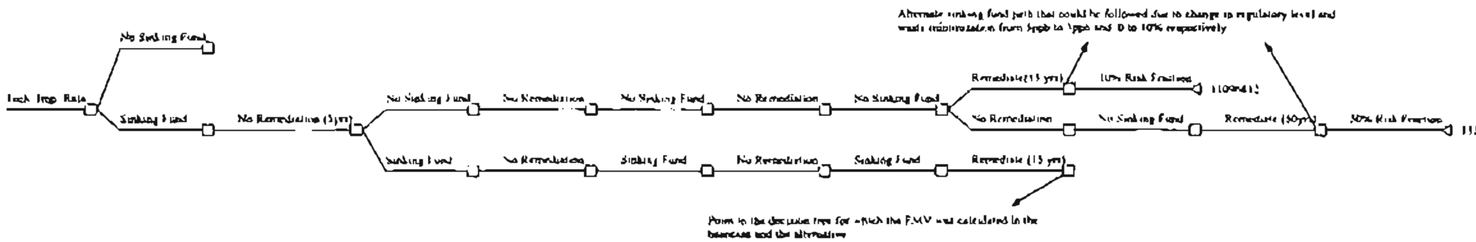


Figure 52. Skeletal tree showing the path followed in determining the expected monetary values for the basecase and the alternatives for a change in the regulatory level and waste minimization from 5ppb to 3ppb and 0% to 10% respectively.

monetary value of about 18% of the basecase cost of $13,402,897 to $15,854,417, for a 10% risk fraction was observed. With an increase in the risk fraction the expected monetary value also increases. For example, when the risk fraction increased to 50% the expected monetary value increases by 33% to $17,837,537. Similar to Case 1 and 5, it would be optimal to follow the path of sinking fund deposit until remediation if both the failure costs and the regulatory levels increased.

CASE 8: Variation of Technology Improvement Rate and Waste Minimization Programs over variations in Risk Aversion Level

The expected monetary values for different increase in technology improvement rates and waste minimization programs were given in Table 15 of Chapter IV for different risk fractions. The percentage differences in expected monetary values for a change in technology improvement rates and waste minimization programs from 0% to 1% and 0% to 10% are shown in Table 29. A 0% technology improvement rate and waste minimization at a 10% risk aversion level was considered as the basecase situation with an expected monetary value of $13,402,897.

Variation in Tech. Improvement Rate from 0 to 1% and WM from 0 to 10%	Percentage difference in expected monetary values for different risk fractions								
	10%			50%			90%		
	10%	50%	90%	10%	50%	90%	10%	50%	90%
	36%	33%	30%	39%	36%	33%	41%	38%	36%

Table 29. Percentage difference in expected monetary values for different risk fractions for variation in technology improvement rate and waste minimization programs.
Base Case: 0% technology improvement rate, 0% waste minimization program and 10% risk aversion level

The variation in technology rate combined with the waste minimization program serves to decrease the projected costs improvement dramatically. The table shows that reductions greater than 35% can be projected for the different risk scenarios. For instance along with a change in the variables, if the risk fraction varied from 50% to 90%, the amount saved by reduction in the projected costs would be from $13,979,937 to $9,351,912 resulting in a gain of $4,628,025 (or 33%) over the basecase condition.

Alternate paths: Under these possible conditions, an alternate path that could be considered was "no sinking fund" from the 5th to the 15th year when remediation was completed. The projected expected monetary value for this path was found to be $9,302,038. This represents a 31% decrease from the base case of 0% technology improvement and waste minimization which had associated cost estimates of $13,402,897. Figure 53 presents a skeletal decision tree showing the alternate paths of sinking fund deposit.

CASE 9: Variation of Technology Improvement Rate and Failure Cost over variations in Risk Aversion Level

The expected monetary values for different technology improvement rates and failure costs were given in Table 16 of Chapter IV for different risk fractions. The percentage differences in expected monetary values for change in technology improvement rates and failure costs from 0% and 10% to 1% and 30%, respectively are shown in Table 30. A situation with 0% technology improvement rate and 10% failure cost at a 10% risk aversion level was considered as the basecase situation.

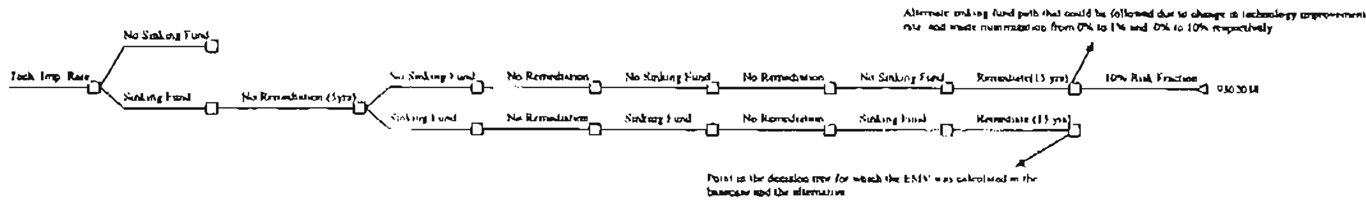


Figure 53. Skeletal tree showing the path followed in determining the expected monetary values for the basecase and the alternatives for a change in the technology improvement rate and waste minimization from 0% to 1% and 0% to 10% respectively.

Variation in Tech. Imp. Rate from 0 to 1% and Failure Cost from 10 to 30%	Percentage difference in expected monetary values for different risk fractions								
	10%			50%			90%		
	10%	50%	90%	10%	50%	90%	10%	50%	90%
	13%	2%	-9%	17%	6%	-4%	20%	10%	-0.3%

Table 30. Percentage difference in expected monetary values for different risk fractions for variation in technology improvement rate and failure cost
Base Case: 0% technology improvement rate, 10% failure cost fraction and 10% risk aversion level

An increase in the technological improvement rate resulted in a decrease in the expected monetary value whereas an increase in the failure cost had the opposite effect. In the combined effect of both the variables, the effect of risk over the levels evaluated played an important role. A very high risk fraction (say 90%) under the alternative increased the expected monetary value which sometimes resulted in an overall increase in the expected monetary value while a lower risk fraction (10%) resulted in a decreased projected cost. For instance, an increase in the risk from 10% to 50%, the expected monetary value decreased by 2% or $291,937 (from $13,402,897 to $13,110,960) while a change in the risk fraction from 10% to 90% increased the expected monetary value to $1,206,275 [Table 16, Chapter IV], about 9% of $13,402,897.

CASE 10: Variation of Waste Minimization Programs and Failure Cost over variations in Risk Aversion Level

The expected monetary values for different waste minimization programs and failure cost were given in Table 17 of Chapter IV for different risk fractions. The percentage differences in expected monetary values for change in waste minimization programs and failure costs from 0% and 10% to 10% and 30%, respectively are shown in

Table 31. A situation with 0% waste minimization program and 10% failure cost fraction with a 10% risk aversion level was considered as the basecase situation with an expected monetary value o $13,402,897.

Variation in WM Program from 0 to 10% and Failure Cost from 10 to 30%	Percentage difference in expected monetary values for different risk fractions								
	10%			50%			90%		
	10%	50%	90%	10%	50%	90%	10%	50%	90%
	22%	12%	2%	25%	16%	6%	28%	19%	9%

Table 31. Percentage difference in expected monetary values for different risk fractions for variation in waste minimization programs and failure cost
Base Case: 0% waste minimization program, 10% failure cost fraction and 10% risk aversion level

In this situation, the increase in failure cost reduces the effect of the waste minimization program, which as shown in Case 3 always leads to a significant reduction in cost. In this example, a 10% waste minimization program was initiated and the failure cost was increased from 10% to 30% of the total cost. Even with the increase in the failure cost, the initiation of waste minimization programs reduced the expected monetary value. If the risk fractions were 50% and 90% in the original and the changed scenario, the expected monetary value reduced by $809,000 (from $13,979,937 to 13,170,937) or about 6% of the basecase.

Alternate Path: An alternate path of "No Sinking Fund" deposit from the 5th year to the 15th year could be followed which resulted in a reduction in the expected monetary value by $2,219,377 from the basecase of $13,402,897 [Table17, Chapter IV] to $11,183,520 [value taken from the decision tree]. Figure 54 presents a skeletal tree showing alternate paths sinking fund paths evaluated for the change in the variables, along with the paths for the basecase and the changed scenario.

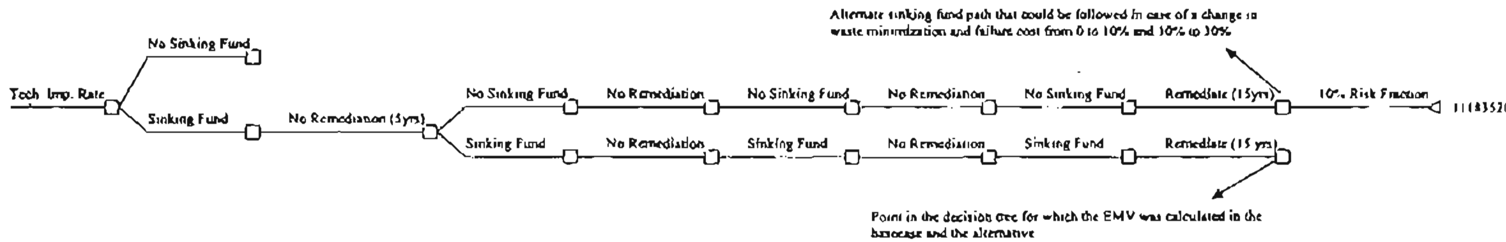


Figure 54. Skeletal tree showing the path followed in determining the expected monetary values for the basecase and the alternatives for a change in the waste minimization and failure cost fraction from 0% to 10% and 10% to 30% respectively.

Effect of Varying Three Variables

The following discussion addresses the complexity in making an optimum decision when three critical variables are varied simultaneously.

<u>*CASE 11: Variation of Regulatory Levels, Technology Improvement Rate, and Waste Minimization Programs over variations in Risk Aversion Level*</u>

The expected monetary values for different regulatory levels, technology improvement rates, and waste minimization programs were given in Table 18 of Chapter IV for different risk fractions. The percentage differences in expected monetary values for changes in the critical variables and different risk fractions are shown in Table 32.

Variation in Regulatory Levels from 5 to 3ppb, 0 to 1% Tech. Improvement, and 0 to 10% WM	Percentage difference in expected monetary values for different risk fractions								
	10%			50%			90%		
	10%	50%	90%	10%	50%	90%	10%	50%	90%
	33%	30%	27%	36%	33%	30%	38%	35%	33%

Table 32. Percentage difference in expected monetary values for different risk fractions for variation in regulatory levels, technology improvement rate, and waste minimization programs.
Base Case: 5μg/l MCL of benzene, 0% technology improvement rate, 0% waste minimization program and 10% risk aversion level

A situation where the variables are 5ppb MCL of benzene, 0% technology improvement rate and waste minimization with a 10% risk aversion level was considered as the basecase situation. In this example, an increase in the technology improvement rate and a greater rate of waste minimization reduced the expected monetary value while a more stringent regulatory level resulted in an opposite effect. For this scenario, a reduction in regulatory level of benzene from 5 to 3ppb resulted in an increase in the expected monetary value by about 16% (from $13,402,897 to $15,523,897), as shown in Case 1. This increase in the expected monetary value was compensated by the increase in the improvement in technology rate and the waste minimization program which then reduced the expected monetary value by an average of 33% from the basecase. When a risk fraction of 50% was used in both alternatives, the reduction in the expected monetary value was $4,565,282, from $13,979,937 to $9,414,655 [Table 18, Chapter IV].

CASE 12: Variation of Regulatory Levels, Technology Improvement Rate, and Failure Cost over variations in Risk Aversion Level

The expected monetary values for different regulatory levels, technology improvement rates, and failure costs were given in Table 19 of Chapter IV for different risk fractions. The percentage differences in expected monetary values for different risk fractions are shown in Table 33. A 5ppb MCL of benzene, 0% technology improvement rate, and 10% failure cost fraction at a 10% risk aversion level with an expected monetary value of $13,402,897 was considered as the basecase situation.

Variation in Reg. Level from 5ppb to 3ppb, 0% to 1% Tech. Imp. Rate, And 10% to 30% Failure Cost	Percentage Difference in expected monetary values for different Risk Fractions								
	10%			50%			90%		
	10%	50%	90%	10%	50%	90%	10%	50%	90%
	-1%	-13%	-26%	4%	-9%	-21%	7%	-4%	-16%

Table 33. Percentage difference in expected monetary values for different Risk Fractions for variation in Regulatory Levels, Technology Improvement Rate, and Failure Cost. Base Case: 5µg/l MCL of benzene, 0% technology improvement rate, 10% failure cost fraction and 10% risk aversion level

In this situation, a change in the regulatory level and the increase in the failure cost increased the remediation cost by 16% and 2%, respectively while an increase in the improvement in technology rate reduced the cost by 15% of the basecase for a risk fraction of 10%. The net result was that at points where the risk fractions were smaller (10% or 50%) than in the basecase (50% or 90%), there was a reduction in the expected monetary value by 4% and 7% of the basecase value of $13,402,897. In situations like these, a change in the sinking fund deposit path from the present condition (where sinking fund deposit was considered from the time of the spill until remediation) would result in a further increase in the expected monetary value.

CASE 13: Variation of Technology Improvement Rate, Waste Minimization Programs, and Failure Cost over variations in Risk Aversion Level

The expected monetary values for different technology improvement rates, waste minimization programs, and failure costs were given in Table 20 of Chapter IV for different risk fractions. The percentage differences in expected monetary values due to changes in the critical values for different risk fractions are shown in Table 34. A technology improvement rate at 0%, 0% waste minimization and 10% failure cost fraction at a 10% risk aversion level with an expected monetary value of $13,402,897 (Table 20, Chapter IV) was considered as the basecase situation.

Variation in Tech. Improvement Rate from 0% to 1%, 0% to 10% WM, and 10% to 30% Failure Cost	Percentage Difference in expected monetary values for different Risk Fractions								
	10%			50%			90%		
	10%	50%	90%	10%	50%	90%	10%	50%	90%
	35%	26%	17%	37%	29%	21%	40%	32%	24%

Table 34. Percentage difference in expected monetary values for different Risk Fractions for variation in Technology Improvement Rate, Waste Minimization Programs, and Failure Cost.
Base Case: 0% technology improvement rate, 0% waste minimization program, 10% failure cost and 10% risk aversion level

The situation described is the opposite of the previous case. Even with an increase in the failure cost from 10% to 30%, the percentage difference in the expected monetary values for the different risk fractions remained positive indicating a reduction in the expected monetary value. The effect of the changes was similar to cases where technology improvement rate and waste minimization were changed simultaneously. Since waste minimization played a dominant role, a change in failure cost did not have a significant impact. As an example situation, if the risk fraction varied from 10% to 90% in the initial and new condition, the expected monetary value decreased by $2,313,857, or 17% from $13,402,897 to $11,089,040 [Table 20, Chapter IV].

Summary of the Effect of Change in Variables

The following section summarizes the effect of the change in the variable values previously presented. Figure 55 is a plot showing the variation of expected monetary value for the different cases considered above. It was assumed that risk aversion level of the decision maker remained constant at 10% in the basecase and the alternative. The basecase again, was a situation with 5ppb MCL of benzene. 0% technology improvement, 0% waste minimization and 10% failure cost fraction. Cases 1 to 13 correspond directly to the material presented in chapters IV and V.

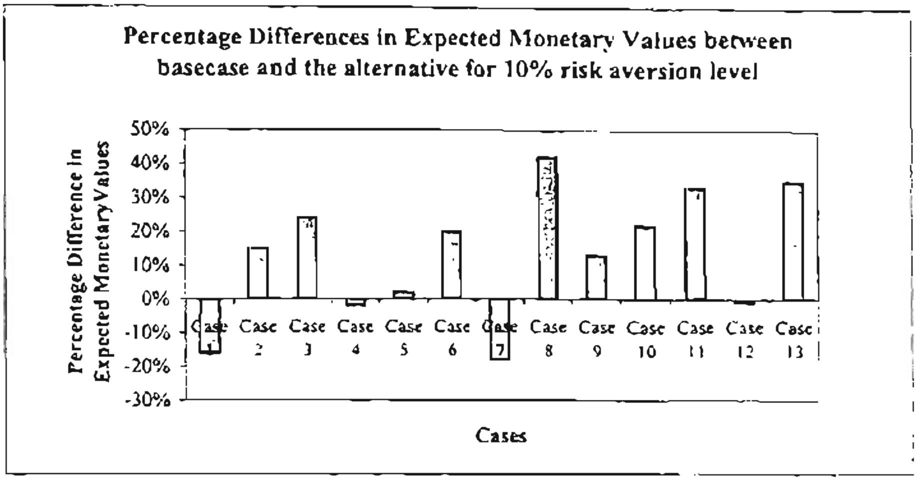


Figure 55. Percentage Difference in expected monetary values between the basecase scenario and for the different cases of variable change at a constant risk fraction of 10%.

Case 1: Change in Regulatory Levels over variations in risk aversion levels

Case 2: Change in Technology Improvement Rates over variations in risk aversion levels

Case 3: Change in Waste Minimization Programs over variations in risk aversion levels

Case 4: Change in Failure Costs over variations in risk aversion levels

Case 5: Change in Regulatory Levels and Technology Improvement Rates over variations in risk aversion levels

Case 6: Change in Regulatory Levels and Waste Minimization Programs over variations in risk aversion levels

Case 7: Change in Regulatory Levels and Failure Costs over variations in risk aversion levels

Case 8: Change in Technology Improvement Rates and Waste Minimization Programs over variations in risk aversion levels

Case 9: Change in Technology Improvement Rates and Failure Costs over variations in risk aversion levels

Case 10: Change in Waste Minimization Programs and Failure Costs over variations in risk aversion levels

Case 11: Change in Regulatory Levels, Technology Improvement Rates and Waste Minimization Programs over variations in risk aversion levels

Case 12: Change in Regulatory Levels, Technology Improvement Rates and Failure Costs over variations in risk aversion levels

Case 13: Change in Technology Improvement Rates, Waste Minimization Programs and Failure Costs over variations in risk aversion levels

The figure shows that an increase in the regulatory level and failure cost (Cases 1 and 4) increases the expected monetary value by 16% and 2%, respectively while an increase in the technology improvement rate and waste minimization (Cases 2 and 3) decreases the expected monetary value by 15% and 24%, respectively. When the regulatory level changes and/or failure cost increases, any deviation from the sinking fund deposit path would result in an increase in expected monetary value. However, a change in the increase in technology improvement rate and the waste minimization program afforded the decision maker an alternative path of making sinking fund deposits or postpone the decision to remediate.

Case 5 shows the combined effect of regulatory level and technology improvement rate. Change in the technology improvement rate reduced the expected monetary value but greater changes in the regulatory level overcame the positive effects of technology improvement rate, thus increasing the overall expected monetary value by 3%. In these situations, consideration of alternate paths of sinking fund deposit depended to a great extent on the regulatory level of benzene. The effects of a stricter regulatory level on the expected monetary value was diminished by the initiation of a waste minimization program (Case 6) and the net result in the expected monetary value was about a 20% decrease. In these situations, the expected monetary value decreased thereby facilitating the decision maker to evaluate more feasible alternate sinking fund deposit path. Case 7 shows the combined effects of regulatory level and failure cost. Since an increase in the individual values of the variables increased the expected monetary value, a combined change in them further increased the expected monetary value ultimately by 18% from ($13,402,897 to $15,854,417). For Case 8, however, in which the waste minimization program and technology improvement rate were varied, the combined effect of a change in the variables resulted in a very large decrease in the expected monetary value by 32%_from $13,402,897 to $8,579,855. In such cases the decision maker can investigate the option of postponing the decision to remediate.

In Case 9, the effect of increases in technology improvement rate far outweighed the effect due to increase in the failure cost. So a change in both the variables reduced the expected monetary value by 13% and facilitated the decision maker to evaluate other feasible alternative sinking fund paths. Similarly, in Case 10 waste minimization programs dominated the effect due to failure cost. Hence the combined effect of these two variables resulted in a reduction in the expected monetary value by 22%.

In case of a change in three variables, there always was a reduction in the expected monetary value for cases where a change in waste minimization program was involved. These are shown in Case 11 and 13 where the expected monetary values are reduced by 33% and 35%, respectively, while Case 12 shows that change in regulatory level, technology improvement rate and failure cost was dominated by increase in the technology improvement rate and increased the expected monetary value by 1% $13,402,897 to $13,484,664.

Figure 56 summarizes the effect of risk on the expected monetary value by showing the variation of the expected monetary value for the different cases considered in the previous section. For the purpose of comparison, a risk fraction of 10% and 90% in the basecase and the new scenarios, respectively, were considered. The effect of risk fraction increased the expected monetary value of the alternative. This effect, in concurrence with changes in other variables, dominated certain cases of variable change (Cases 5, 9, 10 and 12) in such a way that the net expected monetary value resulted in an increase in the changed scenario as compared to the basecase. In Case 5, the change in the risk fraction in conjunction with other variables reduced the expected monetary value by 7% $13,402,897 to $14,336,063.

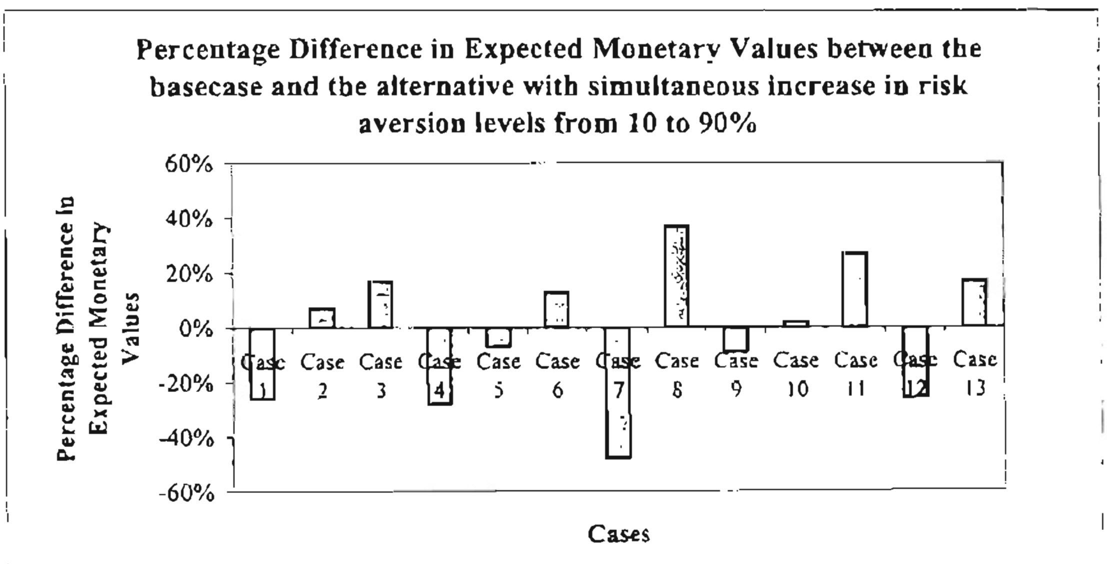


Figure 56. Percentage Difference in expected monetary values between the basecase scenario and for different cases of variable with simultaneous increase in risk averiosn levels from 10% to 90%.

Case 1: Change in Regulatory Levels over variations in risk aversion levels

Case 2: Change in Technology Improvement Rates over variations in risk aversion levels

Case 3: Change in Waste Minimization Programs over variations in risk aversion levels

Case 4: Change in Failure Costs over variations in risk aversion levels

Case 5: Change in Regulatory Levels and Technology Improvement Rates over variations in risk aversion levels

Case 6: Change in Regulatory Levels and Waste Minimization Programs over variations in risk aversion levels

Case 7: Change in Regulatory Levels and Failure Costs over variations in risk aversion levels

Case 8: Change in Technology Improvement Rates and Waste Minimization Programs over variations in risk aversion levels

Case 9: Change in Technology Improvement Rates and Failure Costs over variations in risk aversion levels

Case 10: Change in Waste Minimization Programs and Failure Costs over variations in risk aversion levels

Case 11: Change in Regulatory Levels, Technology Improvement Rates and Waste Minimization Programs over variations in risk aversion levels

Case 12: Change in Regulatory Levels, Technology Improvement Rates and Failure Costs over variations in risk aversion levels

Case 13: Change in Technology Improvement Rates, Waste Minimization Programs and Failure Costs over variations in risk aversion levels

When there was no change in the risk fraction, the change was +1% (Figure 55). Similarly, in Cases 9, 10, 11, and 12 the change in the expected monetary value without change in the risk fraction were 13%, 22%, and -1%, respectively, but due to the increase in risk fraction became -9%, 2%, and -26%, respectively. In the above cases, the variable waste minimization level remained constant. In cases where waste minimization varied, for instance in Cases 3, 6, 11, and 13, though there was a change in the risk fraction from 10% in the basecase to 90% in the alternative, the effect was not critical. The reduction in the expected monetary value was still about 17%, 13%, 27%, and 17%, respectively.

In cases, where the change in other technical variables resulted in an increase in the expected monetary value, the amount associated with the risk fraction coupled and resulted in a very high increase in expected monetary value. This increase could be seen in Cases 1, 4 and 7 where the expected monetary value increases by -26%, -28%, and -48%, respectively from -16%, 2%, and -18% which are the corresponding percentage differences in the expected monetary values for a 10% risk aversion level.

SECTION II: Effect of Sinking Fund on Expected Monetary Value:

The extent to which sinking fund affected the decision alternatives was partially studied by sensitivity analysis. Since the decision tree was analyzed assuming a sinking fund amount of $100,000 per year, it was decided to use a range $50,000 to $500,000 per year for the sensitivity analysis to encompass the original $100,000 figure. The analysis at the 1st year "no sinking fund alternative" (Figure 47, Chapter IV) showed that the optima was to remediate. Similarly, at 1st year "sinking fund" alternative, there was no threshold value for the sinking fund range considered indicating that the optima was not affected by the sinking fund deposit.

When further analysis was done at the 1st year "sinking fund" alternative, by increasing the sinking fund range to $700,000, it was found that a sinking fund threshold of $623,000 per year changed the optima from "remediate" at the 1st year to postponing remediation to the 5th year.

As explained in Chapter IV, the threshold value is that amount of sinking fund beyond which the no remediation alternative was favored. The amount of sinking fund deposit needed to reach the threshold varied depending on the point of analysis in the decision tree, i.e., it depended on the time period for which the deposit was made. From the above paragraph and Table 18 it could be seen that the sinking fund amount needed to reach a threshold at the 1st year of the decision process was about $623,000, while only $469,000 was needed to reach a threshold at the 5th year.

CHAPTER VI

CONCLUSIONS

Summary of Methodology

This study was conducted to provide a decision analysis methodology for a hypothetical refinery manager that was conducive to various situations and at various levels of decision making. A hypothetical oil spill scenario was previously developed by Andrews et al. (1996) for those refineries located in the riparian Arkansas River based on the geohydrologic site characteristics published in Superfund site reports.

A decision tree approach was used in the methodology to identify optimum alternatives under conditions of uncertainty. Uncertainty in regulatory levels, technology improvement rate, waste minimization programs and failure costs was addressed by considering a series of incremental values for each variable. Similarly, the risk aversion level of the decision maker was addressed by considering another set of incremental risk fractions. Sinking fund deposits was considered for different time periods to aid in defining when the decision to remediate should be made.

The objective function, Equation (1) of Chapter III was a cost minimization model that incorporated remediation cost, risk cost, failure cost and benefits. The objective function was used to calculate the cost of each consequence within the decision tree for different risk fractions. The remediation cost used in the objective function was previously estimated by Andrews et al. (1996) using CORA expert system. Risk and failure costs were assumed in terms of fractions of the remediation cost. Benefit was a function of sinking fund, the value of which was assumed arbitrarily. The decision alternative with the least Expected Monetary Value, for a given set of alternatives, was considered the optimum alternative. The effects of the change in the values of the variables used in the tree were categorized into technical and economic variables and their effects studied. The technical variables included regulatory levels, technology improvement rate, waste minimization programs and failure cost and were considered first one at a time, then two and then three together. The economic variable evaluated included benefit cost, i.e., sinking fund deposit.

Summary of Findings

Decision Analysis

Findings from decision analysis include the following:

- Decision analysis provided an optimum environmental management approach for given sets of information under conditions of uncertainty.
- The methodology was flexible to different situations by:
    - ◊ its ability to implement the analytical tool that fit the situation
    - ◊ incorporating an objective function that caters to different risk situations for the decision maker
- Comparison of the Expected Monetary Values in the decision tree indicated that initiation of a sinking fund at a very early stage in the decision process

reduced the Expected Monetary Value. The Expected Monetary Value was reduced to $16,246,080 from $16,257,797 (points 3 and 5 in Table 4, Chapter IV). But the difference in the Expected Monetary Values was only about $11, 717, which is insignificant when compared to the Expected Monetary Value of $16,257,797. So, the time at which sinking fund is initiated was not a significant factor in the reduction of Expected Monetary Values. The effect of the technical and economical variables on the Expected Monetary Values are given below.

Technical Variables

The following findings were made by changing the technical variable first one at a time, then two, and then three variables simultaneously.

- For a risk of 10%, increase in regulatory level and failure cost increased the Expected Monetary Value by 16% and 2%, respectively (Tables 22 and 25, Chapter V). An increase in the technological improvement rate and waste minimization program decreased the Expected Monetary Value by 15% and 24%, respectively with respect to the basecase (Cases 23 and 24, Chapter V).
- Decrease in Expected Monetary Value from the basecase due to change in the variables gave an opportunity for the decision maker to evaluate decisions to postpone remediation.
- A change in technology improvement rate with failure cost or regulatory level decreased the Expected Monetary Value by 2% and 13%, respectively, from the basecase, for a risk level of 10% (Tables 26 and 30, Chapter V). For a high risk aversion level of 90%, for a change in the failure cost and regulatory

level, the Expected Monetary Value increased by 7% and 9% of the basecase (Tables 26 and 30) indicating the high influence of the risk level of the decision maker.

- In situations that involved stringent regulatory levels or increase in failure costs along with initiation of waste minimization program, even at a high risk (90%) the Expected Monetary Value still decreased by 13% and 2% of the basecase (Tables 26 and 31, Chapter V).

Economic Variables

Findings from changing the economical variable include the following:

- Sensitivity analysis on "sinking fund" node at the first year showed that, for the sinking fund range of $50,000 to $500,000, the decision to remediate at the first year would be optimum as compared to postponing remediation to the 5th year (Figure 47, Chapter IV). At the 5th year, for a sinking fund deposit of $469,000 per year, postponing remediation to the 10th year became the optima. Beyond 5th year, sinking fund deposit totally dominated the decision situation in such a way that initiation of sinking fund of any amount always favored postponement of remediation.

REFERENCES

Andrews, C.D., McTernan, W.F., Willett, K.D. (1996). An Evaluation of Select Trade-Offs Between Groundwater Remediation and Waste Minimization for the Petroleum Refining Industry. Journal of Energy Engineering. American Society of Civil Engineers, 122:2:41-60.

Baird, B.F. (1978). Introduction to Decision Analysis. Belmont, California: Wadsworth Publishing.

Decision Analysis by TreeAge (DATA) (1994). Decision analysis software developed by TreeAge Software, Inc. Boston, Massachusetts.

Druzdzel, M. (1997). Internet site of the Decision Analysis and Decision Support Systems, University of Pittsburgh. http://www.pitt.edu/~druzdzel/infsci2130.html.

Freeze, R.A., Massmann, J., Sperling, T., & James, B. (1990). Hydrogeological Decision Analysis: 1. A Framework. Ground Water Journal, 28(5), 738-764.

Jardine, K., Smith, L., Clemo, T. (1996). Monitoring Networks in Fractured Rocks: A decision Analysis Approach. Ground Water, 34(3), 504-518.

Kleindorfer, P.R., Kunreuther, H., Schoemaker, P.J.H. (1993). Decision sciences : an integrative perspective. New York, New York: Cambridge University Press.

Massmann, J., Freeze, R.A., Smith, L., Sperling, T., & James, B. (1991). Hydrogeological Decision Analysis: 2. Applications to groundwater contamination. Ground Water Journal, 29(4), 536-548.

Ossenbruggen, P.J. (1984). Systems Analysis for Civil Engineers. New York, New York: John Wiley and Sons.

Sturk, R., Olsson, L., Johansson, J. (1996). Risk and decision analysis for large underground projects, as applied to the Stockholm ring road tunnels. Tunnelling and Underground Space Technology, 11(2), 157-164.

Wang, T.A. (1995). A Multilevel Decision Analysis Method for Remediation of Contaminated Sites under Conditions of Uncertainty. Master's Thesis. School of Civil and Environmental Engineering. Stillwater, Oklahoma. (unpublished)

White, J.A., Case, K. (1989). Principles of Engineering Economic Analysis. New York, New York: John Wiley and Sons.

APPENDIX A

Codes used in generating

the Expected Monetary Value

for all the alternatives in the decision tree

```
/* This program calculates the Expected Monetary Values for those alternatives where
Sinking Fund was considered throughout and where the Sinking Fund was additionally
considered just before Remediation was planned */
#include <stdio.h>
#include <math.h>

FILE *ofpt,*fp1;
void calculate(float rc,float curper,int year1,int year2);
void cal(int rc,int year1,int year2);
int redeposit(int year);
float power(float x, float y);

main(int argc, char *argv[])

/* The following section of the code reads the input data, which is the remediation cost
determined by Andrews et al., (1996) */

{
     int i,year1,year2,cost1,cost2,cost3,cost4;
     float currentper;
     printf("Enter year1:");
     scanf("%d", &year1);
     printf("Enter year2:");
     scanf("%d", &year2);
     ofpt = fopen("output", "w");
     fp1 = fopen("data50yr.txt", "r");
     for(i=1; i<=9; i++)
     {
          fscanf(fp1,"%d %d %d %d",&cost1,&cost2,&cost3,&cost4);
          cal(cost1, year1, year2);
          cal(cost2, year1, year2);
          cal(cost3, year1, year2);
          cal(cost4, year1, year2);
     }
     fclose(ofpt);
}

float power(float x, float y)
{ float temp=x;
 int i;
 for(i=0;i<y-1;i++)
 temp = temp * x;
 return temp;
}
```

```
void cal(int rc,int year1, int year2)
{
 calculate(rc,0.1,year1,year2);
 calculate(rc,0.5,year1,year2);
 calculate(rc,0.9,year1,year2);
 fprintf(ofpt,"\n");
}

/* This section of the code determines the Amount generated by Sinking Fund for time t1
(in years) */

int redeposit(int year)
{ int temp;
 double rd;
 rd = 100000 * ( power(1.04,year) - 1 ) / 0.04;
 temp = rd;
 return temp;
}

/* The following section calculates and prints the Expected Value of an Alternative by
finding the Total Cost, which includes the Remediation Cost and the Failure Cost, and the
Present Value of the Amount generated by Sinking Fund in the previous section */

void calculate(float rc,float per, int year1,int year2)
{ float tcost1=0,tcost2=0;
 int temp1,temp2,rd1,temp3,temp4,rd2;
 tcost1 = per * .1 * rc;
 tcost1 += rc;
 tcost2 = per * .3 * rc;
 tcost2 += rc;
 temp1 = tcost1;
 temp2 = tcost2;
 rd1 = redeposit(year1);
 temp3 = rd1 + 100000;
 temp4 = rd1/ power(1.04,year2);
 fprintf(ofpt," %d %d \n",temp1-temp4,temp2-temp4);
}
```

```
/* This program calculates the Expected Monetary Values for those alternatives with a
brief period of Sinking Fund deposit and interest till the time of remediation. Sinking
Fund was additionally considered just before Remediation was planned */

#include <stdio.h>
#include <math.h>

FILE *ofpt,*fp1;
void calculate(float rc,float curper,int year1,int year2,int year3);
void cal(int rc,int year1,int year2,int year3);
int redeposit(int year);
float power(float x, float y);

main(int argc, char *argv[])
{
      int i,year1,year2,year3,cost1,cost2,cost3,cost4;
      float currentper;
      printf("Enter year1:");
      scanf("%d", &year1);
      printf("Enter year2:");
      scanf("%d", &year2);
      printf("Enter year3:");
      scanf("%d", &year3);
      ofpt = fopen("output", "w");
      fp1 = fopen("data50yr.txt", "r");
      for(i=1; i<=9; i++)
      {
            fscanf(fp1,"%d %d %d %d",&cost1,&cost2,&cost3,&cost4);
            cal(cost1, year1, year2, year3);
            cal(cost2, year1, year2, year3);
            cal(cost3, year1, year2, year3);
            cal(cost4, year1, year2, year3);
      }
      fclose(ofpt);
}

float power(float x, float y)
{
  float temp=x;
  int i;
  for(i=0;i<y-1;i++)
  temp = temp * x;
  return temp;
}
```

```
void cal(int rc,int year1, int year2, int year3)
{
 calculate(rc,0.1,year1,year2,year3);
 calculate(rc,0.5,year1,year2,year3);
 calculate(rc,0.9,year1,year2,year3);
 fprintf(ofpt,"\n");
}

int redeposit(int year)
{
 int temp;
 double rd;
 rd = 100000 * ( power(1.04,year) - 1 ) / 0.04;
 temp = rd;
 return temp;
}

void calculate(float rc,float per, int year1,int year2,int year3)
{
 float tcost1=0,tcost2=0;
 int temp1,temp2,rd1,temp3,temp4;
 tcost1 = per * .1 * rc;
 tcost1 += rc;
 tcost2 = per * .3 * rc;
 tcost2 += rc;
 temp1 = tcost1;
 temp2 = tcost2;
 rd1 = redeposit(year1);
 temp3 = rd1 * (power(1.04,year2)) + 100000;
 temp4 = temp3 / power(1.04,year3);
 fprintf(ofpt," %d %d \n",temp1-temp4,temp2-temp4);
}
```

```c
/* This program calculates the Expected Monetary Values for the Alternatives with a brief time interval where Sinking Fund was not considered. Sinking Fund was additionally considered just before Remediation was planned */
#include <stdio.h>
#include <math.h>

FILE *ofpt,*fp1;
void calculate(float rc,float curper,int year1,int year2,int year3,int year4, int year5);
void cal(int rc,int year1,int year2,int year3,int year4,int year5);
int redeposit(int year);
float power(float x, float y);

main(int argc, char *argv[])
{
	int i,year1,year2,year3,year4,year5,cost1,cost2,cost3,cost4;
	float currentper;
	printf("Enter year1:");
	scanf("%d", &year1);
	printf("Enter year2:");
	scanf("%d", &year2);
	printf("Enter year3:");
	scanf("%d", &year3);
	printf("Enter year4:");
	scanf("%d", &year4);
	printf("Enter year5:");
	scanf("%d", &year5);
	ofpt = fopen("output", "w");
	fp1 = fopen("data50yr.txt", "r");
	for(i=1; i<=9; i++)
	{
		fscanf(fp1,"%d %d %d %d".&cost1,&cost2,&cost3,&cost4);
		cal(cost1, year1, year2, year3, year4, year5);
		cal(cost2, year1, year2, year3, year4, year5);
		cal(cost3, year1, year2, year3, year4, year5);
		cal(cost4, year1, year2, year3, year4. year5);
	}
	fclose(ofpt);
}

float power(float x, float y)
{ float temp=x;
 int i;
 for(i=0;i<y-1;i++)
 temp = temp * x;
 return temp;
}
```

```
void cal(int rc,int year1, int year2, int year3, int year4, int year5)
{
 calculate(rc,0.1,year1,year2,year3,year4,year5);
 calculate(rc,0.5,year1,year2,year3,year4,year5);
 calculate(rc,0.9,year1,year2,year3,year4,year5);
 fprintf(ofpt,"\n");
}

int redeposit(int year)
{
 int temp;
 double rd;
 rd = 100000 * ( power(1.04,year) - 1 ) / 0.04;
 temp = rd;
 return temp;
}

void calculate(float rc,float per, int year1,int year2,int year3,int year4,int year5)
{
 float tcost1=0,tcost2=0;
 int temp1,temp2,rd1,temp3,temp4,temp5,temp6,rd2;
 tcost1 = per * .1 * rc;
 tcost1 += rc;
 tcost2 = per * .3 * rc;
 tcost2 += rc;
 temp1 = tcost1;
 temp2 = tcost2;
 rd1 = redeposit(year1);
 temp3 = rd1 * (power(1.04,year2));
 rd2 = redeposit(year3);
 temp4 = rd2 * (power(1.04,year4));
 temp5 = temp3 + temp4 + 100000;
 temp6 = temp5 / power(1.04,year5);
fprintf(ofpt," %d %d \n",temp1-temp6,temp2-temp6);
}
```

```
/* This program calculates the Expected Monetary Values for the Alternatives where the
there was a break in the Sinking Fund twice. Sinking Fund was additionally considered
just before Remediation was planned */
#include <stdio.h>
#include <math.h>

FILE *ofpt,*fp1;
void calculate(float rc,float curper,int year1,int year2,int year3,int year4);
void cal(int rc,int year1,int year2,int year3,int year4);
int redeposit(int year);
float power(float x, float y);

main(int argc, char *argv[])
{
    int i,year1,year2,year3,year4,cost1,cost2,cost3,cost4;
    float currentper;
    printf("Enter year1:");
    scanf("%d", &year1);
    printf("Enter year2:");
    scanf("%d", &year2);
    printf("Enter year3:");
    scanf("%d", &year3);
    printf("Enter year4:");
    scanf("%d", &year4);
    ofpt = fopen("output", "w");
    fp1 = fopen("data50yr.txt", "r");
    for(i=1; i<=9; i++)
    {
        fscanf(fp1,"%d %d %d %d",&cost1,&cost2,&cost3,&cost4);
        cal(cost1, year1, year2, year3, year4);
        cal(cost2, year1, year2, year3, year4);
        cal(cost3, year1, year2, year3, year4);
        cal(cost4, year1, year2, year3, year4);
    }
    fclose(ofpt);
}

float power(float x, float y)
{
 float temp=x;
 int i;
 for(i=0;i<y-1;i++)
 temp = temp * x;
 return temp;
}
```

```
void cal(int rc,int year1, int year2, int year3, int year4)
{
 calculate(rc,0.1,year1,year2,year3,year4);
 calculate(rc,0.5,year1,year2,year3,year4);
 calculate(rc,0.9,year1,year2,year3,year4);
 fprintf(ofpt,"\n");
}

int redeposit(int year)
{ int temp;
 double rd;
 rd = 100000 * ( power(1.04,year) - 1 ) / 0.04;
 temp = rd;
 return temp;
}

void calculate(float rc,float per, int year1,int year2,int year3,int year4)
{ float tcost1=0,tcost2=0;
 int temp1,temp2,rd1,temp3,temp4,temp5,temp6,rd2;
 tcost1 = per * .1 * rc;
 tcost1 += rc;
 tcost2 = per * .3 * rc;
 tcost2 += rc;
 temp1 = tcost1;
 temp2 = tcost2;
 rd1 = redeposit(year1);
 temp3 = rd1 * (power(1.04,year2));
 rd2 = redeposit(year3);
 temp4 = temp3 + rd2 + 100000;
 temp5 = temp4 / power(1.04,year4);
 fprintf(ofpt," %d %d \n",temp1-temp5,temp2-temp5);
}
```

```
/* This program calculates the Expected Monetary Values for those alternatives with a
brief period of Sinking Fund deposit and interest until the time of remediation*/

#include <stdio.h>
#include <math.h>

FILE  *ofpt,*fp1;
void calculate(float rc,float curper,int year1,int year2,int year3);
void cal(int rc,int year1,int year2,int year3);
int redeposit(int year);
float power(float x, float y);

main(int argc, char *argv[])
{
      int i,year1,year2,year3,cost1,cost2,cost3,cost4;
      float currentper;
      printf("Enter year1:");
      scanf("%d", &year1);
      printf("Enter year2:");
      scanf("%d", &year2);
      printf("Enter year3:");
      scanf("%d", &year3);
      ofpt = fopen("output", "w");
      fp1 = fopen("data50yr.txt", "r");
      for(i=1; i<=9; i++)
      {
            fscanf(fp1,"%d %d %d %d",&cost1,&cost2,&cost3,&cost4);
            cal(cost1, year1, year2, year3);
            cal(cost2, year1, year2, year3);
            cal(cost3, year1, year2, year3);
            cal(cost4, year1, year2, year3);
      }
      fclose(ofpt);
}

float power(float x, float y)
{ float temp=x;
 int i;
 for(i=0;i<y-1;i++)
 temp = temp * x;
 return temp;
}

void cal(int rc,int year1, int year2, int year3)
{
 calculate(rc,0.1,year1,year2,year3);
```

```
 calculate(rc,0.5,year1,year2,year3);
 calculate(rc,0.9,year1,year2,year3);
 fprintf(ofpt,"\n");
}

int redeposit(int year)
{ int temp;
 double rd;
 rd = 100000 * ( power(1.04,year) - 1 ) / 0.04;
 temp = rd;
 return temp;
}

void calculate(float rc,float per, int year1,int year2,int year3)
{
 float tcost1=0,tcost2=0;
 int temp1,temp2,rd1,temp3,temp4;
 tcost1 = per * .1 * rc;
 tcost1 += rc;
 tcost2 = per * .3 * rc;
 tcost2 += rc;
 temp1 = tcost1;
 temp2 = tcost2;
 rd1 = redeposit(year1);
 temp3 = rd1 * (power(1.04,year2));
 temp4 = temp3 / power(1.04,year3);
 fprintf(ofpt," %d %d \n",temp1-temp4,temp2-temp4);
}
```

```
/* This program generates the decision tree in the form of an outline (text format of the
tree) which could be converted into a tree using options in DATA */
#include<stdio.h>

int stack[10];
int topStack=-1;
int maxStack=10;
int toPop=15;
FILE *fp;
int toggle[4];
int totalTabs[11];

void initTabs() {
	totalTabs[0]=0;
	totalTabs[1]=2;
	totalTabs[2]=4;
	totalTabs[3]=6;
	totalTabs[10]=8;
}

void initToggle() {
	int i;
	toggle[0]=0;
	for(i=1;i<4;i++)
		toggle[i] = 1;
}

void switchToggle(int value) {
	int temp;

	temp=value/5;
	if(toggle[temp] == 1)
		toggle[temp] = 0;
	else
		toggle[temp] = 1;
}

void printTabs(int count) {
	int i,temp;

	temp = totalTabs[count/5];
	for(i=1;i<temp;i++)
		printf("\t");
}
```

```
void printdataNoRe(int temp,int count) {
	char newValue[100];

	printTabs(temp);
	printf("\tNo Sinking Fund [n d]\n");
	printTabs(temp);
	printf("\t\tRemediate (%d yr) [n d]\n",temp);
	printTabs(temp);
	printf("\t\t\t10%% risk [n d]\n");
	printTabs(temp);
	fscanf(fp,"%s",newValue);
	printf("\t\t\t\t10%%Failure Cost Fraction [n t] [p %s]\n",newValue);
	printTabs(temp);
	fscanf(fp,"%s",newValue);
	printf("\t\t\t\t10%%Failure Cost Fraction [n t] [p %s]\n",newValue);
	printTabs(temp);
	printf("\t\t\t50%% risk [n d]\n");
	printTabs(temp);
	fscanf(fp,"%s",newValue);
	printf("\t\t\t\t10%%Failure Cost Fraction [n t] [p %s]\n",newValue);
	printTabs(temp);
	fscanf(fp,"%s",newValue);
	printf("\t\t\t\t10%%Failure Cost Fraction [n t] [p %s]\n",newValue);
	printTabs(temp);
	printf("\t\t\t90%% risk [n d]\n");
	printTabs(temp);
	fscanf(fp,"%s",newValue);
	printf("\t\t\t\t10%%Failure Cost Fraction [n t] [p %s]\n",newValue);
	printTabs(temp);
	fscanf(fp,"%s",newValue);
	printf("\t\t\t\t10%%Failure Cost Fraction [n t] [p %s]\n",newValue);
}

void printdata(int temp,int count,int toggle) {
	char newValue[100];

	printTabs(temp);
	if(toggle != 0) {
		printf("\tNo Remediation (%d yr)[n d]\n",temp);
		printTabs(temp);
		printf("\t\tNo Sinking Fund [n d]\n");
	}
	else
```

```
		printf("\t\tSinking Fund [n d]\n");
		printTabs(temp);
		printf("\t\t\tRemediate (%d yr) [n d]\n",temp);
		printTabs(temp);
		printf("\t\t\t\t10%% risk [n d]\n");
		printTabs(temp);
		fscanf(fp,"%s",newValue);
		printf("\t\t\t\t\t10%%Failure Cost Fraction [n t] [p %s]\n",newValue);
		printTabs(temp);
		fscanf(fp,"%s",newValue);
		printf("\t\t\t\t\t30%%Failure Cost Fraction [n t] [p %s]\n",newValue);
		printTabs(temp);
		printf("\t\t\t\t50%% risk [n d]\n");
		printTabs(temp);
		fscanf(fp,"%s",newValue);
		printf("\t\t\t\t\t10%%Failure Cost Fraction [n t] [p %s]\n",newValue);
		printTabs(temp);
		fscanf(fp,"%s",newValue);
		printf("\t\t\t\t\t30%%Failure Cost Fraction [n t] [p %s]\n",newValue);
		printTabs(temp);
		printf("\t\t\t\t90%% risk [n d]\n");
		printTabs(temp);
		fscanf(fp,"%s",newValue);
		printf("\t\t\t\t\t10%%Failure Cost Fraction [n t] [p %s]\n",newValue);
		printTabs(temp);
		fscanf(fp,"%s",newValue);
		printf("\t\t\t\t\t30%%Failure Cost Fraction [n t] [p %s]\n",newValue);
}

void push(int new) {
		if(topStack == maxStack) {
				printf("Stack Full\n");
				exit(-1);
		}
		topStack++;
		stack[topStack]=new;
}

int pop() {
		int temp;

		if(topStack == -1) {
				exit(-1);
		}
		temp = stack[topStack];
		topStack--;
```

```
        return temp;
}

void printResult(int newElement) {
        int temp;

        if(newElement <= 15) {
                push(newElement);
                if(newElement == 0) {
                        printdataNoRe(1,topStack);
                        switchToggle(newElement);
                }
                else {
                        printdata(newElement,topStack,toggle[newElement/5]);
                        switchToggle(newElement);
                }
                printResult(newElement+5);
        }
        else {
                printdata(50,topStack+1,1);
                printdata(50,topStack+1,0);
                do {
                        temp = pop();
                        if(temp == 15) {
                                printdata(temp,topStack,toggle[temp/5]);
                                switchToggle(temp);
                                printdata(50,topStack+2,1);
                                printdata(50,topStack+2,0);
                        }
                } while(temp >= toPop);
                toPop -= 5;
                if(temp == 0)
                        return;
                printResult(temp);
        }
}
```

```
void main() {
        initToggle();
        initTabs();
        fp = fopen("untitled.txt","r");
        printTabs(topStack);
        printf("Base Case [n d]\n");
        printResult(0);
        push(0);
        push(0);
        printResult(10);
        fclose(fp);
}
```

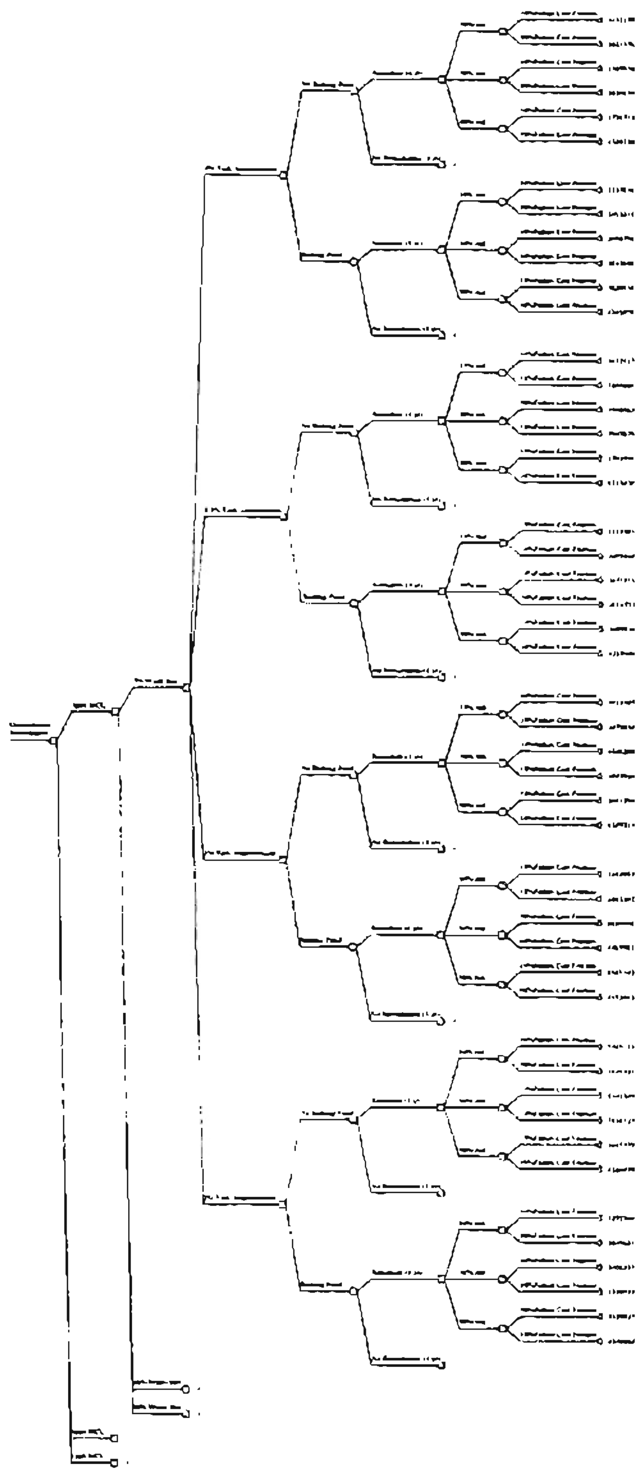


Figure B-1-1. Decision tree showing expected monetary values for a one year time period following the nodes 5ppb MCL of Benzene, and 0% Waste Minimization

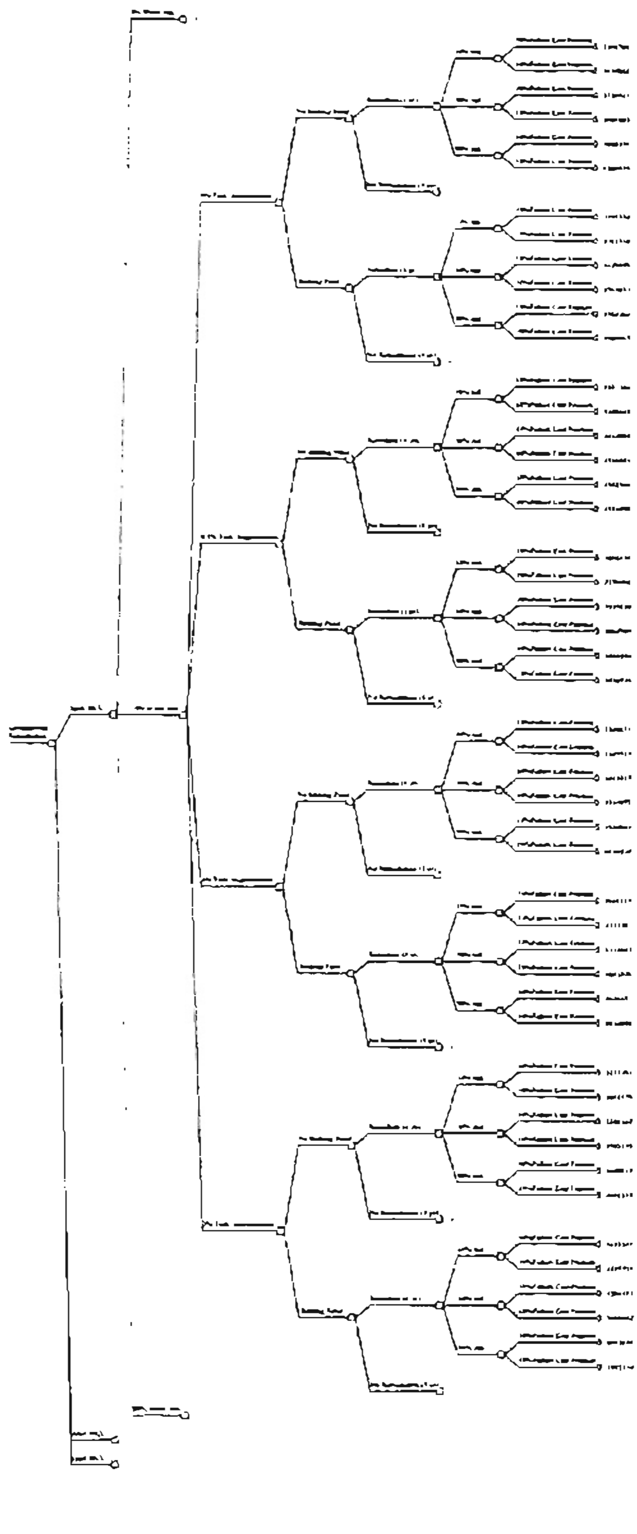


Figure B-1-2. Decision tree showing expected monetary values for a one year time period following the nodes 5ppb MCL of Benzene, and 10% Waste Minimization

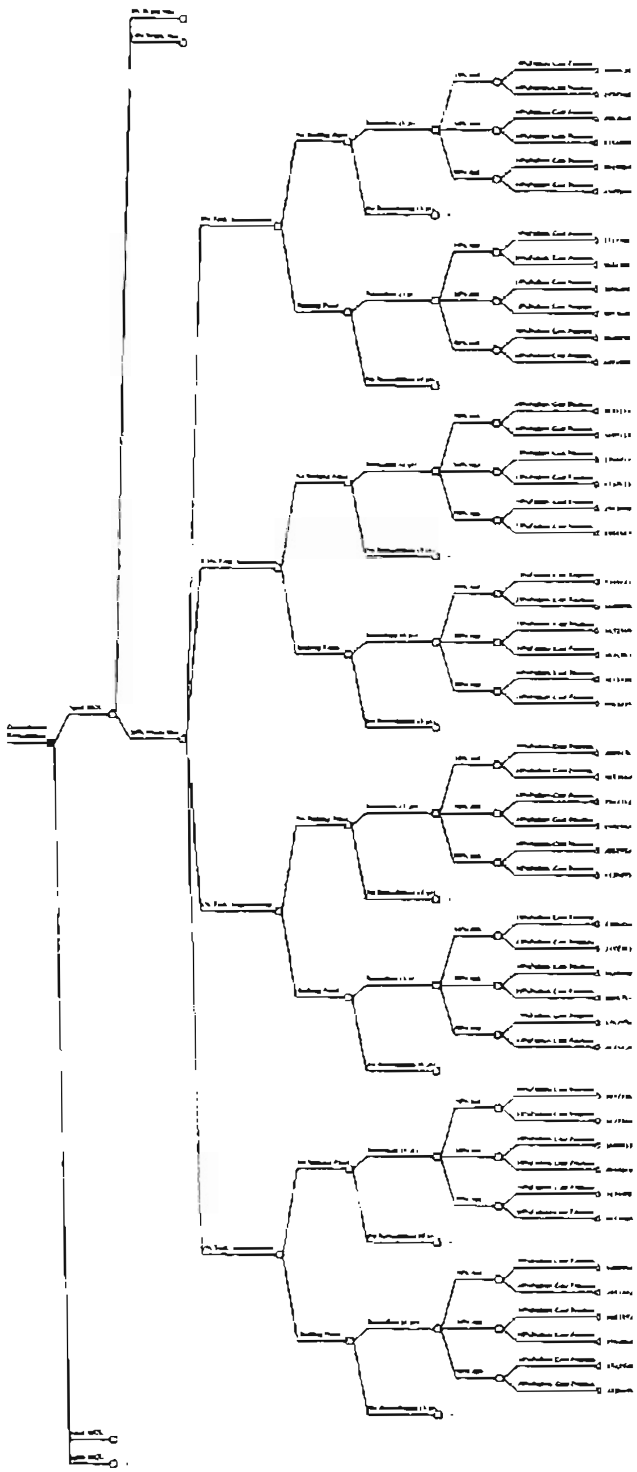


Figure B-1-3. Decision tree showing expected monetary values for a one year time period following the nodes 5ppb MCL of Benzene, and 20% Waste Minimization

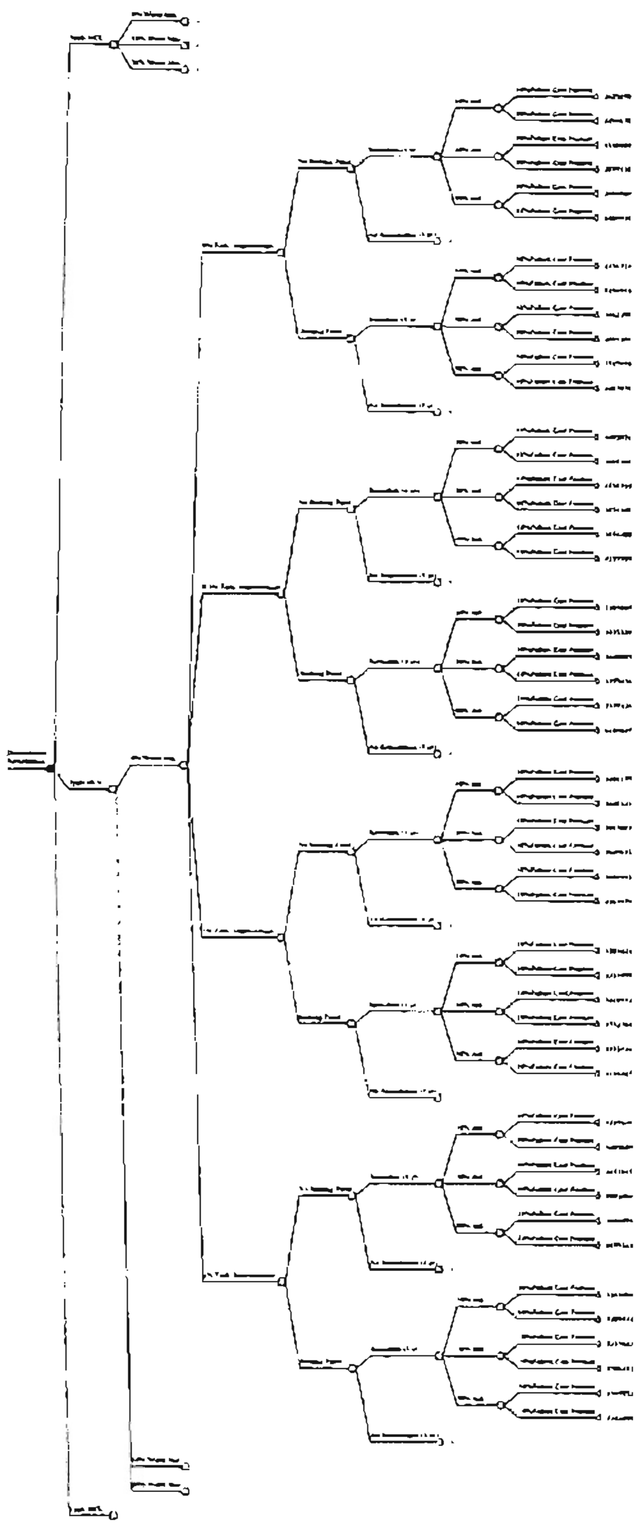


Figure B-1-4. Decision tree showing expected monetary values for a one year time period following the nodes 3ppb MCL of Benzene, and 0% Waste Minimization

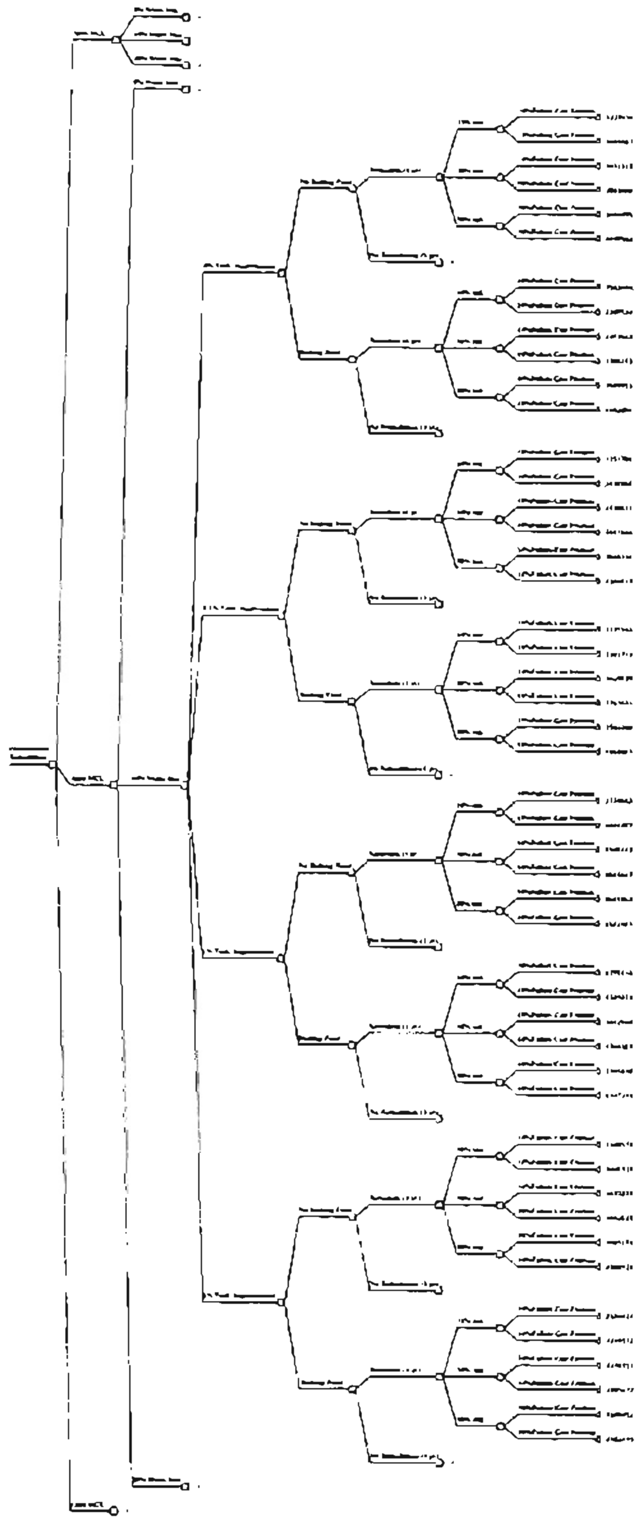


Figure B-1-5. Decision tree showing expected monetary values for a one year time period following the nodes 3ppb MCL of Benzene, and 10% Waste Minimization

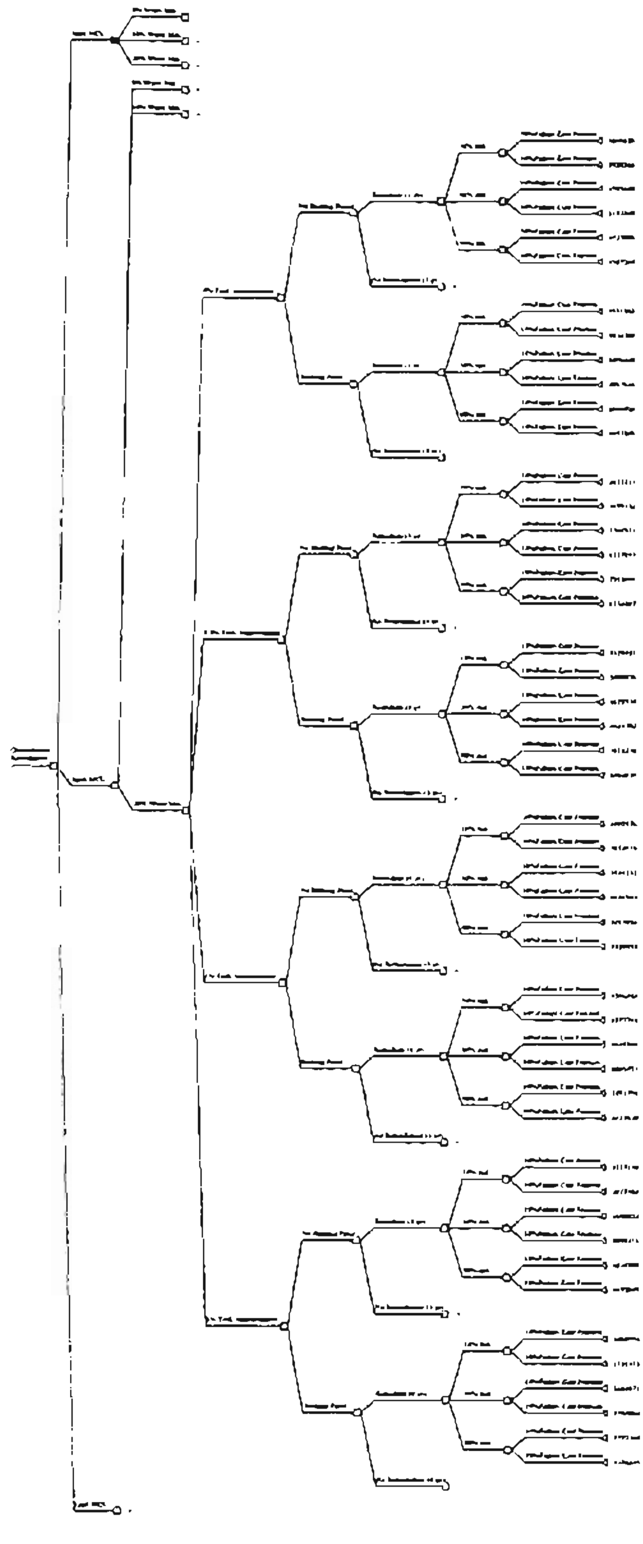


Figure B-1-6. Decision tree showing expected monetary values for a one year time period following the nodes 3ppb MCL of Benzene, and 20% Waste Minimization

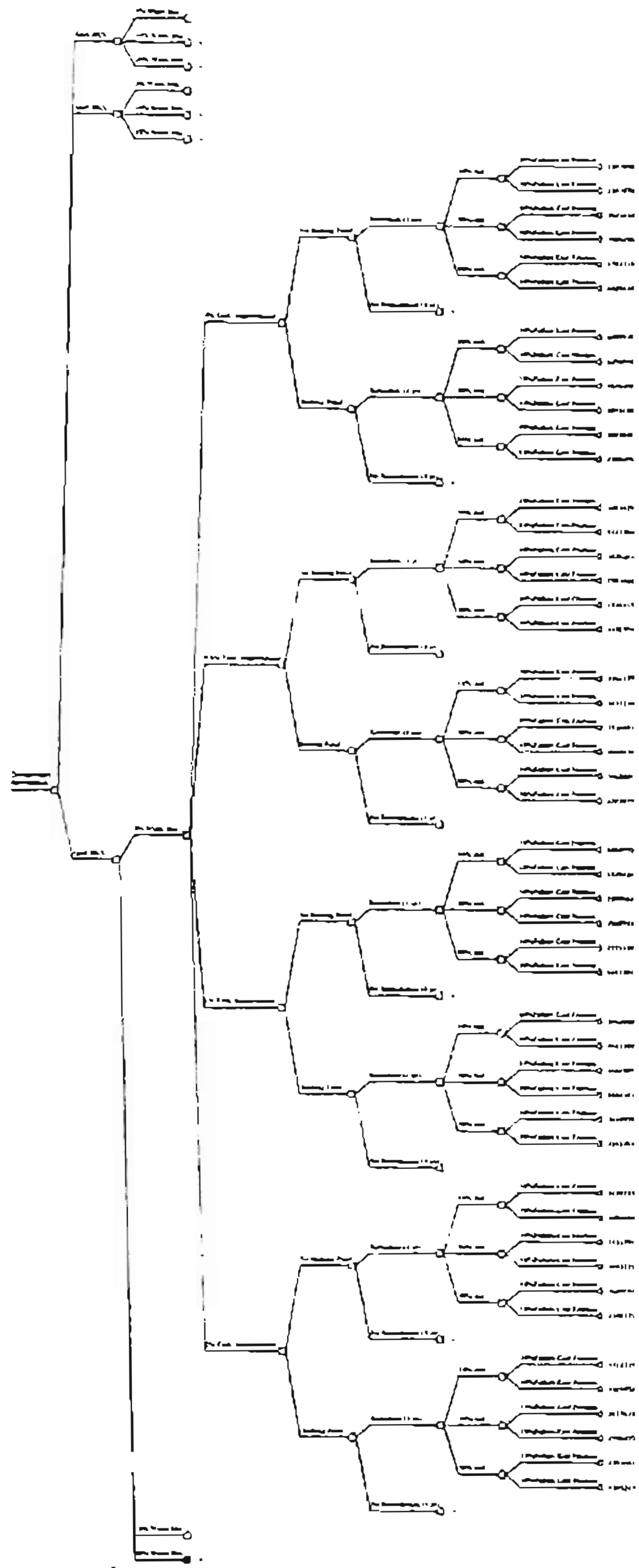


Figure B-1-7. Decision tree showing expected monetary values for a one year time period following the nodes 1ppb MCL of Benzene, and 0% Waste Minimization

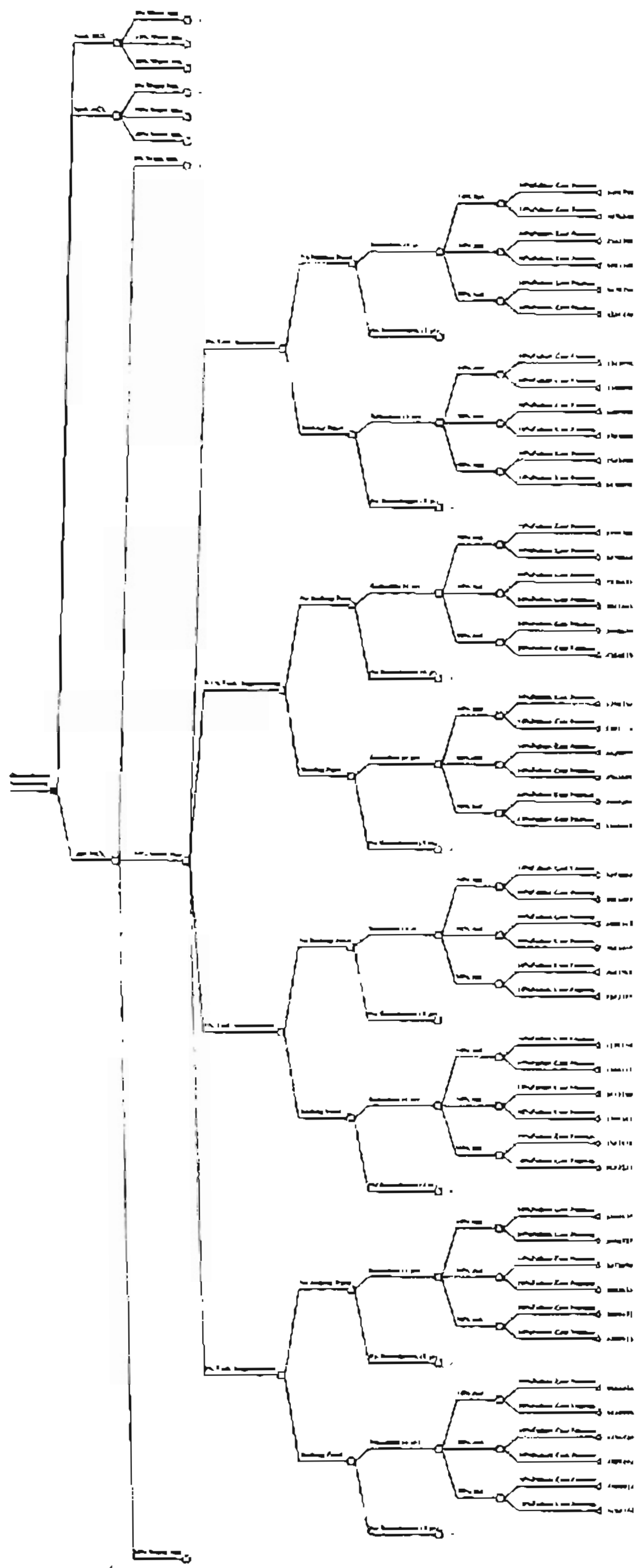


Figure B-1-8. Decision tree showing expected monetary values for a one year time period following the nodes 1ppb MCL of Benzene, and 10% Waste Minimization

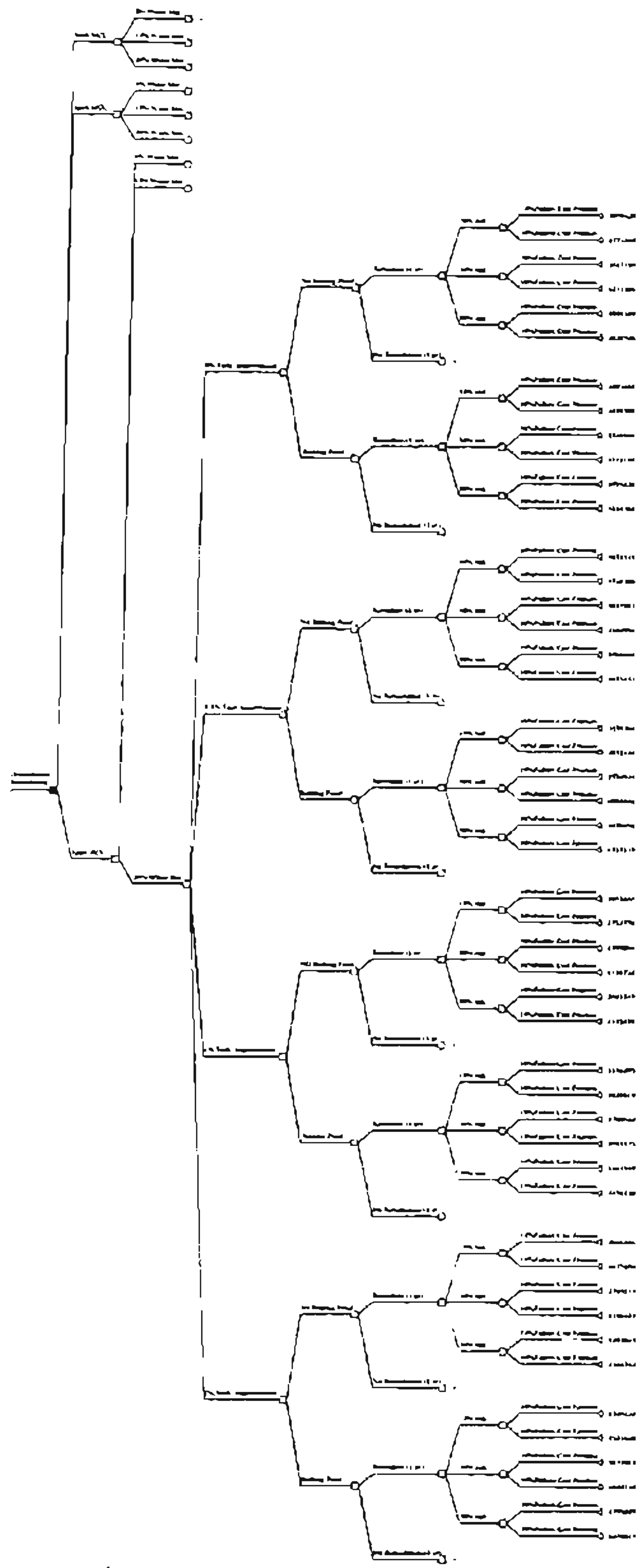


Figure B-1-9. Decision tree showing expected monetary values for a one year time period following the nodes 1ppb MCL of Benzene, and 20% Waste Minimization

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VITA

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