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PREDICTED COSTS OF ENVIRONMENTAL CONTROLS FOR A
COMMERCIAL OIL SHALE INDUSTRY

Volume 2 — A Subjective Self-Assessment of Uncertainty in the
Predicted Costs

MASTER

By
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July 1979

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Charles H. Prien Center for Oil Shale Research
Denver Research Institute
Denver, Colorado

U. S. DEPARTMENT OF ENERGY

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CONTENTS

	<u>Page</u>
ACKNOWLEDGMENT	ii
FIGURES	vi
TABLES	viii
1.0 EXECUTIVE SUMMARY	1
1.1 OBJECTIVE	1
1.2 METHODOLOGY AND STRUCTURE	1
1.3 RESULTS AND DISCUSSION	2
2.0 DESCRIPTION OF SUBJECTIVE PROBABILITY ASSESSMENT	5
2.1 USE OF PROBABILITIES	6
2.2 INTERPRETING SUBJECTIVE PROBABILITIES	6
2.3 ASSESSING SUBJECTIVE PROBABILITY DISTRIBUTIONS	8
2.3.1 A Simple Example of Probability Encoding	8
2.3.2 An Actual Assessment	11
2.4 THE BENEFITS OF SUBJECTIVE PROBABILITY ASSESSMENT	13
3.0 METHODOLOGY AND STRUCTURE	14
3.1 INTRODUCTION	14
3.2 STRUCTURING THE PROBLEM	15
3.2.1 Defining the Critical Variables	16
3.2.2 Disaggregating the Problem	19
3.2.3 Defining Each Assessment--Sensitivity Analysis	22
3.2.4 Final Selection of Assessments	26
3.3 BIASES	27
3.3.1 Anchoring Bias	28
3.3.2 Availability Bias	28
3.3.3 Unstated Assumptions Bias	29
3.3.4 Coherence Bias	29

	<u>Page</u>
3.4 THE MECHANISM OF AN ASSESSMENT	30
3.4.1 The Overall Basic Assumptions	30
3.4.2 Determining the Results of an Assessment	31
3.4.3 Combining Probability Distributions--	
3.5 PROBLEMS OUTSIDE THE METHODOLOGY	38
3.5.1 Expressing Values Without Uncertainty	38
3.5.2 Expressing Unassessed Uncertainty	39
3.5.3 Managing Probabilistic Dependency	39
3.5.4 Uncertainty in Costing	40
4.0 ASSESSMENT RESULTS AND DISCUSSION	41
4.1 ASSESSMENTS PERFORMED	41
4.2 RESULTS OF ANALYSES	41
4.2.1 Ammonia Absorber	41
4.2.2 Stretford Process--H ₂ S	47
4.2.3 Stretford Process--Other Critical Variables	52
4.2.4 Phosam Ammonia Recovery	55
4.2.5 Organic Removal	61
4.2.6 Spent Shale Disposal	67
4.2.7 Slurry Backfilling	73
4.3 AREAS NOT ASSESSED	76
4.3.1 Impact of "Critical Variables Without Experts"	76
4.3.2 Discussion of Areas Not Assessed	81
5.0 SUMMARY AND CONCLUSIONS	82
5.1 UNCERTAINTY IN TOTAL COST	82
5.1.1 Subjective Probability Distributions on Total Cost	82
5.1.2 Total Impact of Unassessed Uncertainty	95
5.2 CONCLUSIONS ON THE COMPLETENESS OF THE UNCERTAINTY ANALYSIS	95
5.3 USE OF THE ASSESSMENT PROCESS TO PINPOINT NEEDED RESEARCH	98
REFERENCES	100

FIGURES

	<u>Page</u>
2-1 Graph of Cumulative Subjective Probability Distribution; mpg of U.S. Autos	10
2-2 Subjective Probability Distribution; mpg of U.S. Autos	10
3-1 Project Division of Expertise	21
3-2 Inventory of TOSCO II Environmental Control Cost Centers	23
3-3 Cumulative Probability Distribution for the Quantity of X	32
3-4 Cumulative Probability Distribution for X	33
3-5 Subjective Probability Distribution for X	33
3-6 Discrete Subjective Probability Distribution Over Cost for Controlling X	35
3-7 Discrete Subjective Probability Distribution Over Cost for Two Separate Assessments	36
4-1 Areas of Significant Uncertainty	42
4-2 Areas Not Analyzed	43
4-3 Assessment Results for Ammonia Absorption, Paraho Process	45
4-4 Assessment Results for Ammonia Absorption, MIS and MIS/Lurgi Processes	46
4-5 Assessment Results for the Stretford Process, Paraho Process	48
4-6 Assessment Results for the Stretford Process, TOSCO II Process	49
4-7 Assessment Results for the Stretford Process, MIS Process	50
4-8 Assessments for NO _x and Mercaptans, Paraho Process	54
4-9 Assessments for NO _x and COS, MIS Process	56
4-10 Assessment Results for the Phosam Unit, Paraho Process	57
4-11 Assessment Results for the Phosam Unit, TOSCO II Process	58

	<u>Page</u>
4-12 Assessment Results for the Phosam Unit, MIS and MIS/Lurgi Processes	59
4-13 Assessment Results for Organic Removal, BOD Loading, All Processes	62
4-14 Assessment Results for Organic Removal, Paraho Process	63
4-15 Assessment Results for Organic Removal, TOSCO II Process	64
4-16 Assessment Results for Organic Removal, MIS and MIS/Lurgi Processes	65
4-17 Assessment Results for the Pollution Control Cost of Spent Shale Disposal, Paraho Process	68
4-18 Assessment Results for the Pollution Control Cost of Spent Shale Disposal, TOSCO II Process	69
4-19 Assessment Results for the Pollution Control Cost of Spent Shale Disposal, MIS Process	70
4-20 Assessment Results for the Pollution Control Cost of Spent Shale Disposal, MIS/Lurgi Process	71
4-21 Assessment Results for the Capital Cost of Slurry Backfilling Spent MIS Retorts, MIS/Lurgi Process . . .	74
4-22 Assessment Results for the Operating Cost of Slurry Backfilling Spent MIS Retorts, MIS/Lurgi Process . . .	75
5-1 Subjective Probability Distributions for Total Pollution Control Cost for Paraho Process	91
5-2 Subjective Probability Distributions for Total Pollution Control Cost for TOSCO II Process	92
5-3 Subjective Probability Distributions for Total Pollution Control Cost for MIS Process	93
5-4 Subjective Probability Distributions for Total Pollution Control Cost for MIS/Lurgi Process	94

TABLES

	<u>Page</u>
1-1 Summary of Subjective Probability Distributions for Total Cost of Pollution Control for Oil Shale by Process and Regulatory Scenario	4
2-1 Example of Cumulative Subjective Probability Distribution, Auto Mileage in U.S.	9
3-1 Assessment Results for the Quantity of X	32
3-2 Change in Cost of Control for Values of X	34
4-1 Biokinetic Constants for Three Wastewaters	77
4-2 Aeration Basin Relative Volume Under Various Conditions	77
4-3 Summary Statistics on Upper Aquifer Water Quality, Tract C-a, Piceance Creek Basin, Comparison to Volume I Study Values for Boron, Fluoride, Ammonia, and Phenol.	80
5-1 Subjective Probability vs. Total Cost for Pollution Control, Paraho Process, Less Strict Scenario	83
5-2 Subjective Probability vs. Total Cost for Pollution Control, Paraho Process, More Strict Scenario	84
5-3 Subjective Probability vs. Total Cost for Pollution Control, TOSCO II Process, Less Strict Scenario	85
5-4 Subjective Probability vs. Total Cost for Pollution Control, TOSCO II Process, More Strict Scenario	86
5-5 Subjective Probability vs. Total Cost for Pollution Control, MIS Process, Less Strict Scenario	87
5-6 Subjective Probability vs. Total Cost for Pollution Control, MIS Process, More Strict Scenario	88
5-7 Subjective Probability vs. Total Cost for Pollution Control, MIS/Lurgi Process, Less Strict Scenario	89
5-8 Subjective Probability vs. Total Cost for Pollution Control, MIS/Lurgi Process, More Strict Scenario	90

	<u>Page</u>
5-9 Cost Impact of Unassessed Uncertainty in Cents per Barrel Syncrude Equivalent	96
5-10 Comparison of Cost Impact of Uncertainty for Cost Centers Assessed, Change in Cost per Barrel Syncrude Equivalent, High, Low, and Range	99

1.0 EXECUTIVE SUMMARY

1.1 OBJECTIVE

All the environmental questions associated with oil shale production will never be answered fully until a commercial industry is actually in operation. Long before this time, however, many important decisions must be made by both government and industry to insure that the oil shale resources are developed in an environmentally acceptable manner. Volume I uses an engineering approach to carefully examine the environmental control technology requirements for a commercial oil shale industry. The optimal pollution control strategies, the appropriate control technologies, and the costs of environmental controls are predicted using currently available data. These data inevitably contain some significant uncertainties.

The most important accomplishment of Volume I is the creation of a large data base on oil shale pollution control which can be used as input to decision making. Volume II identifies and quantifies the uncertainties in Volume I without extensive additional engineering effort.

1.2 METHODOLOGY AND STRUCTURE

The uncertainties in Volume I were quantified using an established methodology for subjective probability encoding.[1,2] The critical variable affecting the cost and performance of pollution control equipment was identified to be the composition of the input stream to the equipment. Given an accurate description of the composition of the input stream to any piece of pollution control equipment which uses well developed technology, the design, emission levels, and cost may be specified with accuracy. Knowledge of the composition of the input stream, however, is incomplete at this time. Because

the participants in the work presented in Volume I have recently studied the problems extensively, they can be considered to be expert at the uncertainties.

The methodology used requires judgments on uncertainty without additional engineering efforts and therefore is a process of quantifying opinion. Judgments as to the range and distribution of values for critical variables (usually key potential pollutant concentrations) are derived for each variable. Subjective probability distributions over the possible range of values for each variable are generated. Pollution control costs are then calculated directly for representative values of each variable, and subjective probabilities assigned to each cost. The same level of pollution control is required for each value of the variable.

All subjective probability distributions over cost are combined to produce an overall probability distribution for total cost of pollution control for each oil shale process in Volume I. In performing all calculations, the rules of probability are strictly followed.

Each critical variable identified is carefully examined for uncertainty and potential cost impact. Those variables judged to contain more than trivial uncertainty and potential cost impact were assessed. Pollution control costs were determined by scaling the designs presented in Volume I. All participants in the engineering effort were involved in the assessment and analysis process, and the final results represent their collective opinion.

1.3 RESULTS AND DISCUSSION

Substantial uncertainty was found in several critical variables, allowing a broad range of possible values. Calculations of the cost impact associated with such broad ranges, however, did not always result in significant differences. Seven major areas of pollution control activity were judged to warrant the assessment effort. Three of these areas were found to contain significant uncertainty and additional research is suggested. These areas are:

- o H₂S removal from the retort gas stream (Stretford process)

- o Organic removal from process wastewaters (Bio-oxidation or other alternatives)
- o Slurry backfilling of spent Modified In Situ (MIS) retorts.

The overall results of the assessment and analysis process are summarized in Table 1-1 in terms of total cost for pollution control. The distributions have been divided into three ranges in this table. A center range is given which contains 80% to 90% probability, and the costs outside this range with probabilities are given. The full distributions can be found in Section 5.0. The subjective probability distributions are a quantification of opinion. The probability of encountering costs below the low figure or above the high figure for each process and scenario is judged to be nearly zero.

**Table 1-1. Summary of Subjective Probability Distributions
For Total Cost of Pollution Control for Oil Shale
By Process and Regulatory Scenario**

<u>Oil Shale Process and Regulatory Scenario</u>	<u>Range of Total Cost per Barrel Syncrude Equivalent (Dollars)</u>	<u>Approximate* Subjective Probability (Percent)</u>
Paraho		
Less strict	0.67 - 0.76	14%
	0.76 - 0.95	80%
	0.95 - 0.99	4%
More strict	0.66 - 0.78	15%
	0.78 - 0.97	81%
	0.97 - 1.01	2%
TOSCO II		
Less strict	1.43 - 1.52	5%
	1.52 - 1.69	83%
	1.69 - 1.73	13%
More strict	1.64 - 1.74	6%
	1.74 - 1.90	83%
	1.90 - 1.91	13%
Modified In Situ (MIS)		
Less Strict	2.02 - 2.27	10%
	2.27 - 2.65	87%
	2.65 - 2.68	3%
More strict	2.36 - 2.61	10%
	2.61 - 2.94	87%
	2.94 - 3.03	3%
MIS/Lurgi		
Less strict	1.68 - 1.86	17%
	1.86 - 2.19	82%
	2.19 - 2.28	5%
More strict	1.84 - 1.91	6%
	1.91 - 2.31	89%
	2.31 - 2.43	6%

*Actual distributions are discrete (not continuous) so probabilities are approximate. Also, totals do not always equal 100% due to rounding.

2.0 DESCRIPTION OF SUBJECTIVE PROBABILITY ASSESSMENT

Volume I reports estimates of the cost of pollution control for commercial shale oil production. By definition, estimates contain uncertainties. To be useful for decision making some measure of these uncertainties is necessary. The objective of Volume II of this study is to measure the uncertainty that is contained in these cost estimates by making subjective probability assessments.

Volume II provides a thorough examination of the uncertainty in the work of the engineering team which is presented in Volume I. It may be tempting to interpret these subjective probability distributions as representing the relative frequencies of costs of future plants. Under this interpretation one would say that 25% of the future plants would cost less than the 0.25 portion of the cumulative probability distribution. This would imply that the average cost of an oil shale plant in the future would be equal to the expected value of the cost distribution. However, this interpretation is inconsistent with the intentions and the procedures of the subjective probability distributions. For the purpose of this report the subjective distributions are best interpreted as a means of making the opinions of the engineering team explicit.

The pollution control costs estimated in Volume I are a function of a set of assumptions. Volume II uses the collective opinion of the engineering team to assess the uncertainty in these assumptions and the potential impact of this uncertainty on cost. Rather than merely presenting ranges for cost without explanation, as is done in many engineering studies, this volume contains cost ranges along with justification, explanation, and interpretation for each.

2.1 USE OF PROBABILITIES

In general, a decision-maker would feel comfortable basing judgments about the uncertainties of pollution control costs on objective evidence. Such evidence might be relative frequencies from actual multiple observations, or the results of repeatable experiments in pollution control.

Conducting several engineering studies or experiments on the cost of controlling pollution in oil shale processes would be desirable to the decision-maker from a narrow point of view. Given such a sample, confidence intervals (in the classical, inferential statistical sense) of the true cost could be calculated for meeting pollution control standards. Of course, this assumes that an ideal situation exists which requires that all such studies or experiments be accurate representations of the real world situation which will be encountered upon commercialization. Even if such a selection of samples were feasible, it is neither practical nor cost effective to conduct the many studies or experiments needed to provide such data.

However, it is possible to go beyond a simplistic recognition of the existence of uncertainties by using subjective (judgmental) probability estimates. Such estimates are derived by using an established process of obtaining and quantifying individual judgments about uncertain quantities. For this study a detailed methodology was used and a structure* was developed which may be applied to other pollution control studies.

2.2 INTERPRETING SUBJECTIVE PROBABILITIES

Some general comments about subjective probabilities will be helpful. First, it must be stressed that subjective probability is a quantification of an individual's opinion. Second, although subjective probabilities are not derived from objective data, they should be treated in a manner which is consistent with the axioms of probability theory.

* The methodology used is established[1,2] (subjective probability encoding). It is the structure of or framework for the probabilistic assessment that was developed in this study. For simplicity, the combination of methodology and structure will be referred to as methodology in this report.

Since subjective probabilities represent judgment, individual opinions may legitimately differ. There is no one "correct" subjective probability distribution. There are, however, assessment techniques which allow an individual's subjective probability distribution to represent his best judgment. These techniques are used here to assess the subjective ability distributions presented in this volume and are described in the next section.

In addition, the overall results represent the combined subjective probability assessment of a number of individuals. As will be described later (see Section 3.0), the oil shale processes are divided into areas of expertise. Individuals expert in these divisions are questioned concerning the probabilities of various impacts. The costs of these impacts are calculated and the results are recombined or convoluted into an overall probability distribution of costs.

To perform these calculations, the rules of probability are followed. For example, the probability of an event occurring is less than or equal to one, and greater than or equal to zero. And, the probability of two independent events both occurring is the product of the individual probabilities.

To put the probability assessments presented in this volume into a context useful for decision-makers, a broad range of interpretations may be made. The most valid is that the subjective probability distributions represent the opinions of the engineering team concerning the uncertainty contained in the cost estimates. The decision-maker can combine these distributions with his own judgments and opinions about the expertise of the engineering team to draw his own conclusions about pollution control costs in oil shale production.

As stated above, opinions (and subjective probabilities) can legitimately vary from person to person. It is best to interpret the subjective probability assessments as an input into any attempt to estimate the uncertainty. In general, use of subjective probabilities enables the engineering team and decision-maker to use additional information in the analysis, even though that information represents opinions or judgments rather than engineering data. The resulting distributions over cost in a decision making context should be interpreted as follows: If the decision-maker himself is

not knowledgeable about the uncertainties but is willing to rely on the engineers who performed the study (i.e., is willing to use their judgments about uncertainty), and if he adheres to the axioms of probability, then he should take the composite computed probability distributions as his own.

2.3 ASSESSING SUBJECTIVE PROBABILITY DISTRIBUTIONS

Subjective probability assessment is also known as probability encoding. There are well-established procedures for making these judgments and simple examples of these procedures exist[1,2].

This subsection consists of two parts: first, a simple example; and second, a discussion of one of the assessments actually conducted for this study.

2.3.1 A Simple Example of Probability Encoding

Very few, if any, of us know for certain the mileage obtained on the average by cars driven in the U.S., but subjective probability assessment can quantify an individual's opinion. For example, a subject may feel that it is extremely unlikely that the actual mileage will be less than 5 mpg or greater than 40 mpg. This establishes the range of the subjective probability distribution.

Next, the analyst can determine the median (the point which divides the distribution into equally likely halves). This is done by asking a person to place a series of hypothetical bets. The analyst first asks: "Would you rather bet that the mileage is between 5 mpg and 20 mpg or between 20 mpg and 40 mpg?" If the person bets on the 5-20 mpg range, the question is then changed: "Would you rather bet that the mileage is between 5 mpg and 15 mpg or between 15 mpg and 40 mpg?"

This procedure is repeated until the person is indifferent to betting on either subrange--this implies that in the subject's mind it is equally likely that the mileage will be in either range. The dividing value, say 15 mpg, is the median.

Next, the quartiles are determined. The analyst may ask: "If I were to tell you that the mileage obtained by autos in the U.S. is between 5 and

15 mpg, would you rather bet that the mileage is between 5 and 11 mpg or between 11 and 15 mpg?" As before, the division point is varied until the person assigns an equal probability to the two subdivisions--i.e., the subject is indifferent to betting on either subrange. This point might be, for example, 13 mpg. So the lower quartile is 13 mpg.

Now, the third quartile is determined. The analyst may ask: "If this time I were to tell you that the mileage is between 15 mpg and 40 mpg, would you rather bet that the mileage is between 15 and 20 mpg or between 20 and 40 mpg?" Again, the dividing point is varied until the subject is indifferent to betting on either subrange. For example, this dividing point might turn out to be 22 mpg.

At this time the analyst has defined several points on a cumulative subjective probability distribution and the range of this distribution. Table 2-1 contains this information, including the endpoints.

Table 2-1
EXAMPLE OF CUMULATIVE SUBJECTIVE PROBABILITY DISTRIBUTION;
AUTO MILEAGE IN U.S.

<u>Cumulative Probability</u>	<u>Miles Per Gallon</u>
0%	5
25%	13
50%	15
75%	22
100%	40

To insure that this distribution reflects the subject's true beliefs, a series of consistency check questions are asked. For example, according to Table 2-1, the probability of being between 13 mpg and 22 mpg or outside this range (5 to 13 and 22 to 40) is the same (50%). If a person would rather bet on the inside range (13 to 22), then inconsistency is implied. The analyst should reassure the person that inconsistency is common in this type of procedure, particularly on the first try, and that the numbers can be changed until he is comfortable with them. The assessment process should be repeated until the consistency checks are satisfied.

Suppose, for this example, that the original distribution is consistent. Then Table 2-1 describes some points on the cumulative subjective probability distribution. Figure 2-1 is a graphic representation of Table 2-1.

From Figure 2-1 the probability of various mileage ranges can be determined. According to this person the probability of the mpg being between 15 and 20 is about 20% ($0.70 - 0.50$). A discrete subjective probability distribution can be derived in this manner. Figure 2-2 illustrates this point.

Figure 2-1
Graph of Cumulative Subjective Probability Distribution

Figure 2-2
Subjective Probability Distribution; MPG of U.S. Autos

Figure 2-2 is merely a quantification of an individual's uncertainty about the variable being analyzed. This example illustrates the way in which subjective probability, as used in this report, should be interpreted. There is only one average mileage figure for cars driven in the U.S.* There is no

* We are supposing here that "average mileage" is well defined in the sense that the average mileage of a specific set of cars at a specific time (e.g., calendar year 1979).

probability distribution over this figure in the sense that 25% of the time it is less than some given value and 50% of the time it is less than some other (larger) value. Instead, the distribution here only quantifies some individual's opinion about that figure in the sense that he is more willing to bet that it is between 5 and 20 mpg than between 20 and 40 mpg and that he "expects" it to be about 15 mpg.

Also, translating a continuous distribution with an infinite number of values and associated probabilities into a discrete distribution such as Figure 2-2, in which values within a range of 5 mpg share the same probability, is an approximation which results in some loss of accuracy.

In performing such an assessment, the analyst must be aware of possible biases. These are discussed in the next section, though a simple example will illustrate the point. If the person drives a VW Rabbit (which gets high mileage) he may unrealistically think the average mileage is high. Discussions prior to the assessment should establish in the person's mind that gas-guzzlers are also on the road, so that he will not be biased by his individual experience.

2.3.2 An Actual Assessment

For reasons which will be explained later (in Section 3.0), a crucial variable requiring assessment is the amount of ammonia (NH_3) produced by each oil shale process. The amount of NH_3 which will actually be produced by some future commercial plant is an uncertain quantity, but subjective probability assessment by a member of the engineering team, an expert on oil shale processes, yields a quantification of expert judgment on uncertainty in the ammonia value.

After proper definition of the variable (tons per stream day, tpsd, of NH_3 produced by a process, Paraho in this case) and motivation of the person to be questioned (motivation introduces subjective probability assessment to the person and attempts to counteract any biases which could result in distributions which do not reflect the person's true state of knowledge), the process proceeds.

The basic objective is to establish the cumulative subjective probability distribution for tpsd of NH_3 for the Paraho process. The first step is to

locate the lower and upper bounds for tpsd of NH_3 . These values should define virtually all possible NH_3 concentrations, in the subject's opinion.

To establish the upper limit on the tpsd of NH_3 that could come from the Paraho process the person is asked for the value such that he would be extremely surprised if NH_3 exceeded it. If, at this time, the person seems to be blocked and unable to supply an answer, the analyst can help. For example, the analyst might ask: "Could 1000 tpsd be produced?" The person may respond: "No! That's impossible, but" At least the analyst has started the process. The person should understand that any of the numbers he supplies can be changed as the assessment progresses.

In this case, 176 tpsd is established as the upper limit. The person thinks 176 tpsd of NH_3 for the Paraho process is highly unlikely, but not absolutely impossible. Then the lower limit on NH_3 is established. The lower value is found to be 73 tpsd.

To check the results so far, the analyst may ask: "Now, what you're saying is that the commercial Paraho plant is very unlikely to produce less than 73 tpsd or more than 176 tpsd of NH_3 under any circumstances. Is that correct?" Assuming the answer is "yes," the median and upper and lower quartiles of the cumulative subjective probability distribution are determined as illustrated before. The median is determined, using the betting procedure, to be 146 tpsd.

Similarly, the quartiles are found to be 130 tpsd and 150 tpsd. For this study, it was found that any attempt to determine finer resolution than quartiles of the cumulative subjective probability distribution was unrealistic. The next step is a consistency check.

After all of the betting procedures, establishment of the quartiles, consistency checks, and adjustments of the values, the cumulative subjective probability distribution for NH_3 produced by the Paraho process is complete. By dividing the range (73 to 176 tpsd) into classes and determining the probability for each class from the cumulative distribution, the subjective probability distribution is formed.

Although the engineering team is uncertain of the actual amount of ammonia which will be produced by a commercial Paraho process, subjective assessment allows considerable description of the nature of this uncertainty as it is viewed by the team. Similar subjective probability assessments were conducted for all processes, for all areas of significant uncertainty.

The next section (3.0) describes the methodology and structure applied in this study. Section 4.0 presents the results with discussion for each assessment and combines or convolutes the individual assessments for all processes into total subjective probability distributions over cost per barrel of syncrude equivalent.

2.4 BENEFITS OF SUBJECTIVE PROBABILITY ASSESSMENT

A number of benefits of substantial value to a decision-maker are produced by the subjective probability assessment process which would not result from an engineering study without such assessments. The benefits summarized below are illustrated by the work described in the remainder of this report.

- o The analysis allows for detailed examination of uncertainties in a systematic manner. Each point in the engineering study associated with a pollution control cost is examined.
- o Due to the systematic nature of the assessment process all significant areas of uncertainty in the engineering study are inventoried.
- o Areas of uncertainty in the engineering study which do not have a significant impact on results or conclusions are also inventoried so that effort is not wasted studying unimportant points.
- o The nature and impact of significant uncertainties are revealed by the assessment process.
- o The complex, overall impact of uncertainty on the results and conclusions in the engineering study can be determined in a rigorous manner from components which are manageable.
- o The composite uncertainty of the entire engineering team is represented in the total subjective probability distributions over costs for each oil shale process.
- o Insight into the thought processes used in the engineering study is gained through the assessment process.
- o Critical areas of needed research are identified and the critical parameters are defined, which is useful in planning research priorities.

3.0 METHODOLOGY AND STRUCTURE

3.1 INTRODUCTION

At the beginning of work on the engineering portion (Volume I) of this report, the engineering team found insufficient data on a number of critical parameters which affect the pollution control strategies and the control costs. The traditional "hard science" solution for this problem was, of course, adopted. Good average values or "best" estimates were assumed and the selections adequately referenced. Therefore, decisions were not made arbitrarily. This approach gives the appearance of certainty where there really may be very little, but it is a comfortable approach for scientists and engineers who are being required to provide answers.

A notable feature of subjective probability assessment is that it is a very uncomfortable experience for scientists and engineers, who are accustomed to studying each problem in-depth, referencing everything in a scholarly manner, calculating results with eloquent completeness, and never, never just plain guessing. The assessment techniques used in this study required the members of the engineering team to give answers which are not based on hard data. This experience feels, to an engineer, much like guessing.

Given enough time and resources, almost all uncertainty could be eliminated through additional research and engineering. Unfortunately, the decision-maker would have to wait much longer than he wished (or could wait) for answers to his questions, and such definitive information would be very expensive. The need to make a decision and a limitation on resources forces a compromise. Recognizing that such compromises must be made, use of subjective probabilities maximizes the effectiveness of decision making under conditions of uncertainty.

After finishing the engineering portion of a study such as this, an engineering team has carefully considered all uncertainties, although not in an entirely systematic manner, and collectively should be familiar with all pertinent subject matter of concern to the decision maker. Through funding a limited research and engineering study and using the best team he can find, the decision-maker has created his experts for encoding of uncertainty with a relevant information base. The technique described here seeks to extract unbiased expert opinions and quantify them as subjective probability distributions for use in decisionmaking.

Overall then, the recommended approach when decisions must be made in a complex problem area containing significant uncertainty is as follows:

- o Select the best experts available.
- o Subject these experts to an intense but limited period of studying the problem in a rigorous, scientific fashion.
- o Using subjective probability assessment extract and quantify the expert opinions.

A word of caution is in order at this point. The decision-maker should be sure that the output of the scientific study period is of high quality. If the experts selected are not really expert, and their scientific analysis is not thorough, subjective probability assessments can still be extracted but will be of correspondingly less value. The last step does nothing to improve the quality of the first two, but, its output is completely dependent upon them.

3.2 STRUCTURING THE PROBLEM

The encoding tools briefly discussed in the preceding section are straightforward, and can be applied without difficulty providing the problem is properly structured. Properly structuring the problem, knowing what questions to ask, where and how to apply the tool, and how to interpret the results, is essential to obtaining the desired assessments.

Cookbook-type of instructions on how to structure the problem should not be expected. Creativity on the part of the project participants and cooperation from all parties concerned are required. Each and every

assessment must be individually structured, and many different situations requiring individual treatment are encountered.

3.2.1 Defining the Critical Variables

Decision Variables vs. State Variables: Most pollution control activities considered in this study involve placing equipment on process or waste streams to remove from these streams components which would otherwise result in undesirable emissions. Since the engineering effort concerned itself mainly with the environmental control equipment and not with processing equipment, the composition of process and waste streams can be considered uncontrollable factors, i.e., the engineering team could not change process parameters and design to affect the composition of these streams. In reality, the composition of most process and waste streams will be unaffected by process changes.

The quantity of those components in the process and waste streams treated were identified as the critical variables for assessment. Where the actual value of a critical variable was found to be uncertain, subjective probability encoding was used to quantify opinion as to its value, producing a cumulative probability distribution such as Figure 2-1. Pollution control costs were calculated directly for values of the variable within the range of the distribution and probabilities assigned, producing a new distribution of cost versus probability. The entire process is described more fully in the discussion to follow.

A variable which cannot be controlled is called a state variable and the assessment process can be legitimately applied to such a variable. Variables which can be controlled are called decision variables, and assessment of such variables is not meaningful.[1] The composition of the input stream to a pollution control can be seen to be a state variable. The design (and therefore cost) of the equipment and the emission levels were found to be decision variables for the following reasons. If the composition of the input stream is accurately described, and well developed technology is used to control this stream, the emissions can be specified with considerable certainty. If the composition of the input stream and the desired emission levels are accurately specified, the required control technology and its cost also can be described with considerable certainty.

To summarize, in structuring the analysis it was found necessary to assess uncertainty in the inputs to the pollution control equipment only. Given a specified emission level, it is then possible to calculate precisely the cost of meeting the regulation.

Composition of Inlet Streams as Critical Variables: The inlet stream to a pollution control device may contain many chemical compounds which are potential pollutants. Many of the compounds which are identified as important potential pollution sources may not significantly contribute to the uncertainty for one or more of the following reasons:

- o The actual value of the variable is precisely known.
- o Changes in the value of the variable over the expected range has an insignificant impact on the performance and cost of a control device.
- o Control of other variables is much more difficult and results in a high level of control for the variable being considered over a wide range of values.

In summary, each variable must be carefully examined to determine if variation in its value is possible and significant. If so, an assessment is warranted.

Cost as a Critical Variable: Not every pollution control activity has critical input variables which can be defined in a manner amenable to assessment. An example of this is in solid waste management. Pollution is controlled using a complex procedure or set of activities rather than a piece of equipment. The characteristics of these wastes are fixed and known, but the regulatory requirements are still evolving. Therefore, the basic uncertainty relates to what must be done to sensibly control these wastes. Possible answers to this question can be expressed almost directly in dollars and can be assessed directly in terms of cost.

To summarize, when pollution is controlled by using a procedure rather than a piece of equipment, the critical variable or unknown is the procedure itself and the quantifiable measure of the variable is cost. In

this study it was found to be impossible to quantify in any other way this type of variable, a management procedure, so that it could be assessed.

Regulatory Scenarios as Fixed Quantities: Although the actual regulations which will be promulgated for a commercial oil shale industry must be recognized as unknowns which may have significant impact, the regulatory scenarios for this study were taken as "given." This assumption is a major premise of the subjective probability distributions presented. However, as discussed in Volume I, there are only a limited number of situations to which regulatory scenarios can apply, so most results are not affected by this assumption. The spread between the "less strict" and "more strict" total costs shown in Section 2.0, Volume I, can be taken as measure of the impact of this regulatory uncertainty. The final results reported in this volume are presented as distributions around the total cost values from Volume I.

The assumption of regulatory scenarios as "given" was not used for assessment of uncertainty in solid waste disposal. Future regulations can be expected to have a significant impact on disposal costs, and at this time are uncertain. The assessments performed consider the regulatory uncertainties as well as other issues.

Critical Variables Without Experts: The recommended overall approach is to select the "best experts available"; in a few instances a problem was encountered--no experts! In some cases, values for a critical parameter could be selected from the literature and used. Some parameters were such that no member of the engineering team had any experience determining values during the study or at any other time. An example of such a parameter is the concentration of fluoride in excess mine water. The members of the engineering team were not asked for their best judgment on such parameters since they had no experience upon which to base an opinion.

The assessment process can be used to quantify opinion even though the subject has no experience upon which to base a judgment but the distribution obtained is likely to be quite broad. In this study, the members of the engineering team objected to being placed in this position. The objective of

Volume II is to quantify expert opinion for use in decisionmaking, so to use opinions which are unquestionably not expert simply for the sake of completeness was judged to be detrimental. Also, the team members questioned in such situations never developed confidence in their answers. Instead, they felt the process did not provide any new or enhanced insights into the particular uncertainties considered.

The obvious solution to this problem is to find an expert. This was done, but outside experts could not be subjected to the full assessment procedure. Hence, the uncertainty in the value of some parameters is expressed as a range rather than a distribution.

Another situation also can be labeled as "Critical Variables Without Experts." The cost of biological oxidation depends upon the value of the biokinetic constants. There are three such constants and there is no good theoretical basis for predicting their values. The relationship of these constants to design and cost is complex, requiring computer modeling to characterize. The values of these constants are never estimated but are determined experimentally. See the next section for the actual treatment used in this situation.

3.2.2 Disaggregating the Problem

Several assessment interviews were conducted concerning overall cost, and in each case the person interviewed was at a loss to make judgments which were satisfactory to him, and felt negative about the value of the whole process. This occurred for several reasons. While cost was well defined, the critical variables affecting cost were poorly defined, leaving it up to the individual to define the actual parameters to consider. Such a situation is confusing and can lead to substantial bias. The person could not effectively visualize the movement of all critical variables at the same time. The problem was too complex for a meaningful judgment to be made. Decision variables as well as state variables had to be considered at the same time by the person. The person interviewed thought he could affect the outcome by choices which he could make, and sought further definition of the question in order to define the decision variable values and separate them from the state variable values. No member of the engineering team felt he was expert enough to

consider the overall results. A number of experts in a number of disciplines worked together to produce Volume I. No one person is competent to judge uncertainty in the overall results.

Division of Expertise: Even an individual assessment dealing with a single piece of control equipment on a single process with well defined critical variables, several expert opinions are needed. One person may be able to judge the distribution of the critical variables as they are produced by the retorting process, another may be able to judge the impact of the variables on the design and performance of the control equipment. A third individual may be needed to judge the impact of design changes on cost. By combining information from several persons in this manner, a subjective probability distribution over cost for a single piece of equipment is obtained. An assessment such as this does represent the collective opinion of more than one expert.

Figure 3-1 shows a simplified flow diagram of a hypothetical oil shale process and is used to illustrate the division of expertise in this study. In general, DRI is expert on the retorting processes. Stone and Webster Engineering (S&W) did all work on air pollution control, and Water Purification Associates (WPA) designed the water management systems. Every subjective probability distribution of cost versus probability involves DRI and at least one other organization, some involve all three. DRI conducted all assessments.

An example illustrates this point. Assume that a subjective probability distribution is determined over the cost of the ammonia recovery in the water treatment system. DRI is first questioned to obtain a distribution for ammonia produced by the process. The ammonia is found primarily in the retort gas stream which goes to the ammonia absorber to be removed using water. Water from the ammonia absorber containing ammonia, H_2S , and organics then becomes the input stream for the ammonia recovery system. Water Purification Associates are the experts on the recovery system (Phosam). In order to assess the impact of changes of the input stream on the cost of the system, WPA needs to know the quantity of ammonia and water, among other things, which is delivered to the system. To get an exact answer to this question it is necessary to consult Stone and Webster Engineering about the output of the

FIGURE 3-1. PROJECT DIVISION OF EXPERTISE

ammonia absorber. The output expected by S&W is affected by the input specified by DRI. Hence, all three organizations are involved in this single assessment. This example illustrates one reason cooperation is necessary.

To summarize, the first step in disaggregation of the problem is a complete description of the division of expertise among the various contributors to the engineering portion of the study.

Inventory of Cost Centers: The next step in structuring the problem is straightforward. An inventory of items contributing to cost is made for each process by carefully studying the engineering report. As an example, the inventory for the TOSCO II process is shown in Figure 3-2. All equipment for both regulatory scenarios is combined in one list.

3.2.3 Defining Each Assessment--Sensitivity Analysis

Sensitivity analysis is the next step in structuring the problem. It is the process of identifying the cost center which can have a significant impact on cost due to uncertainty.

Sensitivity analysis requires an informal interview process involving the experts on the engineering team. Each piece of equipment and each activity associated with a cost must be discussed in detail with the appropriate experts from the team.

For each cost center, the magnitude and nature of uncertainty must be determined. Uncertainty generally will be found in the critical variables. However, it may also be found that changes in critical variables have no impact or only limited impact on cost.

Cost Center Discussions: Many cost centers are not worth assessing because they either contain little uncertainty or the impact of uncertainty is trivial. Identifying these centers and eliminating them from the reduces the problem to something manageable.

Sensitivity analysis should answer all questions necessary for dividing the inventory into centers to be assessed, and centers not to be assessed.

Figure 3-2. Inventory of TOSCO II Environmental Control Cost Centers

Water:

Clarifier
Cooling Tower Makeup Treatment
Boiler Feed Treatment
Foul Water Stripper
Ammonia Recovery (Phosam) System
Bio-oxidation Organic Removal System
Oil Water Separator
Domestic Waste Treatment
Equalization Basin

Air:

Less Strict
Regulatory
Scenario

Primary Crusher Baghouse (1)
Fine Crusher Baghouses (4)
Ore Storage Baghouse (1)
Preheater Venturi Scrubbers (6)
Elutriator Venturi Scrubbers (6)
Shale Wetter Venturi Scrubbers (6)

or

More Strict
Regulatory
Scenario

Primary Crusher Baghouse (1)
Fine Crusher Baghouses (4)
Ore Storage Baghouses (1)
Preheater Baghouses (6)
Elutriator/Wetter Precipitator (6)

SO₂:

Stretford System

Hydrocarbons:

Low Flare and Thermal Oxidizer
Thermal Oxidizer

NO_x:

Boiler Burners
Ammonia Storage System

Solid Waste:

Spent Shale Disposal Area
Arsenic Disposal

The mechanism of adapting to changes in critical variables is discussed in detail. For changes in the input level of a particular pollutant the same piece of equipment may be scaled up or down. A piece of equipment selected in the engineering study may require no changes over a certain range. For values at the upper end of the range the piece of equipment may require modification. At extreme values a different approach to pollution control may be necessary.

To summarize, sensitivity analysis should determine the critical variables which may be uncertain and the mechanism by which each cost center adapts to changes in these variables.

Discussion of Critical Variables: The interviews discussed above accurately identify critical variables and allow variables to be discarded which do not affect costs. Also, by this time the list of assessments which need to be performed should be smaller since some areas with little uncertainty will be found.

Several questions are important to the discussion of critical variables. First, how accurately has the value of the variable been predicted by the engineering study? Next, is there significant uncertainty? Is there a dependency between variables? If so the value of one variable might be calculated from the value of another. If the dependency is not straightforward, multiple conditional subjective probability assessments may be required. Two variables may move together because they are both dependent on a third variable. That variable may then be indicated as the critical variable to encode, even though it may not seem to affect directly a piece of control equipment. The two dependent variables could then be calculated from the third state variable.

It is important to determine the conditions which lead to changes in the value of the variables. Such information is valuable in formulating the questions to be used for the assessments. The interviewer must set the conditions for each assessment; if he is unaware of an important condition affecting critical variables, the subject may assume an improper condition and bias the results. For example, a variable may be in a certain range only during interrupted situations. The individual may concentrate his efforts to estimate values for this situation, when the entire oil shale process would be

a failure if that condition were the norm. The assessment which is supposed to estimate uncertainties under successful commercial operation conditions would have been biased.

Carefully discussing the conditions which lead to changes in the values of critical variables can also identify decision variables which have been initially considered as state variables. An area of uncertain importance may also be uncovered. The actual value of a decision variable for a commercial operation may be significantly uncertain. Final selection may represent a tradeoff between environmental control costs and production costs, but the engineering team may only have a data base of the environmental costs. Such variables are treated in this study as state variables since the person being questioned cannot affect the values by his decisions.

Finally, detailed discussion of critical variables may identify what were earlier called "Critical Variables Without Experts." When these are discovered, it is necessary to go outside the engineering team to discuss their importance. This should be done first, as part of the sensitivity analysis.

Methods of Calculating Cost: Sensitivity analysis involves the generation of new cost figures. Critical variables, must be identified and new values for these variables must be determined. New cost figures can be calculated.

Subjective probability assessment allows estimation of uncertainty using expert opinion without the need for extensive additional engineering. The method recommended is to scale the original cost figures derived in the engineering study to the new values of the variables. This approach is not significantly different than actual re-engineering, for this study.

It is necessary to discuss the methods of scaling costs for each cost center with the appropriate experts from the engineering team. Parts of the total cost of a piece of equipment may need changing while others remain the same. Scaling should accurately estimate real changes, not just new cost figures. Where an actual change in technology or approach is indicated by changes in a critical variable, the cost for a new piece of equipment was not determined by detailed engineering, but was estimated from cost figures determined in other studies. This occurred rarely so that significant inaccuracy was not introduced by this procedure.

To complete the sensitivity analysis, the cost impact of identified uncertainties can be estimated. Cost centers which show trivial changes can be rejected. Some cost centers can be rejected without any calculation because their total impact on cost is small. For others, calculated cost changes may be so small that actual assessment is not warranted. The object should be to eliminate those cost centers which obviously are not worth assessing. After the assessments in this study were completed, some cost centers originally thought to be important were found to be trivial.

3.2.4 Final Selection of Assessments

At this point the final selection of assessments is made and all the information necessary for each assessment assembled. In this study cost centers are rejected if the following items are found to be true from the sensitivity analysis:

- o Sensitivity analysis indicates the uncertainty in critical variables is small enough to be trivial or unassessable.
- o The total cost of control is trivial compared to other costs.
- o Anticipated possible changes in cost are trivial.
- o The control operates only in interrupt situations.

Although a number of cost centers were eliminated using these selection rules, these centers are not entirely ignored in the sections to follow. For those variables (associated with cost centers) which are actually assessed, the following items were assembled.

- o The person to be questioned.
- o An understandable definition of the variable in terms relevant to the person to be questioned.
- o The value or values of the variable used in the engineering study for the specific cost center to be assessed. (Often several scales were calculated for this value to allow the subject to choose the units he finds most comfortable.)
- o A complete description of anything affecting the value of the variable to be used to set conditions. These were presented as assumptions the subject is asked to make.

- o A list of reasons which explain why it is important to assess the uncertainty in the variable.
- o A list of questions designed to determine the reasons for the answers given by the person questioned. The assumptions he makes must be identified.

It is not necessary to compile an exhaustive collection of information in the above areas. The interviewer just needs to be well prepared. He will find it necessary to be flexible as the assessments progress. The interviewer needs to be in control of the situation and sensitive to problems and biases which may appear so that the approach may be adapted as needed.

3.3 BIASES

Care was taken during the actual interview process to minimize bias. It is important to understand the major sources of bias and to be aware of the measures taken to minimize it. Biases are of general concern in any subjective probability encoding effort and relate to the methodology described in Section 2.0. The discussion of these biases has been placed here so that the measures taken in this study to overcome them can be related to the structuring of the problem.

A definition of bias as it applies to subjective probability encoding follows:

"Conscious or subconscious discrepancies between the subject's response and an accurate description of his underlying knowledge are termed biases." [1]

Four major types of bias will be defined and the measures taken to guard against each bias will be described. The definitions were supplied by Woodward-Clyde Consultants* who assisted in development of the structure used in this study.

*These definitions are based on the discussion in "Probability Encoding in Decision Analysis" by C.S. Spetzler and C-A.S. Stael von Holstein, ORSA-TIMS-AIEE Joint National Meeting, Atlantic City, NJ, November 8-10, 1972.

3.3.1 Anchoring Bias

Definition: Focusing on an initial value (such as an average) and making adjustments to yield a distribution.

This source of bias is discussed first because it is unavoidably introduced into the assessments. Volume I, the engineering report, contains over 160 tables. There are so many numbers in the report, that a person being questioned must begin by reviewing the relevant figures in Volume I. Such an anchor produces a central bias[1] or narrowing of the distribution. To overcome this tendency, a good deal of care is taken to establish the extreme values of the distribution at the beginning of an assessment. The mechanisms which determine upper and lower limit values are discussed with the subject until he feels that all reasonable (but often extreme) possibilities short of complete process failure have been determined. The actual assessment procedure begins only after the subject has reviewed the possible range of the variable and the circumstances that would cause it to fall in any part of the range. Using this procedure, the value from the engineering study often was in a position on the final distribution different from what one might expect if the subject had focused his attention strongly on this value of the variable.

3.3.2 Availability Bias

Definition: Judging the probability of an event by the ease with which instances of it can be brought to mind.

There is a natural tendency to emphasize information which is easiest to recall. Information can be easy to recall because it made a strong impression, is familiar, comes from a recent experience, etc. Since experts are being questioned, it is expected that they have knowledge from outside the current study. However, they have recently participated in an intensive study, perhaps developing new information; therefore their current experience, the easiest to recall, is more relevant. The project information is more valuable than the outside information it replaces or updates. No extra effort

was made to counteract an availability bias. Outside information was most used to establish the limits of the distributions.

3.3.3 Unstated Assumptions Bias

Definition: Conditioning responses based upon an assumption or set of assumptions which are not explicitly stated.

During the first few trial assessments, it was determined that this bias can be a serious problem. The subject who is not given all the assumptions he should make has to make some on his own which are not related to the interviewer. Such unstated assumptions are then taken as "given" by the subject. In some instances it was found that uncertainty that the interviewer had hoped to assess was eliminated by an unstated assumption.

Several steps were taken to overcome this bias during the actual assessments. Considerable effort was devoted to preparing information for each assessment by carefully setting the conditions. This has been discussed before. Next, the subject was continuously asked to state the assumptions he was making during the assessment. These were recorded and discussed. Finally, each interviewer was familiar with the subject matter of the assessment and could discuss assumptions knowledgeably with the subject.

3.3.4 Coherence Bias

Definition: Probabilities are assigned to events based only on a few logical and complete (coherent) explanations, namely, those scenarios that can be imagined which lead to the occurrence of the event.

Basing assessments on logical and complete scenarios becomes a bias when the subject focuses only on a few such scenarios.

Two features of the current study counteract incorporation of this bias. First, the subject matter was complex, leading to a continuum of scenarios rather than just a few which could be chosen and made logically

complete. Second, the effort to counteract the anchoring bias and unstated assumptions bias, kept the perspective broad.

3.4 THE MECHANISM OF AN ASSESSMENT

3.4.1 The Overall Basic Assumptions

Several important overall assumptions are a basis to all assessments. Each person is instructed to make these assumptions at the start of the assessment procedure. An explanation of each assumption follows.

The Assumption of Perfect Knowledge: The subjects were asked to assume that the oil shale developers will have "perfect" knowledge when a piece of equipment is installed. The assessment process is designed to uncover the true beliefs of the engineering team. Although a team member may be uncertain of the true value of a critical variable in a commercial oil shale development, the developer at that time in the future will not have uncertainty and will install the correct piece of equipment.

Not making this assumption can cause the subject to restrict his considerations. For example, the true belief about uncertainty may be that a variable extends over a broad range, but above a certain value a different technology than the one selected in the engineering study may be required to control this variable. The subject consciously or subconsciously may be reluctant to admit to a belief that the variable may be in this range, because he makes the unstated assumption that the technology chosen in the engineering study will be installed. He imagines a substantial cost penalty and double investment to remove the first piece of equipment and install a new piece of equipment. Instead, he should assume that the correct piece of equipment is installed for any particular value of the variable.

The "Assumption of Perfect Knowledge" removes a very common unstated assumption bias.

The Assumption of Proper Operation: The subject is asked to assume that the oil shale process functions properly. Extreme values for a variable can be generated if one assumes major processing failures, even if the subject does

not truly believe that will ever be encountered. Attempting to establish the limits of a variable, the subject may be pressured to make this unstated assumption. This unstated assumption is unreasonable because it implies failure to successfully commercialize the basic process. This problem is so common that it should be guarded against from the start.

The Assumption of No Limits: Without being specifically instructed to do otherwise, the subject assume he is to consider possibilities only within the bounds of the current engineering study. Surprise is usually evident when a subject is told that he can broaden his consideration.

3.4.2 Determining the Results of an Assessment

If the methodology outlined to this point is properly followed, a cumulative probability distribution such as Figure 3-3 can be obtained for a critical variable, X. The values of X determined by the assessment and used to plot Figure 3-3 are shown in Table 3-1. The values shown for the 0 percentile and the 100 percentile are the limits determined at the start of the assessment. The quartiles, 25%, 50% and 75% are then determined.

Next, the cumulative probability distribution over the quantity of X must be converted to a distribution over cost. First, the full range of the variable between the limits is divided into approximately equal inclusive intervals. Commonly five intervals were used. The probability for each interval is determined using the plot of the results, read directly from the abscissa. This is shown in Figure 3-4 which is the same as Figure 3-3. The probability of the second interval (27-40 ppm), for example, is approximately 0.46 (0.58-0.12). In a similar manner each interval is estimated. The results can be replotted as a discrete distribution of probability vs. values of X, as shown in Figure 3-5.

Next, the midpoints of each interval are determined. These values are used to calculate new cost figures. At this time it is beneficial to discuss again the methods of calculation with the appropriate experts.

The hypothetical results of such calculations for variable X are shown in Table 3-2. Remember that the assessment relates to a specific process model, and the results cannot be generalized to include other models. For each process model, a new assessment for variable X must be made. A value

Figure 3-3. Cumulative Probability Distribution
For the Quantity of X

Table 3-1. Assessment Results for the Quantity of X

<u>Cumulative Probability</u>	<u>Quantity (PPM)</u>
25%	28
50%	38
75%	44
100%	80

Figure 3-4. Cumulative Probability Distribution

Figure 3-5. Subjective Probability Distribution for X

for production level and the capital recovery factor for the specific process model must be used.

Table 3-2. Change in Cost of Control For Values of X

X** (PPM)	Probability That X Falls In Each Range	Annual Capital Cost (10 ³ \$)	Annual Operating Cost (10 ³ \$)	Total Annual Cost (10 ³ \$)	Cost Per Barrel (¢)	Δ Cost Per Barrel (¢)
50*	---	4,000	2,000	6,000	33.0	---
17	0.12	1,880	940	2,820	15.5	-17.5
31	0.46	2,860	1,430	4,290	23.6	-9.4
45	0.30	3,720	1,860	5,580	30.6	-2.4
59	0.11	4,490	2,250	6,740	37.0	+4.0
73	0.01	5,210	2,610	7,820	42.9	+9.9

*Value used in engineering study

**Central value from each discrete interval shown in Figure 3-5.

Table 3-2 assumes that the cost of control (both capital and operation costs) can be scaled to new values of X using the formula:

$$C_X = \left(\frac{X}{50}\right)^{0.7} C_S$$

where: C_X = Cost for any value of X in the range.

C_S = Engineering study value cost at 50 ppm X.

Usually the scaling is more complex. The total annual cost for controlling X is derived as described and then converted to a cost per barrel of Syncrude Equivalent (see Volume I for explanation of Syncrude Equivalent)

for the specific process by dividing by the anticipated annual output of the process. The change in cost relative to the engineering value is then calculated. It is shown in the last column. Assuming a capital recovery factor of 0.1607 (see Volume I for explanation of capital recovery factors), the annual capital costs listed are for a piece of equipment with a value of \$25,000,000, a high and low of \$32,400,000 and \$11,7000,000 are determined by the hypothetical assessment.

The results are now in the form of changes in control cost with associated probabilities which can be represented graphically as shown in Figure 3-6. In all cases the zero point represents the value from the engineering study (Volume I). From this distribution, it is apparent that in the opinion of the engineering team, the actual cost of controlling X is likely to be less than the cost given in the engineering study, but there is a greater than 12 percent chance that it will cost more. The possible cost savings is greater than the possible cost increase.

Figure 3-6. Discrete Subjective Probability Distribution Over Cost for Controlling X

Presenting information in this form gives the decision maker insight into the cost of controlling X, with the associated uncertainties. If only a

range for the cost is given, a more extensive and systematic study of the problem is necessary to define a distribution. The decision maker is presented with a thorough answer which contains usable information.

3.4.3 Combining Probability Distributions--The Convolution Process

By this point in the analysis information has been synthesized which is useful to a decision maker. His problem is still difficult, though, because of the large number of separate probability distributions. It is difficult to assess the overall impact of uncertainty by reviewing individual distributions, so the distributions need to be combined.

The decision maker needs to know the probability distribution over the sum of all costs. The probability that the cost, z , will be equal to any given value, a , is computed using the relationship:

$$P(z=a) = \sum_{X \leq a} P(X_i) \cdot P(y=a-X_i \mid X_i)$$

where $Z=X+Y$ and X and Y are costs. Operationally this is done as follows. Assume two discrete distributions produced by two assessments are available as shown in Figure 3-7.

Figure 3-7. Discrete Subjective Probability Distribution Over Cost for Two Separate Assessments

Individual cost values, $C_{X_1}, \dots$, etc. for one assessment and $C_{Y_1}, \dots$ etc. for the second assessment are shown. Values are then combined in pairs until all combinations have been made, yielding a new distribution. This would be done as follows:

$$C_{X_1} + C_{Y_1} = C_{1,1}$$

$$P_{X_1} \cdot P_{Y_1} = P_{1,1}$$

$$C_{X_2} + C_{Y_1} = C_{2,1}$$

$$P_{X_2} \cdot P_{Y_1} = P_{2,1}$$

$$C_{X_5} + C_{Y_1} = C_{5,1}$$

$$P_{X_5} \cdot P_{Y_1} = P_{5,1}$$

$$C_{X_1} + C_{Y_2} = C_{1,2}$$

$$P_{X_1} \cdot P_{Y_2} = P_{1,2}$$

etc.

etc.

A new distribution, Z, is treated which has, in this case, 25 values ($N_x \cdot N_y = N_z$).

This new distribution is then combined, point by point, with another assessment to yield a further convoluted distribution with 125 values. Obviously, the number of calculations which must be made quickly becomes too large to reasonably do manually. In theory, all assessments could be combined in this manner, but a means of reducing the amount of calculation necessary was devised for use in this study.

After combining three assessments, the resulting distribution is divided into a new, smaller set of intervals using Sturges rule as a guide for determining the approximate size of an interval. The rule is as follows:

$$i = \frac{\text{range}}{1 + 3.322 \log N}$$

Where: Range = total

Spread in new
distribution

N = Number of
points

i = interval size.

As an example, if the combination of three assessments gives a new distribution with a total spread of 64¢, 8 intervals of 8¢ each would be used.

The midpoint of each interval is then picked as a representative value and assigned a probability equal to the probability that the cost falls in that interval. This yields a new simpler distribution which incorporates all the important features of the previous distribution. The new distributions, representing several assessments, are then convoluted until the process is complete.

An overall distribution for each process model is obtained which represents the total uncertainty actually assessed for that process. Convolution was performed using total annual cost figures rather than cost per barrel of oil.

3.5 PROBLEMS OUTSIDE THE METHODOLOGY

3.5.1 Expressing Values Without Uncertainty

During the selection of the important cost centers and associated critical variables to be assessed, some cost centers were rejected as unimportant. All cost centers are included in the final overall distribution, however, in a simple way. All assessment results are converted to cost distributions which are then convoluted to produce one overall distribution showing the changes in costs reported in Volume I. It is a simple matter to convert this distribution to a subjective probability distribution over total cost.

For example, assume the I total cost given in Volume I for a particular process and regulatory scenario is \$2.00, and that the overall distribution produced by convolution has a range of -\$0.50 to +\$0.63. The subjective probability distribution over total cost then has a range of \$1.50 to \$2.63; a distribution between these points is described by adding or subtracting the appropriate amount from \$2.00 for each point. The total distribution contains all cost centers, not only those where uncertainty was assessed.

3.5.2 Expressing Unassessed Uncertainty

As discussed earlier, a few areas of significant uncertainty were discovered. They could not be fully assessed because the critical variables were "variables without experts." At a minimum, a sensitivity analysis was performed in these instances. Since no probability distributions could be determined for these variables, the associated uncertainty could not be incorporated in the final probability distribution over total cost.

The treatment of critical variables without experts is as follows. First, the cost calculated in the engineering study for managing variables is used as a point estimate with insignificant uncertainty and becomes part of the unassessed baseline. Then, to provide the decision-maker with information on uncertainty the key issues are discussed and the results of the sensitivity analysis presented but not combined with the assessments. No attempt is made to go further.

3.5.3 Managing Probabilistic Dependency

Two types of probabilistic dependency* were considered for this study. First, two critical variables can be dependent or vary together in some manner. If the movement of one variable is dependent upon the other in a way which can be described mathematically no real problem is encountered. The distribution for the dependent variable can be calculated from the distribution of the independent variable and no assessment is required. This situation occurred in several cases. If, however, two variables move together but the relationship is uncertain, a complex subjective probability assessment must be performed. First, one variable is assessed. Then, the second variable is assessed. Given specific values of the first, a third variable can be added and assessed at given values of the first two, etc. Fortunately, the situation was never encountered. If one attempts subjective probability assessment on his own and encounters this situation, he can contact Woodward-Clude Consultants for assistance.

* Two variables, x and y, are probabilistically dependent if $f(x,y) \neq f(x) \cdot f(y)$.

There is another type of dependency which does not present a problem. Two or more cost centers may depend upon the same variable. A distribution for each cost center can be presented separately, and the combined distribution is obtained by simply adding up the costs from all centers for each common value of the variables. Where several cost centers depend upon the same variable, convolution is not even necessary.

3.5.4 Uncertainty in Costing

The uncertainty in determining the installed cost of a piece of equipment has not been considered, although obviously this uncertainty is present in all cost centers. This issue was discussed with the members of the engineering team and a "standard" uncertainty was determined. Experience led to the conclusion that a piece of equipment, if installed as designed, will actually cost from +20% to -10% of the predicted cost. This uncertainty can be narrowed by obtaining firm bids from the equipment vendors.

A portion of the capital cost of a piece of equipment is recovered each year, and only that portion is reflected in the pollution control costs per barrel of oil. Of the total annual control costs approximately 45% is capital recovery for aboveground processes and 55% for the in situ processes. Therefore, the actual costing uncertainty for equipment amounts to only +10% to -5%, when expressed on an annual or cost-per-barrel basis.

Costs for new values of the critical variables (the range determined by subjective assessments) were determined by scaling from the value determined in Volume I. This introduces error of an unknown magnitude, although it is thought to be small.

Probability distributions are not available for these particular variables. Be aware that this unassessed uncertainty exists in the results to follow.

4.0 ASSESSMENT RESULTS AND DISCUSSION

4.1 ASSESSMENTS PERFORMED

Sensitivity analysis yielded the significant uncertainties shown in Figure 4-1. Environmental controls and critical input variables are listed in Figure 4-1. Subjective probability assessment was used, as described before, to quantify the uncertainty as viewed by the engineering team.

The engineering team can be defined as all individuals who worked on Volume I of the project and who made any technical contributions. The individuals assessed for any variable are not identified. As discussed before, the judgments of several experts were required generally to develop a probability distribution on cost.

Figure 4-2 lists those control areas found generally not to contain sufficient uncertainty (in terms of cost impact) to allow and/or warrant an assessment effort. The critical variables are listed for each area along with the rationale for exclusion. Each of these areas will be discussed more fully.

The results of individual analyses are presented for all processes by type of environmental control or activity. Then a probability distribution over cost of environmental controls is derived for each oil shale process.

4.2 RESULTS OF ANALYSES

4.2.1 Ammonia Absorber

Ammonia is found in the retort gas produced by all processes, except TOSCO (see Volume I). The quantity of ammonia produced was individually assessed for each process and this data used to generate cost distributions.

Figure 4-1. Areas of Significant Uncertainty

<u>Control</u>	<u>Critical Variables</u>
Ammonia Absorber	NH ₃ in retort gas
Stretford	H ₂ S in retort gas NO _x in retort gas COS in retort gas CS ₂ in retort gas SO ₂ in retort gas Mercaptans in retort gas
Phosam Ammonia Recovery	NH ₃ in input stream H ₂ O in input stream
Organic Removal	BOD Biokinetic Rate Constants*
Spent Shale Disposal	Cost (See Results)
Slurry Backfilling	Cost (See Results)
Hot Precipitator (MIS/Lurgi)	Grain Loading*
Excess Mine Water Treatment	F*, B*, NH ₃ *, Phenol*

*"Critical Variables Without Experts," hence complete assessments not obtained. See Results.

Figure 4-2. Areas Not Analyzed

<u>Control</u>	<u>Critical Variables</u>	<u>Rationale</u>
Clarifier		
Cooling Tower Makeup Treatment		
Oil Water Separator	Cost	Cost of control trivial by comparison; uncertainty small
Domestic Waste Treatment		
Equalization		
Boiler Feed Treatment		
Particulate Control Devices	Gas Flow Rate Particle Loading	Uncertainty small; Trivial Δ Cost
Thermal Oxidizer (TOSCO)	Hydrocarbons in gas stream	Uncertainty small
Low Flare and Thermal Oxidizers	Hydrocarbons in gas stream	Operates only in interrupt
Turbine Water Injection	Temperature	Uncertainty small
Boiler Burners	Cost	Cost trivial
Ammonia Storage	Cost	Uncertainty small
Arsenic Disposal	Cost	Uncertainty small

The results of these assessments are summarized in Figures 4-3 and 4-4. The figures present the results in four parts. In the upper left-hand corner of each figure, the results of the assessment for the critical variable are presented in tabular form as a cumulative probability distribution. The range of the critical variables was then divided into intervals and a representative value was chosen for each interval. These are presented in the upper right corner, along with the probability that the variable will fall in each interval. In the center of each figure, the calculated costs for each value of the variable are listed, and at the bottom, the probability of each change in cost is plotted.

Initial interviews discovered that the quantity of ammonia produced can be controlled by changing processing parameters. Assuming all processing parameters are fixed at the values assumed in the engineering study, little uncertainty exists in the value of this critical variable--i.e. it is a decision variable. However, there is uncertainty as to the exact quantity of ammonia which the developers will choose to produce in a commercial plant, since changing ammonia quantity can effect other outputs, most notable of which is oil yield.

Upper and lower limits for the subjective probability distribution for ammonia were obtained through use of estimations of the maximum and minimum amounts of ammonia which could be produced deliberately by controlling process conditions. The remainder of the distribution then reflects expert judgment as to the actual value within the upper and lower limits, which will be produced in a commercial plant.

The ammonia absorbers for the three processes are all of the same design, but for each process, cost was determined separately. Using the engineering point estimates (Volume I) as base values, capital cost can be scaled to other values of ammonia using the following relationship:

$$C_2 = C_1(I_2/I_1)^{0.7}$$

where:

C_1 = capital cost estimate, Vol. I

I_1 = ammonia value, Vol. I

I_2 = new ammonia value

C_2 = cost estimate for ammonia value I_2

Operating costs were found to vary directly with ammonia quantity.

Figure 4-3. Assessment Results for Ammonia Absorption Paraho Process

Critical Variable Assessment		Intervals With Probabilities For Critical Variables		
Cumulative Probability	Variable Value (TPSD* NH_3)	Interval (TPSD)	Representative Value (TPSD)	Probability
0%	73	73-93	83	0.04
25%	130	93-113	103	0.09
50%	146	113-133	123	0.15
75%	150	133-153	146*	0.59
100%	176	153-173	163	0.13
*Tons per Stream Day		>173	173	~0

*Study Value

Change In Cost With Change In Variable Value

Variable Value (TPSD)	Capitol Cost (10 ⁶ \$)	Operating Cost (10 ⁶ \$)	Sum of Cost Changes (10 ⁶ \$)
83	4.31	0.89	-1.01
103	5.01	1.10	-0.68
123	5.67	1.53	-0.15
146	6.39	1.56	0
163	6.91	1.74	+0.26
173	7.20	1.85	+0.42

Probability Distribution on Cost

Figure 4-4. Assessment Results for Ammonia Absorption
MIS and MIS Lurgi Processes

Critical Variable Assessment		Intervals With Probabilities For Critical Variables		
Cumulative Probability	Variable Value (TPSD)*	Internal (TPSD)	Representative Value (TPSD)	Probability
0%	140	< 140	140	0
25%	210	140-190	165	0.17
50%	281	190-240	215	0.19
75%	310	240-290	281*	0.22
100%	518	290-340	315	0.33
		> 340	340	0.09

*Tons Per Steam Day

*Study Value

Change In Cost With Change
In Variable Value

Variable Value	Capital Cost	Operating Cost	Sum of Cost Changes
165	6.68	0.93	-1.19
215	8.03	1.21	-0.67
281	9.69	1.58	0
315	10.50	1.77	+0.33
340	11.07	1.91	+0.58

Probability Distribution on Cost

Paraho Process: Although the range of possible ammonia values is large, the distribution is quite sharp and the uncertainty is small. The results show an 87% chance (subjective probability) of the actual cost being less than or equal to the study value and a 72% chance of it being greater or equal, with an expected value of -\$90,000 relative to the study value.

MIS Processes: Both the MIS and MIS/Lurgi processes do not produce ammonia. There is more uncertainty in MIS processes than the Paraho process. This may relate to the lower availability of data for the MIS process. The distribution can be seen to be broad and flat, with a greater probability that the cost will be more than or equal to the study value (64%), than the probability of being less than or equal to it (58%). The expected value is \$170,000 less than the study value.

The distribution illustrates an interesting point. The engineering team made every effort to be conservative. In this case, the cost shown in the engineering study is more than the expected value, reflecting intentional oversize. However, the assessment process has forced closer scrutiny of this important uncertainty and has revealed a belief that there is a better chance for ammonia absorption to cost more than estimated in Volume I, than for it to cost less. The engineering team actually had no idea this was the case until their beliefs were quantified. In fact, they felt they had been conservative.

4.2.2 Stretford Process - H₂S

The Stretford process costs can be affected by more than one critical variable. However, the variables appear to be independent both in terms of the way in which they are produced and in terms of their impact on the process. The assessment results for H₂S are presented first and separately from the results for the other critical variables. These results are presented in Figures 4-5 through 4-7.

In the TOSCO process, H₂S is released both from the retort and from the refinery. The preliminary interviews suggested that there is very little

Figure 4-5. Assessment Results for the Stretford Process
Paraho Process

Critical Variable Assessment		Intervals With Probabilities For Critical Variables		
Cumulative Probability	Variable Value (PPM H ₂ S)	Internal (PPM)	Representative Value (PPM)	Probability
0%	1,500	<1,750	1,750	0.07
25%	2,500	1,750-2,250	2,000	0.18
50%	3,000	2,250-2,750	132 TPSD*	0.13
75%	3,300	2,750-3,250	3,000	0.32
100%	4,000	3,250-3,750	3,500	0.29
		>3,750	3,750	0.01

*Tons Per Stream Day 5, Study Value
Change In Cost With Change
In Variable Value

Variable Value (PPM)	Capital Cost (10 ⁶ \$)	Operating Cost (10 ⁶ \$)	Sum of Cost Changes (10 ⁶ \$)
1,750	15.61	2.99	-2.33
2,000	16.98	3.44	-1.66
132 TPSD	20.18	4.58	0
3,000	21.61	5.14	+0.79
3,500	23.74	6.01	+1.99
3,750	24.71	6.42	+2.57

Probability Distribution on Cost

Figure 4-6. Assessment Results for the Stretford Process
TOSCO II Process

<u>Critical Variable Assessment</u>		<u>Intervals With Probabilities For Critical Variables</u>		
<u>Cumulative Probability</u>	<u>Variable Value (TPSD S)*</u>	<u>Internal (TPSD)</u>	<u>Representative Value (TPSD)</u>	<u>Probability</u>
0%	173	<173	173	~0
25%	187	173-185	179	0.15
50%	192	185-199	192*	0.70
75%	200	199-211	205	0.15
100%	211	>211	211	~0

*Variable value given as S, not H₂S, in all cases.

*Study Value

Change In Cost With Change In Variable Value

<u>Variable Value (TPSD)</u>	<u>Capital Cost (10⁶\$)</u>	<u>Operating Cost (10⁶\$)</u>	<u>Sum of Cost Changes (10⁶\$)</u>
173	9.31	5.09	-0.66
179	9.50	5.26	-0.45
192	9.91	5.65	0
205	10.31	6.03	+0.45
211	10.50	6.21	+0.66

Probability Distribution on Cost

Figure 4-7. Assessment Results for the Stretford Process
MIS Process

Critical Variable Assessment		Intervals With Probabilities For Critical Variables		
Cumulative Probability	Variable Value (TPSDS)*	Interval (TPSD)	Representative Value (TPSD)	Probability
0%	72	72	—	20
25%	108	72-100	86	0.20
50%	144	100-125	112	0.15
75%	158	125-150	144*	0.27
100%	264	150-175	162	0.26
		175	175	0.12

*Variable value given as S, not H₂S, in all cases.

*Study Value

Change In Cost With Change In Variable Value

Variable Value (TPSD)	Capital Cost (10 ⁶ \$)	Operating Cost (10 ⁶ \$)	Sum of Cost Changes (10 ⁶ \$)
86	19.2	3.87	-3.86
112	22.6	5.07	-2.07
144	26.2	6.49	0
162	28.2	7.32	+1.18
175	29.5	7.88	+1.97

Probability Distribution on Cost

uncertainty regarding the value of this variable (from both sources), but an assessment was conducted anyway. The distribution obtained (Figure 4-6) was tight and symmetrical.

The Lurgi process is similar to the TOSCO process (minus a refinery) in terms of uncertainty in the value of the H_2S variable. After the assessment experience with the TOSCO process, a decision was made not to assess H_2S in the Lurgi process, even though a separate Stretford process handles the gas cleanup. It is judged that the cost impact of any uncertainty is trivial. Hence, the assessment results, in terms of the cost impact of uncertainty, are the same for the MIS and MIS/Lurgi processes.

A second decision also was necessary. It was feared that there might be a dependency between NH_3 quantity and H_2S quantity in the retort gas stream. This would require several assessments for H_2S at several given values of NH_3 for each process. A review of available analytical data on NH_3 and H_2S in the retort gas stream, however, strongly suggested no dependency. Also, it is the judgment of engineering team experts knowledgeable in the retorting processes, that there is no dependency.

Scaling of the Stretford costs to new values of the variable H_2S was accomplished using the following relationship:

$$C_2 = C_1(I_2/I_1)^{0.6}$$

where:

C_1 = capital cost estimate, Vol. I

I_1 = H_2S or S value, Vol. I

I_2 = new H_2S or S value

C_2 = Cost estimate for value I_2

Operating costs were projected to change in direct proportion to H_2S or S quantity.

For the TOSCO process, little uncertainty is reflected in the assessment results, as discussed before. For the MIS and MIS/Lurgi processes (same assessment for both) and the Paraho process, a broad, flat distribution was found, suggesting substantial uncertainty. An unusual feature is also found in these distributions--both are bimodal. The assessments were repeated several times, including the required consistency checks, to assure that these results are actually the true beliefs. The bimodal nature is partly a result of converting the continuous cumulative distribution to a discrete

distribution, and also reflects a very flat lower end tail to the probability distribution on cost.

The opinion of the engineering team, quantified by assessment, is that there is a 75% chance that the Stretford cost for the Paraho process will be equal to or greater than the value reported in Volume I, and a 38% chance that it will be equal to or less. Also the expected value of \$400,000 greater than the value reported in Volume I. Hence, the Volume I estimate is revealed to be, upon closer examination, probably slightly low. The expected value does not pinpoint the "true" value, but is one of several parameters which characterize the distribution. The possibility of the cost for H₂S removal being understated does not imply that the Stretford process is expected to encounter difficulties, but rather implies that the actual quantity of H₂S removed is likely to be higher than the quantity estimated in Volume I.

This particular assessment (Paraho) reveals two interesting features of the assessment process. First, the distributions are not always "text book" smooth. Second, the person preferred to be asked for H₂S values using the units of parts per million (ppm) for this analysis, and the unit of tons per stream day (tpsd) for the other analyses. The person was allowed to choose the units he found to be most comfortable, and in this case he did not use the same units for all processes.

The interpretation of the MIS and MIS/Lurgi assessment results for the Stretford process shows that there is a slightly greater chance that it could cost more rather than less than the Volume I results (65% $\geq$ study value; 62% $\leq$ study value). However, the range of possible costs below the study value is almost twice as large as the range above and there is a significant chance that the costs that are ultimately realized will be substantially less than the study value.

4.2.3 Stretford Process--Other Critical Variables

All the variables other than H₂S shown in Figure 4-1 for the Stretford process were considered together in the initial interviews. Little analytical data is available on the quantity of these constituents in the various retort gas streams, but the original investigation by the engineering team of what little data is available lead to the assumption that the levels

would be minimal. However, these gases, even at low levels, can have a detrimental impact on the performance of the Stretford process, and hence warrant careful consideration.

The ammonia absorber functions as a caustic scrubber and is expected to remove SO_2 and perhaps some COS. NO_x , mercaptans (including CS_2) and COS were assessed for those processes judged to have significant uncertainty. An additional tower section is suggested as the solution to the problems presented by these gases. This section would function as a scrubber specifically intended to remove these undesirable gases. Creating this scrubber by addition of this section to the existing Stretford absorption towers is a cost effective way to serve this purpose.

The following estimation procedure was used to calculate the capital cost of this added section:

$$C = 0.4 (\text{Total Stretford Capital Cost})[(\text{ppm}_{\text{gas}} + \text{ppm}_{\text{H}_2\text{S}})/\text{ppm}_{\text{H}_2\text{S}}]^{0.7}$$

where:

C = cost of added tower section at a given total level of detrimental gases

ppm_{gas} = concentration of gases in retort gas stream in parts per million

and

$\text{ppm}_{\text{H}_2\text{S}}$ = concentration of H_2S in retort gas stream in parts per million from Volume I

The factor, 0.4, represents the proportion of the total Stretford process cost attributable to the tower. Operating costs were estimated to increase by 50¢ for each dollar in added capital cost.

Paraho Process: Figure 4.8 shows the results for assessments of NO_x and mercaptan quantities in the Paraho retort gas stream. Before combining the two assessments into an overall two-dimensional joint probability distribution, the cost impact of various levels of these gases, including the maximum possible levels, was estimated. The maximum impact on cost is slightly more than 0.005 dollars per barrel of oil, as shown also in Figure 4.8. This

Figure 4-8. Assessments for NO_x and Mercaptans in the Paraho Process

Assessment for NO _x		Assessment for Mercaptans and CS ₂	
Cumulative Probability	NO _x Quantity (ppm)	Cumulative Probability	Total Mercaptans (ppm)
0%	6	0%	0
25%	20	25%	1
50%	50	50%	4
75%	75	75%	10
100%	250	100%	100

Example Calculation of the Cost Impact of NO_x and Mercaptans in the Retort Gas Stream

NO _x (ppm)	Mercaptans (ppm)	Total (ppm)	Capital Cost ^(a) (10 ⁶ \$)	Operating Cost (10 ⁶ \$)	ΣΔC (10 ⁶ \$)	ΣΔC (\$/Barrel Syncrude Equivalent) ^(e)
0 ^(b)	0	0	8.072 ^(c)	1.38 ^(d)	0	0
10.5	1.25	11.75	8.096	1.38	0.0049	0.00016
75	20	95	8.30	1.40	0.0541	0.0017
250	100	350	8.80	1.44	0.177	0.0056

(a) Total capital cost of Stretford absorption tower

(b) Study value

(c) $\$8.072 = (\$20.18)(0.4)$

(d) $(139,680 \text{ kwh})(330 \text{ stream days/yr})(\$0.03/\text{kwh}) = \$1.38 \times 10^6$ for operation of the absorption tower

(e) assuming 3.1506×10^7 barrels per year of syncrude equivalent

maximum impact was judged insignificant relative to the impacts of other uncertainties, and hence the assessment was taken no further.

TOSCO II Process: It is the opinion of the engineering team that very little COS and no NO_x and SO_2 is present in the TOSCO retort gas stream. Hence, no assessments were made. Mercaptan levels were assessed assuming all gas streams (retort and refinery) are combined into a feed for the Stretford process. The maximum impact on cost (at 200 ppm mercaptan) is 0.0002 dollars, and the impact of this uncertainty is judged to be trivial.

MIS Process: Assessments were performed for NO_x and COS. These results are presented in Figure 4-9. The maximum cost impact at a combined maximum detrimental gas level of 227 ppm is approximately 3¢ per barrel. However, the joint probability distribution for both gases should be heavily skewed toward the lower values. For this reason, the cost impact of this uncertainty is judged to be trivial.

MIS/Lurgi: No assessments were conducted for this process model. The MIS portion would be identical to the assessments just discussed, and there should be no more uncertainty in the Lurgi process than in the TOSCO process which was discussed previously.

4.2.4 Phosam Ammonia Recovery

The assessment results for the Phosam ammonia recovery system are summarized in Figures 4-10 through 4-12. The distributions for ammonia quantity for the Paraho, MIS and MIS/Lurgi processes have already been presented in connection with the ammonia absorber. Since the TOSCO process does not require an ammonia absorber, no distribution could be generated. Little uncertainty exists in estimating the quantity of ammonia produced in the TOSCO process since it is produced in the refinery. Nevertheless, a subjective probability distribution was obtained and is presented in tabular form in Figure 4-11.

Figure 4-9. Assessments for NO_x and COS
in the MIS Process

<u>Assessment for NO_x</u>		<u>Assessment for COS</u>	
<u>Cumulative Probability</u>	<u>NO_x Quantity (ppm)</u>	<u>Cumulative Probability</u>	<u>COS Quantity (ppm)</u>
0%	2	0%	0
25%	5.5	25%	8
50%	15	50%	13
75%	30	75%	17
100%	200	100%	27

Figure 4-10. Assessment Results for Phosam Unit
Paraho Process

Change in Cost With Change
in Variable Value

<u>Variable Value (TPSD)</u>	<u>Capital Cost (10⁶\$)</u>	<u>Operating Cost (10⁶\$)</u>	<u>Sum of Cost Changes (10⁶\$)</u>
83	5.00	3.48	-0.77
103	5.46	4.32	-0.52
123	5.87	5.16	-0.28
146*	6.31	6.12	0
163	6.61	6.84	+0.20
173	6.78	7.25	+0.32

*Study Value

Probability Distribution on Cost

Figure 4-11. Assessment Results for Phosam Unit
TOSCO II Process

<u>Critical Variable Assessment</u>		<u>Intervals With Probabilities for Critical Variables</u>		
<u>Cumulative Probability</u>	<u>Variable Value (TPSD)</u>	<u>Interval (TPSD)</u>	<u>Representative Value (TPSD)</u>	<u>Probability</u>
0%	130	130-132.5	131	0.02
25%	133.5	132.5-135	134	0.84
50%	134*	135-137.5	136	0.13
75%	134.4	137.5-140	139	0.01
100%	140			

* Study Value

Change In Cost With Change In Variable Value

<u>Variable Value (TPSD)</u>	<u>Capitol Cost (10⁶\$)</u>	<u>Operating Cost (10⁶\$)</u>	<u>Sum of Cost Changes* (10⁶\$)</u>
131	5.98	5.00	-0.026
134	6.04	5.12	0
136	6.08	5.19	+0.016
139	6.13	5.31	+0.041

*After NH₃ Credit

Probability Distribution on Cost

Figure 4-12. Assessment Results for the Phosam Unit
MIS and MIS-Lurgi Processes

Change in Cost With Change
in Variable Value

<u>Variable Value (TPSD)</u>	<u>Capital Cost (106\$)</u>	<u>Operating Cost (106\$)</u>	<u>Sum of Cost Changes** (106\$)</u>
140	6.36	5.20	-0.99
165	6.82	6.13	-0.80
215	7.65	7.99	-0.45
281*	8.60	10.45	0
315	9.05	22.71	+0.22
340	9.36	12.65	+0.38

*Study Value

**After Ammonia Credit

Probability Distribution on Cost

Water quantity is a second critical variable affecting the cost of the Phosam unit. As the ammonia quantity changes, the water quantity must also be changed in direct proportion to retain a constant removal efficiency for the ammonia absorber. For this reason, no assessment of water quantity is necessary.

The Phosam unit contains several components which must be viewed separately. The ammonia stripping, distillation and absorption section costs scale with the square root of the ammonia quantity. The water stripper section scales with the square root of the water quantity. Since water quantity changes in direct proportion to ammonia quantity to retain ammonia removal efficiency, all components can be scaled together using ammonia as the only variable. All operating costs scale directly with ammonia quantity except steam for the water stripper section. For this section, approximately 12 lbs. of steam are required per 100 lbs. of water feed. However, if the ratio of water to ammonia is maintained, again one variable can be used and all operating costs scaled together. Use of the Phosam unit also requires an annual royalty charge which remains unchanged over the range of ammonia quantities judged possible.

After scaling the capital and operating cost and converting these to a total annual charge, the quantity of ammonia recovered must be credited against these costs. For this credit, a \$100 per ton figure was used. Although ammonia market prices fluctuate substantially, this figure was selected in Volume I as being reasonably conservative. It was felt before the assessments that increased ammonia production by the retorting processes might make its recovery at least a breakeven proposition if not slightly profitable. This was not found to be the case given the assumed design parameters of the Phosam unit. However, it is felt that the design would, in practice, be further optimized, reducing the capital and operating costs. Hence the assessment distributions may be shifted to the high end.

Paraho Process: The assessment for the Paraho process shows a belief that there is a better chance of a cost savings than there is a chance of a cost increase ($87\% < \text{study value}$; $72\% > \text{study value}$). Also the range of possible cost savings is greater than that of cost increase, suggesting that there is

some probability of significant cost savings, while the potential cost overruns are not as great. The distribution is concentrated near the study value, with an expected value \$90,000 less than the study value.

TOSCO Process: The results shown in Figure 4-11 can be seen to be very tightly distributed about the study value, with an insignificant chance that costs will be greater than the study value.

MIS and MIS/Lurgi Processes: Substantial uncertainty in the MIS and MIS/Lurgi processes results in a broad and flat distribution. (See Figure 4-12) There is a better chance of a cost increase than there is a chance of a cost savings ($64\% \geq$ study value; $58\% \leq$ study value), but the expected value is \$130,000 less than the study value. Also the possible cost savings are larger than the possible increases.

4.2.5 Organic Removal

The assessment results for organic removal wastewater treatment costs are summarized in Figures 4-13 through 4-16. This series of assessments has several unique features. First, the assessment for values of the critical variable was run only once. It was judged that there should be virtually no difference in the uncertainty from process to process in the BOD (Biological Oxygen Demand) loading. Wastewater requiring treatment for organic removal is, in all cases, retort gas condensate after pretreatment. Since the probability distribution for BOD values is the same for all processes, the remainder of each assessment measures the differing impact of this uncertainty from process to process. A second unique feature of these assessments is the discovery of a breakpoint. Initial interviews revealed that a switch to a different treatment process would occur above a certain level of cost. In the engineering study, biological oxidation was the treatment process of choice, but above a certain cost of treatment, wet air oxidation treatment would have equivalent cost. Wet air oxidation is expensive, but would remove all organics, including high concentrations and those compounds which might be a

Figure 4-13. Assessment Results for Organic Removal
BOD Loading, All Process

Assessment Results
for BOD

<u>Cumulative Probability</u>	<u>BOD Loading (PPM)</u>
0%	2,000
25%	9,000
50%	10,000
75%	11,000
100%	15,000

Cumulative Probability Distribution
For BOD

Figure 4-14. Assessment Results for Organic Removal
Paraho Process

Change in Cost With Change
in Variable Value

<u>Variable Value (PPM)</u>	<u>Capital Cost (106\$)</u>	<u>Operating Cost (106\$)</u>	<u>Sum of Cost Changes (106\$)</u>
2,850	3.92	0.28	-2.28
4,550	6.26	0.44	-1.74
6,250	8.59	0.61	-1.19
7,950	10.93	0.77	-0.65
10,000*	13.75	0.97	0
10,500**	14.44	1.02	+0.16

*Study Value

**Breakpoint

Probability Distribution on Cost

Figure 4-15. Assessment Results for Organic Removal
TOSCO II Process

Change in Cost With Change
in Variable Value

<u>Variable Value (PPM)</u>	<u>Capital Cost (106\$)</u>	<u>Operating Cost (106\$)</u>	<u>Sum of Cost Changes (106\$)</u>
2,850	3.19	0.22	-1.86
4,550	5.10	0.35	-1.43
6,250	7.00	0.48	-0.99
7,950	8.90	0.61	-0.56
10,000*	11.20	0.76	0
10,500**	11.76	0.80	+0.10

*Study Value

**Breakpoint

Probability Distribution on Cost

Figure 4-16. Assessment Results for Organic Removal
MIS and MIS-Lurgi Processes

Change in Cost With Change
in Variable Value

<u>Variable Value (PPM)</u>	<u>Capital Cost (106\$)</u>	<u>Operating Cost (106\$)</u>	<u>Sum of Cost Changes (106\$)</u>
2,850	8.89	0.64	-5.61
4,550	14.20	1.03	-4.28
6,250	19.50	1.41	-2.94
7,950	24.80	1.79	-1.61
10,000*	31.20	2.26	0
10,500**	32.60	2.36	+0.35

*Study Value

**Breakpoint

Probability Distribution on Cost

problem to bio-oxidation. The switchover would occur above a certain BOD level which corresponds to the breakpoint cost. This level is 10,500 ppm BOD loading.

The full cumulative probability distribution for BOD loading is shown in Figure 4-13 with a range from 2,000 ppm to 15,000 ppm. Conversion of this distribution to a discrete distribution of BOD loading versus probability shows the effect of the breakpoint. Five intervals are given up to 10,500 ppm. All remaining probability is then contained in the point, 10,500 ppm, even though the BOD loading range extends to 15,000 ppm, because wet air oxidation would not experience a cost change in this range (10,500 to 15,000 ppm).

Distributions for cost versus probability are shown in Figures 4-14 through 4-16. Due to the breakpoint in treatment technology discussed above, there is virtually no chance that the costs would exceed the maximum costs for these distributions.

Both capital and operating costs for bio-oxidation treatment were scaled directly with BOD loading. Water quantity was found to contain little uncertainty and the impact of any changes in it is minor. At the beginning of the engineering study, a target was set of 200 ppm BOD in the treated water. An estimated level of 50 ppm was achieved with no cost penalty. No correction for this high target level was incorporated in the engineering results.

Discussion of All Oil Shale Processes: The uncertainty is different for each process. The results are interpreted in the same manner, because critical variable distribution was used in all cases. The range of the impact of uncertainty is indeed very broad, but most of the probability is found to be near the study value. The probability of exceeding the study value cost is greater in all cases than the probability of a cost savings (79% $\geq$ study value; 63% $\leq$ study value). Although the range extends far below the study value, the expected value is only, for example, \$130,000 per year less for the Paraho process.

4.2.6 Spent Shale Disposal

Spent shale disposal was a difficult area for the assessment process. There are several reasons. First there are no simple, critical variables which can be quantified readily and which have a straightforward, calculable impact on cost. There are many variables which have an impact on cost in complex ways.

The sponsor defined the solid waste disposal procedures by requesting a cost comparison between management of spent shale as a solid waste and management as a hazardous waste. The terms "solid waste" and "hazardous waste" have a very specific legal meaning. Regulations specify, in considerable detail, how such materials shall be managed. Within this legal/regulatory framework there is very limited flexibility. A material is classified a solid waste or a hazardous waste for purposes of regulation based on specific characteristics. A substantial portion of the uncertainty which must be considered relates to the eventual regulatory response to spent shale disposal. In all other assessment areas, regulatory response has been taken as a "given," not a source of uncertainty. In this assessment area, such uncertainty must be considered as well as technical issues. Also regulatory uncertainty was not considered before for spent shale disposal in the project, because the sponsor had defined it not to exist.

To overcome these difficulties, the individual being interviewed was specifically instructed to estimate the actual cost of shale disposal, rather than to estimate the uncertainty in the two cases (scenarios) considered in the engineering study. The individual being interviewed was also allowed to incorporate his judgment into the subjective cost estimations as to the uncertainties inherent in, and the impacts of, future regulations. The individual was allowed free access to the results presented in Volume I, and questions were continuously asked to ascertain the assumptions being made. These costs are then compared to the values in Volume I for both regulatory scenarios by converting to values for change in cost relative to the Volume I value for each scenario.

The results are presented in Figures 4-17 through 4-20. The costs specified are total annual cost for pollution control in spent shale disposal including both capital charges and operation costs on a levelized equivalent

Figure 4-17. Assessment Results for the Pollution Control Cost of
Spent Shale Disposal
Paraho Process

<u>Assessment Results</u>		<u>Conversion To Discrete Distribution</u>		
<u>Cumulative Probability</u>	<u>Cost in 10⁶\$ Per Year</u>	<u>Cost Interval (10⁶\$)</u>	<u>Representative Value (10⁶\$)</u>	<u>Probability</u>
0%	2.0	2.0 - 3.5	2.75	0.50
25%	2.5	3.5 - 5.0	4.25	0.35
50%	3.5	5.0 - 6.5	5.75	0.12
75%	4.5	6.5 - 8.0	6.5	0.03
100%	8.0			

Change in Cost vs. Probability
by Regulatory Scenario

<u>Probability</u>	<u>Scenario</u>	
	<u>Less Strict</u>	<u>More Strict</u>
0.50	-2.38	-5.79
0.35	-0.88	-4.29
0.12	+0.62	-2.79
0.03	+1.37	-2.04

Figure 4-18. Assessment Results for the Pollution Control Cost of
Spent Shale Disposal
TOSCO II Process

<u>Assessment Results</u>		<u>Conversion To Discrete Distribution</u>		
<u>Cumulative Probability</u>	<u>Cost in 10⁶\$ Per Year</u>	<u>Cost Interval (10⁶\$)</u>	<u>Representative Value (10⁶\$)</u>	<u>Probability</u>
0%	1.0	1.0 - 1.5	1.25	0.12
25%	1.75	1.5 - 2.0	1.75	0.26
50%	2.25	2.0 - 2.5	2.25	0.19
75%	3.25	2.5 - 3.0	2.75	0.11
100%	4.0	3.0 - 3.5	3.25	0.17
		3.5 - 4.0	3.5	0.15

Change in Cost vs. Probability
by Regulatory Scenario

<u>Probability</u>	<u>Scenario</u>	
	<u>Less Strict</u>	<u>More Strict</u>
0.12	-1.64	-3.84
0.26	-1.14	-3.34
0.19	-0.64	-2.84
0.11	-0.14	-2.24
0.17	+0.36	-1.84
0.15	+0.61	-1.59

Figure 4-19. Assessment Results for the Pollution Control Cost of
Spent Shale Disposal
MIS Process

<u>Assessment Results</u>			<u>Conversion To Discrete Distribution</u>	
<u>Cumulative Probability</u>	<u>Cost in 10⁶\$ Per Year</u>	<u>Cost Interval (10⁶\$)</u>	<u>Representative Value (10⁶\$)</u>	<u>Probability</u>
0%	2.0	2.0 - 2.5	2.25	0.09
25%	2.75	2.5 - 3.0	2.75	0.41
50%	3.0	3.0 - 3.5	3.25	0.29
75%	3.4	3.5 - 4.0	3.75	0.16
100%	4.5	4.0 - 4.5	4.0	0.05

Change in Cost vs. Probability
by Regulatory Scenario

<u>Probability</u>	<u>Scenario</u>	
	<u>Less Strict</u>	<u>More Strict</u>
0.09	-1.44	-3.29
0.41	-0.94	-2.70
0.29	-0.44	-2.30
0.16	+0.06	-1.79
0.05	+0.31	-1.55

Figure 4-20. Assessment Results for the Pollution Control Cost of Spent Shale Disposal MIS-Lurgi Process

<u>Assessment Results</u>		<u>Conversion to Discrete Distribution</u>		
<u>Cumulative Probability</u>	<u>Cost in 10⁶\$ Per Year</u>	<u>Cost Interval (10⁶\$)</u>	<u>Representative Value (10⁶\$)</u>	<u>Probability</u>
0%	0.5	0.5 - 0.7	0.6	0.25
25%	0.7	0.7 - 0.9	0.8	0.42
50%	0.8	0.9 - 1.1	1.0	0.24
75%	0.95	1.1 - 1.5	1.1	0.09
100%	1.5			

Change in Cost vs. Probability
by Regulatory Scenario

<u>Probability</u>	<u>Scenario</u>	
	<u>Less Strict</u>	<u>More Strict</u>
0.25	-0.48	-1.43
0.42	-0.28	-1.23
0.24	-0.08	-1.03
0.09	+0.02	-0.93

basis over the life of the plant (see Section 10.0, Volume I for an explanation of how disposal costs are converted to equal annual payments).

Several general judgments are common to all four assessments. In all cases, it is judged that full hazardous waste management regulations will never be applied. In all cases, continuous revegetation will be practiced, and 20 years of post-closure monitoring and maintenance will not be necessary (see Volume I, Section 7.0). For the less strict scenario of Volume I, a very conservative approach was developed through the combination of all conservative suggestions found in the development plans for four processes studied. Some activities proposed for the less strict scenario may not be necessary, most notably the impermeable lining in the disposal area, but significant uncertainty still surrounds this issue.

Each assessment also contains its own special characteristics, and each will now be discussed.

Paraho Process: The Paraho assessment produced a smooth curve with no unusual features. A much greater probability of the cost being less than the less strict scenario study value rather than more was found. The more strict scenario value is above and outside the entire distribution.

TOSCO II Process: The TOSCO assessment also shows a higher probability of the cost being less than the less strict scenario value than the probability of the cost being more, but also has some unusual features. Again, a bimodal distribution is uncovered (see Stretford process assessment results). This reflects consideration of two important factors which have opposite impacts. First, the TOSCO spent shale has a high carbon content which conceivably under regulations yet to be proposed could be judged to present a hazard. The response to this hazard could impose a small additional cost or could add substantially to the cost. At some point between these two extremes, it is expected that the developers of the TOSCO process would choose to eliminate the hazard, rather than manage it. This would be done by burning the carbon residue on the spent shale. As discussed in Volume I, Section 7.0, this would eliminate the hazard and make disposal much less complex, and hence less

expensive. Burning the carbon residue should also provide an advantage in terms of energy recovery. This factor was specifically excluded from consideration in the assessment and is not reflected in the results.

There is also a reasonable possibility that TOSCO will use a spent shale burner even if the carbon residue is not judged to pose a hazard. Such judgment is reflected in the assessment results.

Again, the more strict scenario value from Volume I falls above and outside the distribution.

MIS Process: The MIS assessment also produced the conclusion that raw shale disposal pollution control will probably cost less than shown in Volume I for the less strict scenario. An important consideration is that native rock is the material being managed, and elaborate controls will not be required. There was also judged to be a reasonable possibility that above ground retorting will be started after the MIS technology is successfully commercialized, and the raw shale will be stored rather than disposed. The result would be management of lesser quantities of material.

MIS/Lurgi Process: It was judged that few special precautions will be required since the spent shale should be mostly impermeable. Application of hazardous waste regulations appears, through the assessment, to be judged very unreasonable.

4.2.7 Slurry Backfilling

Slurry backfilling only applies to one of the process models, MIS/Lurgi (see Volume I). No pilot scale research has been done to date and considerable uncertainty still surrounds this pollution control measure. As in the spent shale disposal assessment, cost itself was found to be the appropriate, quantifiable variable. In this case, capital and operating costs were separately assessed. Figures 4-21 and 4-22 show the results. As before (spent shale disposal), the cumulative distribution is converted to a discrete distribution then to a distribution showing change in cost versus probability. Capital cost is converted to change in annual capital charge for this distribution.

Figure 4-21. Assessment Results for the Capital Cost of
Slurry Backfilling Spent MIS Retorts
MIS-Lurgi Process

<u>Assessment Results</u>			<u>Conversion to Discrete Distribution</u>	
<u>Cumulative Probability</u>	<u>Cost in 10⁶\$ Per Year</u>	<u>Cost Interval (10⁶\$)</u>	<u>Representative Value (10⁶\$)</u>	<u>Probability</u>
0%	2.95	2.9 - 4.7	3.8	0.20
25%	5.0	4.7 - 6.5	5.6	0.47
50%	6.0	6.5 - 8.3	7.4	0.29
75%	7.0	8.3 -10.1	9.2	0.04
100%	12.0	10.1 -12.0	10.1	~0

Change in Capital Cost vs. Probability

<u>Probability</u>	<u>Change in Annual Capital Cost (10⁶\$)</u>
0.20	+0.07
0.47	+0.36
0.29	+0.65
0.04	+0.93
~0	+1.08

Figure 4-22. Assessment Results for the Annual Operating Cost
of Slurry Backfilling Spent MIS Retorts
MIS-Lurgi Process

<u>Assessment Results</u>		<u>Conversion to Discrete Distribution</u>		
<u>Cumulative Probability</u>	<u>Cost in 10⁶\$ Per Year</u>	<u>Cost Interval (10⁶\$)</u>	<u>Representative Value (10⁶\$)</u>	<u>Probability</u>
0%	1.5	1.5 - 3.3	2.4	0.22
25%	3.5	3.3 - 5.1	4.2	0.22
50%	5.5	5.1 - 6.9	6.0	0.39
75%	6.5	6.9 - 8.7	7.8	0.14
100%	10.0	8.7 - 10.0	8.7	0.03

Change in Annual Operating Cost
vs. Probability

<u>Probability</u>	<u>Change in Annual Operating Cost (10⁶\$)</u>
0.22	-4.79
0.22	-2.99
0.39	-1.19
0.14	+0.61
0.03	+1.51

The assessment process caused a close re-examination of the original cost estimates. Original capital cost was underestimated. The distribution can be seen to be entirely above the Volume I estimate, with an expected value \$410,000 higher on an annual capital charge basis. Operating costs on the other hand were overestimated in Volume I. The spent MIS retort can be made impermeable with less chemical additives than shown in Volume I.

Checking for unstated assumptions was found to be important in the operating cost assessment. The results reflect the assumption that the cemented spent shale produces an impermeable barrier with only sufficient strength to control subsidence. The assumption that enough strength was needed to allow pillar removal was not made. In investigating these assumptions, the individual was asked to estimate subjectively the upper limit if sufficient strength was desired for pillar removal. A figure of \$30 million annual operating cost was found for maximum strength. This can be compared with the \$10 million found if just impermeability and subsidence control is desired. The distribution for the higher figures was not further defined, but is expected to be broad, encompassing low values as well. The upper value describes a highly improbable but possible occurrence.

4.3 AREAS NOT ASSESSED

Two types of areas were not assessed. First those areas which are defined in this study as "Critical Variables without Experts" were not assessed, but are shown in Figure 4-1 as containing significant uncertainty. Second, a number of areas, shown in Figure 4-2, were not assessed because the uncertainty was judged to be insignificant. Both areas will now be discussed. For the second types only those areas judged not to contain significant uncertainty which need further explanation over that given in Table 4-2 will be discussed.

4.3.1 Impact of "Critical Variables Without Experts"

Biokinetic Constants in Organic Removal: In Volume I it was mentioned that the bio-oxidation treatment design was based on use of the conservative biokinetic constants for H-coal wastewater. Although an assessment of

biokinetic constants was not possible, a comparison can be made with other sets of constants from other processes with wastewater streams similar to those found in oil shale processing. Table 4-1 shows biokinetic constants from three wastewaters, H-coal, coke oven liquor and synthane wastewater. Reference 3 fully discusses the meaning and use of the constants.

Table 4-1 Biokinetic Constants for Three Wastewaters

	<u>Coke Oven</u>	<u>H-coal</u>	<u>Synthane</u>
k, g soluble BOD/g MLVSS day	1.8	~0.3	~1
Ks, mg BOD/l	0.34	~30	266
y, g VSS/g BOD processed	0.2	0.48	0.37
k _d , day ⁻¹	0.17	0.03	0.033

Table 4-2 shows the relative volume of the aeration basin which results from use of the three sets of constants at several concentrations of microorganisms, 15 day mean cell residence time, and two different levels of influent concentration measured in terms of BOD. Again, reference 3 is used.

Table 4-2 Aeration Basin Relative Volume Under Various Conditions*

<u>Influent Concentration (mg/l BOD)</u>	<u>Microorganism Concentration (mg/l)</u>	<u>Biokinetic Constants</u>		
		<u>Coke Oven</u>	<u>H-coal</u>	<u>Synthane</u>
2,500	2,000	1	5.69	4.19
	3,000	1	5.76	4.24
	4,000	1	5.69	4.19
18,000	2,000	1	5.87	4.38
	3,000	1	5.86	4.38
	4,000	1	5.83	4.34

*Assumes 15 day mean cell residence time for all conditions.

The H-coal biokinetic constants can be seen to result in the largest aeration basin. Actually, a larger difference would exist in practice. The mean cell residence time θ_c , cannot fall below a minimum critical value θ_c^m , and the ratio θ_c/θ_c^m is preferably kept greater than 2. For the two different influent concentrations shown in Table 4-2, the following ratios are found:

	θ_c/θ_c^m		
	<u>Coke Oven</u>	<u>H-coal</u>	<u>Synthane</u>
2,500 mg/l BOD	2.83	1.69	4.55
18,000 mg/l BOD	3-1.67	1.65	5.00

These ratios suggest that the residence time can be shortened from 15 days for the synthane wastewater, and should be lengthened for the H-coal wastewater. The shorter the mean cell residence time required, the smaller the aeration basin needed. Hence, the difference between H-coal and synthane aeration basin volumes would probably be larger than shown in Table 4-2.

Using the Paraho process wastewater treatment system as an example, the aeration basin in the biological oxidation system can be seen in Volume I to be the major capital cost item (Vol. I, Section 6.0) at 84% of the total cost. Assuming the basin can be half as large, a capital saving of \$5.75 million could be realized. This would mean an annual capital recovery charge savings of \$924,000 or approximately 3¢ per barrel of syncrude equivalent.

It is judged that the set of constants used are too conservative. The example just discussed would indicate that a small cost saving is probably possible for all three oil shale processes.

Hot Precipitator-MIS/Lurgi: Volume I lists a grain loading of 10 for the gas stream controlled by the hot precipitator in the MIS/Lurgi process. This piece of equipment is expensive, and any higher grain loading would be difficult to manage. However, no expert was available to give a better estimate of this uncertain parameter through subjective probability encoding.

If the grain loading should exceed 10, the solution is to replace the cyclone specified in the process with a high efficiency cyclone. Such a

cyclone would represent a \$1.5 million investment and would cost the same amount in annual operating expense. On an annual basis this represents a cost of \$1.77 million or 7¢ per barrel of syncrude equivalent.

Excess Mine Water Treatment: Four components of the groundwater treated and discharged for the MIS cases determine the cost of such treatment. These components are boron and fluoride for the less strict regulatory scenario, and ammonia and phenol for the more strict scenario. No expert was available to assess a distribution of concentration for these parameters. However, extensive analytical data is available on this water for tracts C-a and C-b, and excellent statistics can be found for C-a. Table 4-3 compares the boron, fluoride, ammonia and phenol levels found with those assumed in Volume I. The statistical analyses show a reasonable chance of exceeding the Volume I study value only in the case of phenol. The data does not indicate that the mean value will significantly exceed the study value, but rather that the samples analyzed showed a broad range of values. Hence, the excess mine water treatment system would possibly encounter a higher level of phenol than anticipated in Volume I.

One possible solution to this problem is addition of a specific resin absorption system for phenol removal. Such a system is expected to cost approximately 30¢/1000 gallons treated, and not more than \$1.00/1000 gallons. The maximum impact of such a requirement could be an increase in excess mine water treatment cost of 80% for the MIS and MIS/Lurgi processes.

It seems unlikely that such a requirement would be imposed for two reasons. First, the variations in sample values shown in Table 4-3 may be due in part to uncertainties in the sampling and chemical analysis procedures. The statistical procedures applied have no means of estimating or removing this component of variance. Phenol is difficult to analyze at trace levels, and hence such variation is probably present. Second, a resin absorption system would only be necessary to manage intermittent to occasional peaks in phenol levels. On the average, the treatment system proposed would do the required job without such an added system.

Table 4-3. Summary Statistics on Upper Aquifer Water Quality, Tract C-a, Piceance Creek Basin. Comparison to Volume I Study Values for Boron, Fluoride, Ammonia and Phenol

Element	Regulatory Scenarios				Study Value	$\bar{x}$	σ	Statistical Data on Background Study Values								Number of Samples
	Less Strict		More Strict					95% Confidence Int.		Probability of Being $\leq$ Value Shown						
	Proposed	Achieved	Proposed	Achieved				Upper	Lower	25%	50%	75%	90%	95%		
Boron (mg/l)	1.0	0.6-1.2	0.75	0.04-0.08	2-4	0.33	0.003	0.4	0.27	0.15	0.33	0.73	1.49	2.27	144	
Fluoride (mg/l)	2.0	1.5	2.0	0.15	15	0.41	3.84	0.51	0.33	0.17	0.41	1.02	2.31	3.76	144	
Ammonia (mg/l)	—	0.18	0.2	0.10	1.2	0.32	2.31	0.37	0.27	0.18	0.32	0.56	0.93	1.26	121	
Phenol (mg/l)	—	1.0	1.0	0.2	2.5	2.51	4.62	4.12	1.53	0.89	2.51	7.04	17.84	31.09	39	

Source: Tract C-a, Rio Blanco Oil Shale Project, Environmental Baseline Monitoring, Progress Report No. 10, Vol. 2, Appendix 3, Summary Statistics.

4.3.2 Discussion of Areas Not Assessed

Water Treatment: The water treatment system components listed in Figure 4-2 were not assessed for two reasons. First, the cost contribution of each component is very small by comparison with the cost of the components which were assessed. Second, the technology involved in these unassessed parts of the wastewater management systems is standard and simple and hence subject to very little uncertainty.

Particulate Control: Each particulate control device proposed in Volume I was carefully considered for uncertainty. In all cases, except the hot precipitator in the MIS/Lurgi process, little reason to expect significant uncertainty was found. The gas flow rate and grain loading estimates have been made quite accurately. Gas flow rate is determined mechanically (decision variable). The controls selected are capable of operating with increased or decreased grain loadings. If the actual grain loadings are found to be less, the capacity devices as shown in Volume I would still be used. Changes in operating costs would be trivial in this case.

Miscellaneous Control Devices: The rationale for exclusion of miscellaneous control devices from the assessment process are shown in Table 4-2.

5.0 SUMMARY AND CONCLUSIONS

5.1 UNCERTAINTY IN TOTAL COST

5.1.1 Subjective Probability Distributions on Total Cost

The results of the convolution process (described in Section 3.0) are presented in Tables 5-1 through 5-8. Two regulatory scenarios are shown for each oil shale process. The subjective probability distributions on total cost are presented graphically in Figures 5-1 through 5-4. All MIS results assume maximum excess mine water.

Each total cost distribution was calculated separately. As described in Section 3.0, Sturges rule is used to simplify complex intermediate distributions, determining the number of intervals in the simplified versions. Final total cost distributions do not all contain the same number of points.

All final subjective probability distributions have normal distribution shapes. In all cases it appears that the engineering team believes the total costs of pollution control were overestimated. The amount of possible over-estimation is not large for the less strict regulatory scenarios, but is substantial for the more strict scenarios. This is a direct result of the incorporation of hazardous waste disposal regulations into the more strict scenario spent shale management plan. (See Volume I).

The uncertainty is much larger in terms of its cost per barrel impact for the in situ process than it is for the aboveground processes. The TOSCO process has the least uncertainty, as might be expected, since there is more data available on this process than any other. This becomes particularly apparent when the total range of the TOSCO distribution is compared to total control cost on a percentage basis. Making the same comparison for the Paraho, MIS and MIS/Lurgi processes, the cost estimates in Volume I all appear to contain approximately the same percentage uncertainty.

Table 5-1. Subjective Probability vs. Total Cost for Pollution Control,
Paraho Process

Subjective Probability	Change in Total Annual Cost (10 ⁶ \$)	Less Strict Scenario	
		Change in Total Cost Per Barrel Syncrude Equivalent (Dollars)	Total Cost Per Barrel Syncrude Equivalent (Dollars)
0.02	-6.7	-0.21	0.67
0.13	-4.7	-0.15	0.73
0.32	-2.7	-0.09	0.79
0.27	-0.85	-0.03	0.85
0.11	+0.50	+0.02	0.90
0.10	+1.50	+0.05	0.93
0.02	+2.5	+0.08	0.96
0.02	+3.5	+0.11	0.99

Table 5-2. Subjective Probability vs. Total Cost for Pollution Control,
Paraho Process

More Strict Scenario			
Subjective Probability	Change in Total Annual Cost (10 ⁶ \$)	Change in Total Cost Per Barrel Syncrude Equivalent (Dollars)	Total Cost Per Barrel Syncrude Equivalent (Dollars)
0.001	-10.75	-0.34	0.66
0.02	-9.25	-0.29	0.71
0.13	-7.75	-0.25	0.75
0.15	-6.25	-0.20	0.80
0.31	-4.75	-0.15	0.85
0.24	-3.25	-0.10	0.90
0.11	-1.75	-0.05	0.95
0.02	-0.50	-0.02	0.98
0.004	+0.25	+0.01	1.01

Table 5-3. Subjective Probability vs. Total Cost for Pollution Control,
TOSCO II Process

Subjective Probability	Change in Total Annual Cost (10 ⁶ \$)	Less Strict Scenario	
		Change in Total Cost Per Barrel Syncrude Equivalent (Dollars)	Total Cost Per Barrel Syncrude Equivalent (Dollars)
0.002	-3.5	-0.22	1.43
0.05	-2.5	-0.16	1.49
0.36	-1.5	-0.10	1.55
0.33	-0.5	-0.03	1.62
0.14	+0.25	+0.02	1.67
0.11	+0.75	+0.05	1.70
0.02	+1.25	+0.08	1.73

Table 5-4. Subjective Probability vs. Total Cost for Pollution Control,
TOSCO II Process

Subjective Probability	Change in Total Annual Cost (10 ⁶ \$)	More Strict Scenario	
		Change in Total Cost Per Barrel Syncrude Equivalent (Dollars)	Total Cost Per Barrel Syncrude Equivalent (Dollars)
< 0.01	-5.6	-0.36	1.64
0.05	-4.6	-0.29	1.71
0.35	-3.6	-0.23	1.77
0.34	-2.6	-0.17	1.83
0.14	-1.9	-0.12	1.88
0.13	-1.4	-0.09	1.91

Table 5-5. Subjective Probability vs. Total Cost for Pollution Control,
MIS Process

Subjective Probability	Change in Total Annual Cost (10 ⁶ \$)	Less Strict Scenario	
		Change in Total Cost Per Barrel Syncrude Equivalent (Dollars)	Total Cost Per Barrel Syncrude Equivalent (Dollars) *
0.01	-9.5	-0.52	2.02
0.09	-6.5	-0.36	2.18
0.30	-3.5	-0.19	2.35
0.31	-1.0	-0.05	2.49
0.16	+0.5	+0.03	2.57
0.10	+1.5	+0.08	2.62
0.03	+2.5	+0.14	2.68

*Represents high mine water only. For low mine water, subtract 44¢ from each figure.

Table 5-6. Subjective Probability vs. Total Cost for Pollution Control,
MIS Process

Subjective Probability	Change in Total Annual Cost (10 ⁶ \$)	More Strict Scenario	
		Change in Total Cost Per Barrel Syncrude Equivalent (Dollars)	Total Cost Per Barrel Syncrude Equivalent (Dollars)*
0.01	-11.5	-0.63	2.36
0.09	-8.5	-0.47	2.52
0.30	-5.5	-0.30	2.69
0.57	-2.0	-0.11	2.88
0.02	+0.25	+0.01	3.00
0.01	+0.75	+0.04	3.03

*Represents high mine water only. For low mine water, subtract 74¢ from each figure.

Table 5-7. Subjective Probability vs. Total Cost for Pollution Control,
MIS-Lurgi Process

Subjective Probability	Change in Total Annual Cost (10 ⁶ \$)	Less Strict Scenario	
		Change in Total Cost Per Barrel Syncrude Equivalent (Dollars)	Total Cost Per Barrel Syncrude Equivalent (Dollars) *
0.02	-11.7	-0.45	1.68
0.15	-8.5	-0.33	1.80
0.20	-5.5	-0.21	1.92
0.52	-2.0	-0.08	2.05
0.10	+0.75	+0.03	2.16
0.05	+2.25	+0.09	2.22
<0.01	+3.9	+0.15	2.28

*Represents high mine water only. For low mine water, subtract 21¢ from each figure.

Table 5-8. Subjective Probability vs. Total Cost for Pollution Control,
MIS-Lurgi Process

More Strict Scenario			
Subjective Probability	Change in Total Annual Cost (10 ⁶ \$)	Change in Total Cost Per Barrel Syncrude Equivalent (Dollars)	Total Cost Per Barrel Syncrude Equivalent (Dollars) *
0.06	-11.95	-0.46	1.84
0.18	-8.5	-0.33	1.97
0.22	-5.5	-0.21	2.09
0.35	-2.5	-0.10	2.20
0.14	-0.5	-0.02	2.28
0.04	+0.75	+0.03	2.33
0.01	+2.25	+0.09	2.39
<0.01	+3.4	+0.13	2.43

*Represents high mine water only. For low mine water, subtract 34¢ from each figure.

Figure 5-1. Subjective Probability Distributions for Total Pollution Control Costs for Paraho Process

Figure 5-2. Subjective Probability Distributions for
Total Pollution Control Costs for TOSCO II
Process

Figure 5-3. Subjective Probability Distributions for Total Pollution Control Costs for MIS Process

Figure 5-4. Subjective Probability Distributions for
Total Pollution Control Costs for MIS-Lurgi
Process

5.1.2 Total Impact of Unassessed Uncertainty

The point estimates for "Critical Variables Without Experts" (see Sections 3.0 and 4.0) cannot be combined with the subjective probability distributions. Table 5-9 lists these cost centers and their possible impact on total cost per barrel of syncrude equivalent. Their impact is small. The probability of occurrence of these cost impacts was not estimated.

5.2 CONCLUSIONS ON THE COMPLETENESS OF THE UNCERTAINTY ANALYSIS

Estimation of costs associated with most emerging technologies contain substantial error. Initially, costs are underestimated and revised upward as development progresses. This has been apparent in the case of the estimated total cost of producing a barrel of shale oil. A recent analysis has carefully considered the cause of such error and found two important reasons which relate directly to this study.[4] First, it was found that cost estimates increase as the level of detail in the engineering design work increases--knowledge of cost allows for a better estimate. Second, engineering design changes can be a major contributor to increased cost. Other factors such as inflation contribute less to this error of underestimation.

Although the oil shale processes themselves may contain significant technical uncertainties, the pollution controls selected do not. Pollution control technologies which are well understood and have been proven on a commercial scale were used. The cost estimation procedure for the most part relied upon actual current prices obtained firsthand from vendors of the equipment. Installation costs were itemized individually for each piece of equipment. Operating costs were also individually itemized. A high level of engineering detail was possible, even though the oil shale technology itself has not been demonstrated on a commercial scale.

Also, the engineering team has had extensive current experience in the design, installation, and operation of the control technologies selected. For example, a member of the Water Purification Associates staff recently participated in the design of a complete wastewater management system for a synfuels plant in Sasol, South Africa. This plant, a combination of the Lurgi and Fischer-Tropsch processes, is successfully producing gasoline from coal on a commercial scale in an arid region.

Table 5-9. Cost Impact of Unassessed Uncertainty
In Cents per Barrel Syncrude Equivalent

<u>Cost Center</u>	<u>Oil Shale Process</u>			
	<u>Paraho</u>	<u>TOSCO II</u>	<u>MIS</u>	<u>MIS/Lurgi</u>
Bio-oxidation ^(a)	<-3¢	<-5¢	<-13¢	<-9¢
Hot Precipitator	--	--	--	+7¢
Excess Mine Water Treatment ^(b)	<u>--</u>	<u>--</u>	<u>+25¢</u>	<u>+17¢</u>
TOTAL IMPACT	<-3¢	<-5¢	<+12¢	<+15¢

(a) Does not take into account operating cost savings.

(b) Assumes maximum cost of treatment to remove phenol and maximum excess mine water.

Given the ability to look at cost in considerable detail, and a high level of hands-on experience with the actual pollution control technologies, increases in cost which would result from a "better knowledge of cost" should be minimal.

The possibility of design changes must also be examined. Design changes can have two origins--substitution of equipment and changes in institutional requirements. Several alternative technologies may be available for the management of a particular waste stream. Such alternatives were carefully considered during the engineering portion of this study, and selections made which were judged to be optimal. The choices were made using both careful consideration of the technical constraints and a large amount of hands-on experience. Upon commercialization, alternative technologies may be selected. It is highly improbable that such substitution (design changes) would substantially increase cost. Reasonable alternatives appear to have similar costs.

Institutionally induced engineering changes would occur if the environmental regulations actually promulgated for the oil shale industry are considerably more restrictive than those considered in this study. Regulatory uncertainties have been viewed as outside the scope and intent of this study, but rather the purview of the government decision makers. The data base generated by this study is very broad and should allow decision makers to consider regulatory issues in a broad and well informed manner. All regulatory scenarios were supplied by DOE after consultation with EPA (except solid waste management regulations which were specified by DOE only), and the project team had little involvement in the selection process. Most environmental regulations assumed for this study are significantly more restrictive than current regulations applied to other industries.

The assessments of uncertainty presented in Volume II focuses on the most important source of uncertainty--the oil shale processes themselves. Such uncertainty has been quantified and the cost impacts determined. The subjective probability distributions generated can be taken to measure those uncertainties which are outside the control of decision-makers. This analysis of uncertainty is complete and should be helpful in decision-making.

5.3 USE OF THE ASSESSMENT PROCESS TO PINPOINT NEEDED RESEARCH

One of the benefits of the use of the subjective probability assessment process is the identification of areas of needed research. Any cost center found to contain enough uncertainty to warrant an assessment effort is a candidate for further research. Quantification of the uncertainty helps to set priorities.

Table 5-10 shows the high and low values and the range of the subjective probability distributions for the cost centers analyzed. Three cost centers have large associated ranges, and this suggests research is needed. These centers are: the Stretford process; organic removal from wastewater; and slurry backfilling. Spent shale disposal also contains substantial uncertainty, but this uncertainty is entirely due to the use of artificial regulatory scenarios in Volume I.

The Stretford process has been piloted on retort gas already, but now such a process should be piloted with a full complement of retort gas pretreatment activities. Also, more accurate measurement of H_2S , COS , SO_2 , NO_x , and mercaptan quantities in the gas streams is necessary.

Research is now in progress on organic removal in wastewater treatment, sponsored by both government and industry. Answers are badly needed in this area.

Limited research has been performed on slurry backfilling. Further research is needed and major government and industry research programs are presently in the planning stage.

The other uncertainties shown in Table 5-10 are small, indicating extensive research efforts in these areas should not be necessary.

Table 5-10. Comparison of Cost Impact of Uncertainty for Cost Centers Assessed,
Change in Cost per Barrel Syncrude Equivalent,
High, Low and Range

Pollution Control Cost Type	Oil/Shale Process											
	Paraho			TOSCO II			MIS			MIS-Lurgi		
	High Low Range (¢)			High Low Range (¢)			High Low Range (¢)			High Low Range (¢)		
Ammonia Absorber	+1	-3	4	_____			+3	-7	10	+2	-5	7
Stretford Process	+8	-7	15	+4	-4	8	+11	-21	31	+8	-15	23
Phosam Unit	+1	-2	3	+0.3	-0.2	0.5	+2	-5	7	+1	-4	5
Organic Removal	+1	-7	8	+1	-12	13	+2	-31	33	+1	-22	23
Spent Shale Disposal												
Less Strict	+4	-8	12	+4	-10	14	+2	-8	10	+0.1	-2	2.1
More Strict	-6	-18	12	-10	-24	14	-9	-18	9	-4	-2	2
Slurry Backfilling	_____			_____			_____			+10	-18	28

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