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A Cost-Effectiveness Analysis of the *In Situ* Air Stripping Technology at the Savannah River Integrated Demonstration Site

Part 1

by

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Executive Summary

This study reports on an evaluation of a proposed new technology for remediating existing groundwater contamination. Two tasks are undertaken in this report. The first is a conventional cost-effectiveness analysis of the new technology versus existing technologies. In this evaluation several issues are addressed such as the choice of the metric used in the cost-effectiveness analysis, the time period of the evaluation, the appropriate discount rate, and the assumptions used for extrapolation of the field data.

The second task is the extension of the conventional cost-effectiveness analysis to incorporate a decision analysis framework. This extension resolves many issues raised in conducting cost-effectiveness analysis of complex technologies. It allows inclusion of physical modeling, in this case groundwater modeling, to augment the limited field data and to analyze different implementations of the technology.

This study evaluates the performance of the new technology, *in situ* air stripping (ISAS), as compared with a conventional technology that involves the joint use of pump and treat with soil vapor extraction (PT-SVE) using vertical wells.

A simulated ISAS system (using groundwater modeling) showed that there is a return to technology optimization, in that operating costs are substantially lowered by optimizing the operation of the ISAS technology. Thus, the information provided by the groundwater modeling is valuable in conducting the cost-effectiveness analysis.

The cost-effectiveness analysis with the field data demonstrates that ISAS is not cost-effective relative to PT-SVE when the remediation is conducted for very short time periods such as the 21-day field trial. However, over longer term periods such as the 139-day extended trial, ISAS is cost-effective relative to PT-SVE. On the basis of the extrapolated field data for a five-year horizon, the ISAS technology is demonstrated to be superior to the PT-SVE technology.

I. Overview

In situ air stripping (ISAS) is a proposed new groundwater remediation technology that was demonstrated at the Savannah River Integrated Demonstration (SRID) test site in 1990. The ISAS process was designed to remediate soils and sediments above and below the water table as well as groundwater, all contaminated with volatile organic compounds (VOCs). This study evaluates the cost-effectiveness of the ISAS remediation system. In particular, the goal is to investigate the cost-effectiveness of this new environmental technology as compared with conventional technologies for remediation of sites with VOC contamination.

ISAS is based on a simple mass transfer process using horizontal injection and vacuum extraction wells to deliver air and extract contaminants from the subsurface. Two subparallel horizontal wells are used: air is injected under pressure into the lower horizontal well (below the water table); air bubbles through the saturated zone, contacting dissolved, adsorbed, and/or separate phase contaminants, and into the vadose zone (the zone above the water table). Finally, the air and vapors are collected by the upper horizontal gas extraction well. During this process, contaminants are volatilized into the air stream and exit the subsurface through the upper horizontal well. The use of horizontal wells may provide better contact with contaminated subsurface strata than do vertical wells.

To evaluate the cost-effectiveness of the ISAS remediation technology, a performance comparison is done between the new technology and a conventional one. Analysis scenarios are constructed to provide a context for comparison. Finally, the economic comparison of the new and the conventional technology is reported. This section provides an overview of the evaluation. Section II describes the evaluation problem and the physical setting of the

ISAS field demonstrations. Section III presents both short-term and long-term results of the ISAS cost-effectiveness analysis, including an examination of the different criteria for cost-effectiveness. Analysis scenarios are described. Section IV uses the results from groundwater modeling to develop new performance scenarios, examine technology optimization, and demonstrate the role of decision analysis techniques in cost-effectiveness analysis. Section V offers an assessment of the cost-effectiveness of ISAS technology.

Because the aim of the ISAS demonstration was to remove chlorinated solvents in both the vadose zone and in the saturated zone, the baseline or conventional technology selected for comparison consists of two systems. Soil vapor extraction (SVE) using vertical wells is the baseline technology for remediation of the vadose zone, and pump and treat (PT) using vertical wells is the baseline technology for remediation of the saturated zone.

Two tasks are undertaken in this report. The first is a conventional cost-effectiveness analysis of the new technology versus existing technologies. In this evaluation several issues are addressed such as the choice of the metric used in the cost-effectiveness analysis, the time period of the evaluation, the appropriate discount rate, and the assumptions used for extrapolation of the field data. This analysis is presented in Section III.

The second task is the extension of the conventional cost-effectiveness analysis to incorporate a decision analysis framework. This extension resolves many issues raised in conducting cost-effectiveness analysis of complex technologies. It allows inclusion of physical modeling, in this case groundwater modeling, to augment the limited field data and to analyze additional implementations of the technology.

When the technologies being compared are complex and involve many decisions, as is the case for groundwater remediation, decision analysis provides a very useful analytical tool (a decision tree) for dealing with complex problems. The decision analysis approach more fully represents the decisions, recognizes the sequencing or timing issue, takes into account the irreversibilities that may exist, includes new information as it is generated, and is cognizant of the recourse available if the events do not unfold as anticipated. The decision maker chooses from among various branches and is required to make decisions at different times. Decision analysis is needed in this study because there is no unique technology called ISAS that is to be evaluated. The evaluation is done on the best available application of the competing technologies, and this can only be accomplished if all relevant decisions are set out, and the implications of each are taken into account. In this way, the technology is optimized.

Several sources of uncertainty exist concerning the outcomes of decisions taken in implementing a remediation technology: the probability of success, the cost of switching technology midstream, and interactive effects arising from the use of multiple techniques. These uncertainties can be partially resolved with information from field studies, as well as the use of computerized groundwater models.

The methodology used to evaluate the cost-effectiveness of a new environmental technology comprises a performance evaluation and an economic evaluation. The performance evaluation is critical in establishing a balanced comparison from which the economic cost savings of the two (or more) alternative technologies can be calculated. The major components of the methodology are to identify major technology performance characteristics of the new environmental technology; identify appropriate conventional technologies to serve as the baseline for comparison; compare performance between the new technology and the conventional alternatives; use analysis scenarios to provide a realistic context for the performance comparison; perform an economic comparison of the new technology and the conventional alternatives; and use groundwater modeling to construct realistic performance scenarios. Both field-scale characterization and groundwater modeling are used in the cost-effectiveness analysis in order to obtain cost-justified information.

The results of the cost-effectiveness analysis can be summarized as follows: Under a short time frame, ISAS is less cost-effective than the PT-SVE baseline technology. As the time frame of the analysis increases, ISAS becomes more cost-effective, eventually surpassing PT-SVE when a five-year period is analyzed.

II. Description of the Evaluation Problem[1]

The basic physics of ISAS consists of volatilizing contaminants (such as VOCs) into an air stream that is then extracted from the ground. Injected air bubbles contacting dissolved, adsorbed, and/or separate phase contaminants in the aquifer or vadose zone serve as the mechanism for this volatilization. To remove a contaminant from the subsurface in this fashion, the contaminant must easily partition into the vapor phase. Trichloroethylene (TCE) and tetrachloroethylene (PCE) are both easily removed by air stripping. More information on this process is available in [54].[2]

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[1] This section draws heavily from [54].

[2] All references appear in Part 2.

The ISAS field demonstration at the SRID site is fully described in [34]. The characterization data of the SRID site are given in [13]. The characterization study provides baseline information on the geology, geochemistry, hydrology, and microbiology of the demonstration site prior to the test. Concentrations of VOCs in the groundwater and sediments vary vertically and horizontally beneath the site: concentrations measured in groundwater collected from wells before the test (pre-1990) varied from approximately 400 to 1800 ppb TCE, and 20 to less than 200 ppb PCE.

The ISAS demonstration showed the viability of the *in situ* air stripping process for removal of VOCs and demonstrated the presence of access to the subsurface through the use of directional drilling (e.g., horizontal wells). Technical details and results from the ISAS demonstration are (summarized from [34]):

> The ISAS demonstration operated for 139 days. The field test operated at approximately 90% utility (i.e., the system was shut down for repairs or maintenance less than 10% of the time).
>
> A total of almost 16,000 pounds of chlorinated solvents was removed from the subsurface during the test. The extraction rate increased from approximately 109 pounds/day with vacuum extraction only, to approximately 130 pounds/day during the injection of air through the lower horizontal well.
>
> Substantial changes in groundwater VOC concentrations were measured during the test. Most of the monitoring wells at the site exhibited lower concentrations of contaminants and increases in microbial numbers and metabolic activity during the air injection period.
>
> Heterogeneities (both low-permeability and high-permeability zones) influenced the performance of the system. To evaluate the importance of these zones to mass transfer in subsurface remediations, data were collected from monitoring wells, vadose zone piezometers, etc. In addition, geophysical tomography data were collected to image the movement of fluid flow in the subsurface caused by the ISAS air injection and extraction.

The removal rate of chlorinated solvents averaged 115 pounds/day over the 139-day ISAS demonstration.

Extensive pretest and posttest data were collected at the SRID site. The posttest sediment data indicate that more contaminants were destroyed than were simply extracted at the surface. Comparisons of pre- and posttest core data from side-by-side boreholes typically show 20% to 30% reductions in levels of contaminants [14].

The available data from the ISAS demonstration show that contaminant removal can be achieved by either withdrawal of contaminated vapors through the extraction well or by destruction of contaminants in place (e.g., bioremediation). Pounds of VOCs removed in the vapor extraction stream are used as the primary measure of ISAS system performance.

Data presented in [14] indicate that significant reductions in contaminant concentrations occurred in pretest versus posttest core data, which may be attributed to biodegradation. Because contaminant inventories are based on data interpolation and assumptions of geologic properties, they are not included in the quantitative performance scenarios. Such inventory calculations have high uncertainties and large margins of error. Also, pre- and posttest core data for the baseline technologies are not available, so VOC pounds extracted from the vapor stream at the surface are used as the measure of contaminant removal and cost-effectiveness. In addition, total cost per unit of environment remediated and per unit flow of air through the system are reported and assessed.

The baseline or conventional technology used for comparison comprises SVE using vertical wells for remediation of the vadose zone, and PT using vertical wells for remediation of the saturated zone. Both technologies are common practice in current remediation efforts

[58][59]. Both of these technologies have been used at the Savannah River Site (SRS). Also, a pilot study of vertical SVE wells was conducted in 1987 [35]. Therefore, field data from the SRS exist for both the new and baseline technologies analyzed in this study.

For remediation of the vadose zone, both ISAS and SVE employ essentially the same method. Contaminants are volatilized into a moving air stream and are transported to the surface through the extraction well. In the case of ISAS, air is actually injected into the subsurface below the vadose zone. Extraction takes place in a vadose zone well. SVE is a more passive system in that no air is injected into the subsurface. Air enters the vadose zone from the ground surface, and vapors are extracted through the SVE well. The ISAS demonstration suggested that more contaminants were pulled from the vadose zone than from the saturated zone (with vacuum extraction only, the removal rate was about 109 pounds/day; with air injection and vacuum extraction, the removal rate was about 130 pounds/day).

The equivalent PT-SVE system remediates roughly the same subsurface region treated by ISAS at the SRID. The basis of the performance comparison is the amount of contaminant removed from the subsurface.

III. Results Based on Conventional Cost-Effectiveness Analysis

The three criteria used to assess the cost-effectiveness of ISAS are discussed in this section. To obtain data for the long-term comparison, it was necessary to extrapolate beyond existing field data. Extrapolation from the field data and development of the analysis scenarios are described in this section.

A. Criteria for Cost-Effectiveness Evaluation

The following three criteria were developed and applied to evaluate the cost-effectiveness of competing groundwater remediation technologies:

1) dollars per pound of contaminant removed
2) dollars per unit of environment remediated
3) dollars per standard engineering flow rate.

For the 5-year long-term projection, all three criteria are considered. For the 139-day field test, only the first and third criteria are considered.

The first criterion uses the cost per pound of VOC removed to compare the technologies. Because the measurement of VOCs obtained from the vapor extraction stream is fairly accurate, a strong argument is made to use the first criterion. This measure may also be justified on the basis of the mass balance approach. A difficulty with it, however, is the inclusion of contaminant removed underground. Information on the extent of this in-place removal is not available. This omission will bias the results for each of the competing technologies. However, if the underground removal is comparable for different technologies, then the use of dollars per pound of contaminant removed is a valid basis for comparison.

The second criterion better represents the attainment of the regulatory standard—actual removal of the contaminant. Unless the volume of original contaminant in place is known (an unlikely situation in most cases), this measure is difficult to apply and has considerable uncertainty associated with it. Estimates of the volume of the environment that is actually contaminated are imprecise. The volume of the study area vadose zone is 2,656,000 cubic feet (or 74,332 cubic meters), whereas the volume of the groundwater region (below the water table) is 630,000 cubic feet (or 17,849 cubic meters). This amounts to approximately 92,200 cubic meters to be remediated by ISAS. This criterion provides an estimate of the cost per unit volume of the environment remediated.

The third criterion uses the measure of standard engineering flow rate (scfm) through the system. Total costs are compared to this engineering flow rate. This flow rate is measured in terms of the volume of air or groundwater that flows through the system. The flow rate is useful for comparing engineering costs, although it does not address the efficiency of contaminant removal. That is, this approach assumes a perfect correlation between the level of remediation and the flow rate. ISAS uses one horizontal extraction well with a vapor extraction rate of 550-600 scfm. An average vapor extraction rate of 575 scfm is used in the cost-effectiveness analysis. SVE uses four vertical wells with a vapor extraction rate of 250 scfm per well. Thus, the total SVE vapor extraction rate is calculated to be 1,000 scfm for the four wells.

B. Extrapolation of the Field Trial Data and the Various Performance Scenarios

The field trials at the SRID project were conducted for relatively short time periods. The field trials differ in length, and the options are to use only the data for the period that is common to the ISAS and the PT-SVE technologies or to construct an extrapolation of the performance of the techniques that were run for the shorter time period—the PT-SVE system. The shortest time frame is the SVE field trial that ran for only 21 days, which provides the time frame that is used to compare performance based on actual field data. Over the 21 days, ISAS extracted roughly 2,696 pounds, whereas PT-SVE removed about 6,472 pounds. These data are used to construct Analysis Scenario A, "Actual PT-SVE."

The comparison is thus made with the ISAS data for the initial 21 days and the PT-SVE system.

Extrapolation from short-term field data introduces the possibility of errors, so two boundary scenarios are analyzed. The performance scenarios cover a period of 139 days and are constructed from actual field data for ISAS and extrapolations for PT-SVE. For the "low PT-SVE" scenario, an SVE extraction of 10,704 pounds and a PT extraction of 3,250 pounds are used.

To construct the "high PT-SVE" scenario, an SVE extraction rate that is 50% higher than the low extrapolation scenario is assumed. This results in an SVE extraction of 16,056 pounds. Using this extrapolation leads to 19,306 pounds removed for the PT-SVE system, with 16,056 pounds from SVE and 3,250 pounds from PT which is the same as was reported under the "low PT-SVE" scenario. Results of the cost-effectiveness analysis are relatively sensitive to assumptions regarding SVE extraction rates. The higher SVE extrapolation leads to higher carbon recharge costs and higher total site costs. However, the much larger rate of VOC extraction drives average cost per pound significantly lower.

C. Comparison of Short-term Costs

Short-term total costs for each analysis scenario are most sensitive to assumptions regarding the rate of VOC extraction because the extraction rate affects carbon recharge costs. Reasonable bounds within which to consider VOC extraction are established with the extrapolation scenarios for the PT-SVE technology. A summary of costs and effectiveness measures for short-term Analysis Scenario A (the 21-day field data) is presented in

Table 1-III-C-1. (Detailed data for Analysis Scenario A are provided in Tables 2-II-F-1 and 2-II-F-2.)

Table 1-III-C-1. Short-term Analysis Scenario A, "Actual PT-SVE"

	ISAS	PT-SVE
Total Cost	$308,376	$245,353
Total Cost (with carbon recharge)	$325,511	$297,060
Pounds Removed	2,696	6,472
Days	21	21
Dollars/pound	$120.74	$45.90
Dollars/scfm	$566.11	$297.06

The actual system costs over fixed operating periods are reported both including and excluding carbon recharge expenses. Carbon recharge costs depend upon assumptions regarding the VOC extraction rate. In the tables, *Total Cost* refers to the total costs excluding carbon recharge costs incurred during the evaluation. *Total Cost (with carbon recharge)* includes the carbon recharge costs in the total costs. *Pounds Removed* reports the pounds of VOCs removed as measured at the ground surface. *Days* refers to the number of days reported in the data. *Dollars/pound* reports the number of dollars (including the carbon recharge costs) per pound removed. *Dollars/scfm* reports the number of dollars (including the carbon recharge costs) per standard engineering flow rate.

ISAS technology is more capital-intensive than the conventional PT-SVE system due to the initial capital cost involved in horizontal well drilling and installation. Thus, for short-term evaluations such as the 21-day period presented in Analysis Scenario A, "Actual

PT-SVE," PT-SVE is clearly more cost-effective than ISAS in terms of both the dollars per pound removed and the dollars per scfm criteria. For the short-term analysis scenario, ISAS technology costs 2 to 2-1/2 times the baseline (PT-SVE) technology.

Costs and effectiveness measures for short-term Analysis Scenario B are summarized in Table 1-III-C-2. (Detailed data for Analysis Scenario B are provided in Tables 2-II-F-4 and 2-III-F-5 in Part 2.)

Table 1-III-C-2. Short-term Analysis Scenario B, "Low PT-SVE Extrapolation"

	ISAS	PT-SVE
Total Cost	$377,218	$348,616
Total Cost (with carbon recharge)	$478,906	$457,735
Pounds Removed	16,000	13,954
Days	139	139
Dollars/pound	$29.93	$32.80
Dollars/scfm	$832.88	$457.54

For Analysis Scenario B, "Low PT-SVE Extrapolation," ISAS is slightly more cost-effective than PT-SVE using the dollars per pound criterion. However, PT-SVE is more cost-effective when considering the dollars per scfm criterion. For reasons discussed in detail in Part 2, the dollars per pound is a more appropriate criterion for evaluating environmental remediation.

Costs and effectiveness measures for short-term Analysis Scenario C are summarized in Table 1-III-C-3. (Detailed data for Analysis Scenario C are provided in Tables 2-II-F-7 and 2-II-F-8 in Part 2.)

Table 1-III-C-3. Short-term Analysis Scenario C, "High PT-SVE Extrapolation"

	ISAS	PT-SVE
Total Cost	$377,218	$348,616
Total Cost (with carbon recharge)	$478,906	$500,90
Pounds Removed	16,000	19,306
Days	139	139
Dollars/pound	$29.93	$25.95
Dollars/scfm	$832.88	$500.90

For Analysis Scenario C, "High PT-SVE Extrapolation," PT-SVE is more cost-effective than ISAS using both the dollars per pound and the dollars per scfm criteria. ISAS is found to be 115.34% more costly than PT-SVE under the dollars per pound criterion, and 166.28% more costly under the dollars per scfm criterion.

For the three short-term analysis scenarios, using the dollars per pound criterion, PT-SVE technology is generally more cost-effective than ISAS.

D. Long-term (5-year) Cost Comparison

The "long-term low PT-SVE extrapolation" analysis scenario assumes the low PT-SVE extraction is maintained throughout the first year at the 139-day rate. Combined PT-SVE extraction begins at 103 pounds per day for the first year, falls to 77 pounds per day for the second year, then levels off at 51 pounds per day for the third through fifth years. The VOC extraction rate is assumed to be 75% in the second year and 50% for the third through fifth years. Over the 5-year time period, PT-SVE technology removes 121,545 pounds of VOCs. By comparison, ISAS removes a total of 135,780 pounds.

The "long-term high PT-SVE extrapolation" analysis scenario assumes the high PT-SVE extrapolation for the first year. PT-SVE extraction begins at 139 pounds per day for the first year, falls to 104 pounds per day for the second year, then levels off at 69 pounds per day for the third through fifth years. Over the 5-year long-term period, PT-SVE technology removes 64,761 pounds of VOCs are assumed to be removed. Again, ISAS removes 135,780 pounds.

An estimate of cubic meters remediated and dollars per unit of environment remediated can be calculated. Groundwater modeling results show that approximately 50% of the initial VOC contaminant mass in place is removed after 5 years. Over the same 5-year period, approximately 110,230 pounds of VOCs are assumed to be removed. Doubling this amount suggests that approximately 220,000 pounds of VOCs were originally in place, but there is considerable uncertainty associated with this estimate. A one-to-one correspondence between VOC pounds extracted and units of environment remediated is also assumed. For the ISAS extraction of 135,780 pounds, 56,904 cubic meters were remediated. For the low PT-SVE extraction of 121,545 pounds, 50,938 cubic meters were remediated. For the high PT-SVE extraction of 164,761 pounds, 69,050 cubic meters were remediated.

Long-term costs over the 5-year time period for Analysis Scenario D are compared in Table 1-III-D-1. (Detailed data for Analysis Scenario D are provided in Tables 2-II-G-1 and 2-II-G-2.) To evaluate net present value (NPV), a discount rate of 7% is used in this analysis scenario. The results based on alternative discount rates are discussed in Part 2.

Table 1-III-D-1. Long-term Analysis Scenario D, "Long-term Low PT-SVE Extrapolation"

	ISAS	PT-SVE
Net Present Value	$1,298,218	$1,730,122
Net Present Value (with carbon recharge)	$2,122,705	$2,614,863
Pounds Removed	135,780	121,545
Years	5	5
NPV/pound	$15.63	$21.51
NPV/cubic meter	$37.30	$51.33
NPV/scfm	$3,691.66	$2,614.86

For Analysis Scenario D, "Long-term Low PT-SVE Extrapolation," ISAS is somewhat more cost-effective than PT-SVE using the criteria of net present value per pound removed and net present value per cubic meter remediated. However, PT-SVE is more cost-effective when considering the criterion of net present value per scfm.

Long-term costs over the 5-year time period for Analysis Scenario E are compared in Table 1-III-D-2. (Detailed data for Analysis Scenario E are provided in Tables 2-II-G-4 and 2-II-G-5.)

Table 1-III-D-2. Long-term Analysis Scenario E, "Long-term High PT-SVE Extrapolation"

	ISAS	PT-SVE
Net Present Value	$1,298,218	$1,730,122
Net Present Value (with carbon recharge)	$2,122,705	$2,896,654
Pounds Removed	135,780	164,761
Years	5	5
NPV/pound	$15.63	$17.58
NPV/cubic meter	$37.30	$41.95
NPV/scfm	$3,691.66	$2,896.65

For Analysis Scenario E, "Long-term High PT-SVE Extrapolation," the results are the same as those in Analysis Scenario D. ISAS is more cost-effective than PT-SVE using the criteria of net present value per pound removed and net present value per cubic meters remediated. PT-SVE is again more cost-effective when considering the criterion of net present value per scfm.

For the two long-term analysis scenarios, using the criterion of net present value per pound removed, ISAS is less costly than the PT-SVE baseline (representing 72.66% and 88.91% of the baseline technology costs, respectively). This conclusion is clearly consistent with the earlier observation that ISAS is a more capital-intensive technology than PT-SVE. Thus ISAS is more cost-effective over the 5-year long-term time period. An interesting comparison can be made between the "high PT-SVE extrapolation" for the short-term and long-term analysis scenarios. Considering the "high PT-SVE extrapolation" over the short-term time frame, PT-SVE is more cost-effective. However, ISAS is more cost-effective over the long-term time frame due to the carbon recharge costs.

These measures are most sensitive to assumptions regarding the rate of VOC extraction. Reasonable bounds within which to consider long-term VOC extraction were established.

IV. Cost-Effectiveness Analysis Employing Groundwater Modeling

Groundwater modeling provides more complete performance scenarios for both short-term and long-term cost comparison. Groundwater modeling is used to assess "technology optimization," in which different operating conditions and strategies are simulated and examined for the ISAS technology. This modeling supports the decision analysis approach and reinforces the decision theoretic environment, in which the decision maker has available an array of alternatives. Technology optimization includes system management choices such as pulse, cyclic, or continuous pumping. The use of modeling can guide the design of future ISAS systems and other remediation technologies.

A. Overview

"History-matching" of the actual ISAS field test data was used to establish an ISAS long-term performance scenario. Numerical simulations were then made from the "history-matching" of TCE concentration data from the ISAS demonstration. In the modeling results that follow, TCE and PCE each account for about 50% of the VOC mass. An estimate of the total VOC mass may be made by doubling the TCE amount. Using groundwater modeling results, ISAS combined stripping/extraction may be compared to ISAS extraction only.

Preliminary results indicating the number of years required to remove a given fraction of the initial TCE inventory are shown below.

Table 1-IV-A-1. Years Required to Achieve Removal of a Given Percent of TCE

Amount Removed	Stripping/Extraction	Extraction Only
50%	4.3	5.1
75%	8.9	11.4
90%	15.3	22.6
95%	20.6	>27.4

With both stripping and extraction, only 50% of the original TCE is removed after 4.3 years. This illustrates the difficulty of obtaining large removal fractions for a heterogeneous site such as SRID. Results in [49] noted that "air injection has a very small long-term benefit in these predictions because the accessible TCE has been extracted at early time." (p. 5)

B. Long-term Modeling Results

Estimates from history-matching of the ISAS demonstration in [49] suggest a downward revision in total VOC removal for ISAS for the first year and for each of the following years. From ISAS modeling, VOC removal is calculated as 91 pounds per day for the first year, followed by 67, 58, 48, and 38 pounds per day, respectively, for the second through fifth years. Over the 5-year long-term modeling time period, 110,230 pounds of VOCs are assumed to be removed. This compares to the 135,780 pounds removed by ISAS as described in [54] and used in long-term Analysis Scenarios D and E.

Long-term costs over the 5-year time period are compared for the ISAS performance found in the long-term Analysis Scenarios D and E and in an ISAS modeling performance scenario. A discount rate of 7% is used. This estimate of long-term total extraction from ISAS modeling also provides a means to calculate an estimate of the initial contaminant mass in place. With total extraction estimated to be 110,230 pounds at 5 years and a removal percentage of 50%, 220,000 pounds of contaminant are assumed to be in place originally.

Long-term modeling results of ISAS performance are presented in Table 1-IV-B-1 and compared to the results from the long-term Analysis Scenarios D and E.

Detailed data for ISAS modeling are provided in Table 2-III-B-1. ISAS modeling results suggest a lower total of pounds removed, which results in a lower net present value (with carbon recharge) but slightly higher net present value per pounds removed and net present value per cubic meter remediated. Net present value per scfm is slightly lower because net present value (with carbon recharge) is lower.

Table 1-IV-B-1. Summary of Long-term ISAS Modeling Results

	ISAS Modeling Results	ISAS Results from Analysis Scenarios D and E
Net Present Value	$1,298,218	$1,298,218
Net Present Value (with carbon recharge)	$1,926,438	$2,122,705
Pounds Removed	110,230	135,780
Years	5	5
NPV/pound	$17.48	$15.63
NPV/cubic meter	$41.79	$37.30
NPV/scfm	$3,350.33	$3,691.66

C. Technology Optimization

With technology optimization modeling, the study examines the effect of different operating conditions and strategies in order to develop a performance scenario. Optimization of system design and operation can reduce overall system costs, as results in [49] clearly demonstrate. When cyclic (30 days on, 30 days off) injection and extraction was compared to continuous operation in order to assess the effect on system operation costs, results indicate that the TCE mass removed decreased by just 25% when the system was operated only 50% of the time. Such results clearly demonstrate the effect of different operating conditions and strategies on ISAS system performance and point out the potential cost return associated with technology optimization modeling.

1. Short-term Cost Comparison

In the decision tree representation of this problem, different operating strategies for the ISAS system are made available. The study investigates the potential that technology optimization modeling offers for reducing ISAS short-term costs. Results from short-term ISAS technology optimization modeling are presented in Table 1-IV-C-1, which compares these results with the 139-day field data.

Table 1-IV-C-1. Summary of Results from Short-term ISAS Technology Optimization Modeling

	ISAS Technology Optimization Model	ISAS 139-day Field Data
Total Cost	$336,672	$377,218
Total Cost (with carbon recharge)	$412,938	$478,906
Pounds Removed	12,000	16,000
Days	139	139
Dollars/pound	$34.41	$29.93
Dollars/scfm	$718.15	$832.88

Detailed short-term cost data for ISAS technology optimization modeling are found in Table 2-III-C-1. Excluding carbon recharge costs, the ISAS technology optimization operation and maintenance costs are 50% of the ISAS 139-day field test, because the system is assumed to be running only one-half the time. Total costs are lower, but not by the same proportion as pounds removed. Dollars per pound removed are slightly higher, whereas dollars per scfm are somewhat lower.

2. Long-term Cost Comparison

For the long-term cost comparison evaluation, results from ISAS technology optimization modeling are compared to results from the base case ISAS modeling. A reduction in long-term VOC removal of 25% is assumed. Long-term ISAS technology optimization results are presented in Table 1-IV-C-2.

Table 1-IV-C-2. Summary of Results from Long-term ISAS Modeling

	ISAS Technology Optimization Model	ISAS Base Case Model
Net Present Value	$797,172	$1,298,21
Net Present Value (with carbon recharge)	$1,268,337	$1,926,438
Pounds Removed	82,673	110,230
Years	5	5
NPV/pound	$8.63	$17.48
NPV/cubic meter	$36.61	$37.30
NPV/scfm	$2,205.80	$3,350.33

Detailed long-term data for ISAS technology optimization modeling are found in Table 2-III-C-3. In comparing ISAS technology optimization modeling results to ISAS base case modeling results, it is most interesting to observe the percent deviation. All percentages are less than 100%. The ISAS technology optimization model indicates a significant reduction in total costs, both with and without consideration of carbon recharge costs. Net present value per VOC pound removed is reduced by nearly one half. Net present value per cubic meter remediated is also lower. Net present value per scfm is lower by approximately one third. It appears that the modeling of technology optimization shows promising results. Such modeling may guide the design and construction of future ISAS systems.

V. Conclusion

ISAS was demonstrated at the SRID test site in 1990 to be an effective new remediation technology for the removal of chlorinated solvents from contaminated soil and groundwater. ISAS was compared to a baseline groundwater remediation technology (PT-SVE) to assess the cost-effectiveness of ISAS. With groundwater modeling, it was possible to compare a particular field trial, such as the SRID implementation of ISAS, to a projection of how ISAS would perform under ideal implementation.

To compare the cost-effectiveness of ISAS to the baseline PT-SVE system, three metrics were used: dollars per pound of contaminant removed, dollars per cubic meter of environment remediated, and dollars per standard engineering flow rate. For the comparison of short-term costs (21 days and 139 days), only the first and third criteria metrics reported. An estimate of the second metric, dollars per unit of environment remediated, is more problematic. It is included only in the comparison of long-term costs (5 years).

From the dollars per pound of contaminant removed metric, several conclusions may be draw. In the very short (21 days) field trial comparison, ISAS is not as cost-effective as the baseline PT-SVE technology. For the 139-day trial, ISAS is likely to be as cost-effective as the PT-SVE baseline. (In the Low Extrapolation scenario for the PT-SVE technology, ISAS is superior. In the High Extrapolation scenario, ISAS fares less well against the

PT-SVE baseline.) In the long-term (5 years) comparison, ISAS appears to be superior to PT-SVE.

It is worth noting that the ISAS field trial analyzed in this report was a demonstration project. As such, it encountered numerous technical problems in implementation, and these problems may have raised the capital costs significantly. Additional experience with ISAS technology should lead to lower construction and installation costs in future applications. Overall, ISAS appears to be a viable technology for future environmental restoration projects.

Groundwater modeling expands the role of cost-effectiveness analysis by complementing field studies. Field-scale tests are costly and often restricted by physical circumstances. Groundwater modeling results were compared to the long-term analysis scenarios. Furthermore, groundwater modeling results contributed to an estimate of the original contaminant mass in place and to technology optimization assessments.

For the short term, ISAS technology optimization costs were compared with actual ISAS 139-day field-scale test costs. For the long term, ISAS technology optimization costs were compared with ISAS base case modeling costs. One tradeoff that technology optimization modeling points out is: does the penalty of decreased average mass removal justify the decrease in operating costs over the long term? The percent deviation of ISAS technology optimization from the baseline (ISAS modeling) was less than 100% for all categories. These promising results indicate that technology optimization modeling may guide the design and construction of future ISAS systems.

A Cost-Effectiveness Analysis of the *In Situ* Air Stripping Technology at the Savannah River Integrated Demonstration Site

Part 2

by

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Abstract

In situ air stripping with horizontal wells has been demonstrated at the Savannah River Integrated Demonstration Site to be an effective new remediation technology for the removal of chlorinated solvents from contaminated soil and groundwater. Approximately 16,000 pounds of volatile organic compounds were removed by the horizontal vapor extraction well during the 139-day field test in 1990. Several analysis scenarios are constructed that compare *in situ* air stripping with conventional methods for remediation of a site. These analysis scenarios evaluate short-term costs (21 days and 139 days) and long-term costs (5 years) using various assumptions regarding technology performance.

A methodology for conducting comprehensive cost-effectiveness analyses of competing technologies for remediation of groundwater contamination is presented. This methodology integrates economic decision making, groundwater modeling, and field-scale test data. It has the advantage of being able to provide complete evaluation of the competing technologies under a wide variety of implementation and performance scenarios. Field data alone are not sufficient because field implementations are unique and provide no data on alternate implementations. The approach presented here allows several different technologies to be compared and allows the decision maker to compare several methods that have not yet been applied in the field.

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I. Conceptual Framework

A. Introduction

1. Overview of the Task

In situ air stripping (ISAS) is a remediation technology that was demonstrated at the Savannah River Integrated Demonstration (SRID) test site in 1990[1]. The demonstration used two directionally drilled horizontal wells to deliver air and extract contaminants from the subsurface. The ISAS process was designed to remediate soils and sediments above and below the water table as well as groundwater, all contaminated with volatile organic compounds (VOCs).

The primary purpose of this study is to evaluate the cost-effectiveness of the ISAS remediation system. In particular, the goal is to investigate the cost savings possible from using this new environmental technology rather than more conventional technologies for remediation of sites with VOC contamination. A second task is to extend the conventional cost-effectiveness analysis to incorporate a decision analysis framework. This extension resolves many issues raised in conducting cost-effectiveness analysis of complex technologies.

ISAS, as demonstrated at the SRID, is based on a simple mass transfer process using horizontal injection and vacuum extraction wells. Two subparallel horizontal wells are used. Air is injected under pressure into the lower horizontal well (below the water table); air

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[1] The SRID is a collection of demonstrations of new environmental technologies and remediation systems, located at the U.S. Department of Energy (DOE) Savannah River Site, near Aiken, South Carolina. The demonstration, testing, and evaluation of such new environmental remediation methods play an important role in the campaign to clean up the nation's waste sites. New remediation technologies and systems are expected to prove more effective and less expensive for restoring sites with environmental contamination.

bubbles through the saturated zone, contacting dissolved, adsorbed, and/or separate phase contaminants, and continues into the vadose zone (the zone above the water table). Finally, the air and vapors are collected by the upper horizontal gas extraction well (Figure 2-I-A-1). During this process, contaminants are volatilized into the air stream and exit the subsurface through the upper horizontal well. The use of horizontal wells may provide better contact with contaminated subsurface strata than vertical wells.

Previous reports [7][53] outline the methodology used here for evaluating the cost-effectiveness of a new environmental technology. First, a performance comparison is done between the new environmental technology and a similar or related conventional technology (i.e., one used in common practice). Analysis scenarios are constructed to provide a realistic context for comparison. Finally, an economic comparison is made between the new and the baseline technologies.

Because the aim of the ISAS demonstration was to remove chlorinated solvents in both the vadose zone and in the saturated zone (both groundwater and sediments below the water table), the baseline or conventional technology used for comparison consists of two systems. Soil vapor extraction using vertical wells is the baseline technology for remediation of the vadose zone; pump and treat using vertical wells is the baseline technology for remediation of the saturated zone.

The cost-effectiveness analysis of a new environmental remediation system such as ISAS with horizontal wells poses numerous challenges. Among the prevailing issues are:

- The depth of understanding of performance issues

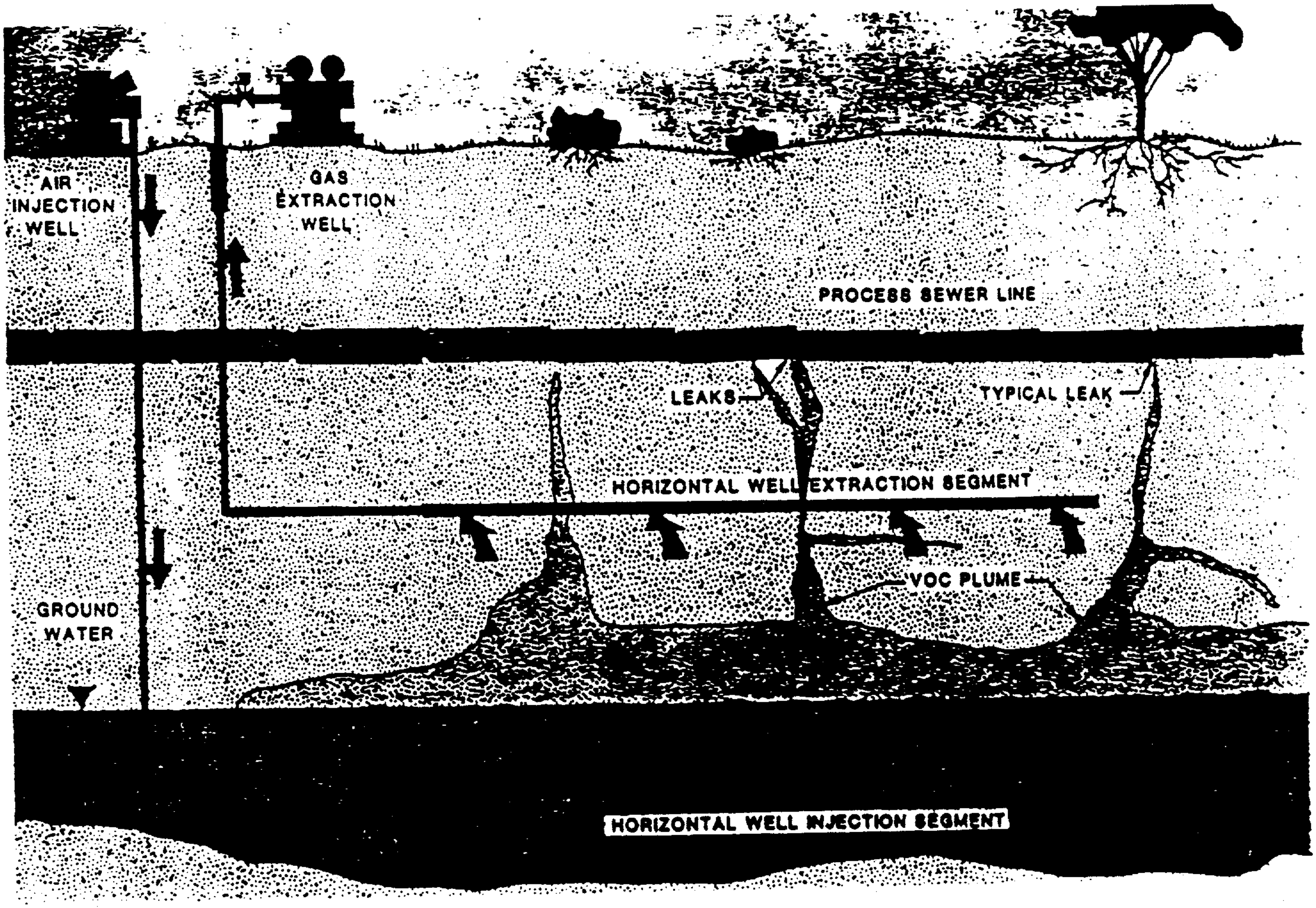

Figure 2-I-A-1. Schematic diagram of horizontal well *in situ* air stripping concept, [63].

Field data from the ISAS demonstration will be used to describe the performance of the system. As such, the performance scenario constructed in this study is a simple, although still useful, estimate. Ongoing efforts in analytical and numerical modeling of the ISAS remediation system will provide further insight. Through such modeling, the subsurface processes at the Savannah River Site (SRS) can be better understood. Also, modeling can be used to extend results and insight to other sites with different subsurface parameters. In addition to modeling, analysis of the SRID pre- and posttest characterization data will add to the understanding of ISAS performance.

- Extrapolation of performance data

  Field data from the SRID demo provides a limited history of observable performance: the ISAS demonstration lasted 139 days. However, evaluations of a new remediation technology must consider performance over time spans of years. Thus, the problem is to make reasonable long-term extrapolations of performance based only on short-term field tests.

- The fact that no single technology can accomplish all cleanup goals

  ISAS with horizontal wells is proposed as one more "tool" in the "toolbox" of technologies for environmental restoration (ER) [13]. That is, it is important to recognize that no one new technology is viewed as the solution to all ER problems. Each ER site is very different in terms of geology, hydrology, type of contamination, cleanup goals, etc. Because of these site differences, no one new technology can be expected to revolutionize the remediation business in terms of cost. Nonetheless, significant cost savings may be achievable by use of new technologies. Thus, this cost-effectiveness study emphasizes that the economic value of ISAS is closely tied to its use in appropriate application areas.

- Demonstration versus full-scale design and wide application

  The SRID program provides simply a demonstration of a new technique. It cannot, by definition, answer all questions about the performance of a new technology. One partial solution to this problem is to employ groundwater models to simulate the performance of new technologies under different conditions.

This study reports on an evaluation of a proposed new technology for remediating existing groundwater contamination. Two tasks are undertaken in this report. The first is a conventional cost-effectiveness analysis of the new technology versus existing technologies. In this evaluation several issues are addressed such as the choice of the metric used in the cost-effectiveness analysis, the time period of the evaluation, the appropriate discount rate, and the assumptions used for extrapolation of the field data.

The second task is the extension of the conventional cost-effectiveness analysis to incorporate a decision analysis framework. This extension resolves many issues raised in conducting cost-effectiveness analysis of complex technologies. It allows inclusion of physical modeling, in this case groundwater modeling, to augment the limited field data and to analyze different implementations of the technology.

This study evaluates the performance of the new technology, *in situ* air stripping (ISAS), as compared with a conventional technology that involves the joint use of pump and treat with soil vapor extraction (PT-SVE) using vertical wells.

A simulated ISAS (using groundwater modeling) showed that there is a return to technology optimization in that operating costs are substantially lowered by optimizing the operation of the ISAS technology. Thus, the information provided by the groundwater modeling is valuable in conducting the cost-effectiveness analysis.

2. Introduction to Cost-Effectiveness Analysis

The problem addressed by the Department of Energy at the Savannah River Site (SRS) is how to choose a least-cost method for the remediation of existing contamination of groundwater. The environmental standard for cleanup is predetermined. As such, a decision maker's objective is to select a technology or set of technologies that meet the standard at the least cost. The appropriate framework is a comprehensive cost-effectiveness analysis of the alternative technologies.

Typically, an analyst is asked to present a set of available options to decision makers, who choose from among these options according to their objective function. In a cost-benefit framework the analyst provides the net present value of each option. Cost-effectiveness analysis is a subset of cost-benefit analysis in that the benefits are assumed to be entirely captured by meeting the regulated standard.[2] In conducting cost-effectiveness analysis, the analyst provides, in the simplest of cases, the cost of each option for meeting the required standard.

B. Integrating Decision Analysis Engineering Models and Groundwater Modeling into a Cost-Effectiveness Analysis

1. The Framework

To evaluate ISAS we propose to integrate an economic decision theory model, a groundwater model, and an engineering model describing the remediation technologies to develop a method of conducting a cost-effectiveness analysis for complex projects. This system is, by necessity, interdisciplinary in nature because the problem to be addressed bridges the disciplines of hydrology, decision theory, and economics.

The analysis yields a more comprehensive cost-effectiveness analysis. Thus, the project evaluation is extended beyond conventional cost-effectiveness analysis by utilizing groundwater modeling activity.

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[2] This raises questions of how we should value a technology that exceeds the standard, or how we should value technologies that fall just short of the standard. Such issues are beyond the scope of this report.

There are three key points to the analysis of technologies for groundwater remediation:

1. The use of decision trees is necessary to identify the alternatives to be analyzed by cost-effectiveness analysis;

2. Groundwater modeling provides the rewards and probabilities depicted in the decision tree and also assists in the structuring of the tree itself; and

3. Data required for the implementation of the decision tree are provided by field tests and groundwater modeling activity.

2. The Basic Structure

The optimizing condition depends on the objective (eg., cost minimization), the decision variables, and the constraints imposed by engineering considerations, groundwater flows, and economics.

Thus, the integrated model framework consists of three components:

1. The groundwater model represents the contaminant transport within the aquifer. The model reports the relationship between groundwater conditions (specifically the contaminant level) and the decision variables represented in the management process. Further it relates the management or decision variables (number of wells, configuration of wells, pressure gradients, well operation profile, etc) to the output (contaminant level, dispersion, etc);

2. The engineering model consists of costs of the physical configuration and operation of the remediation technology; and

3. The decision model or the management model relates the objective to be attained (eg., cost minimization), the costs of failure (penalty function), and the timing of the decisions (modeled as a decision tree)

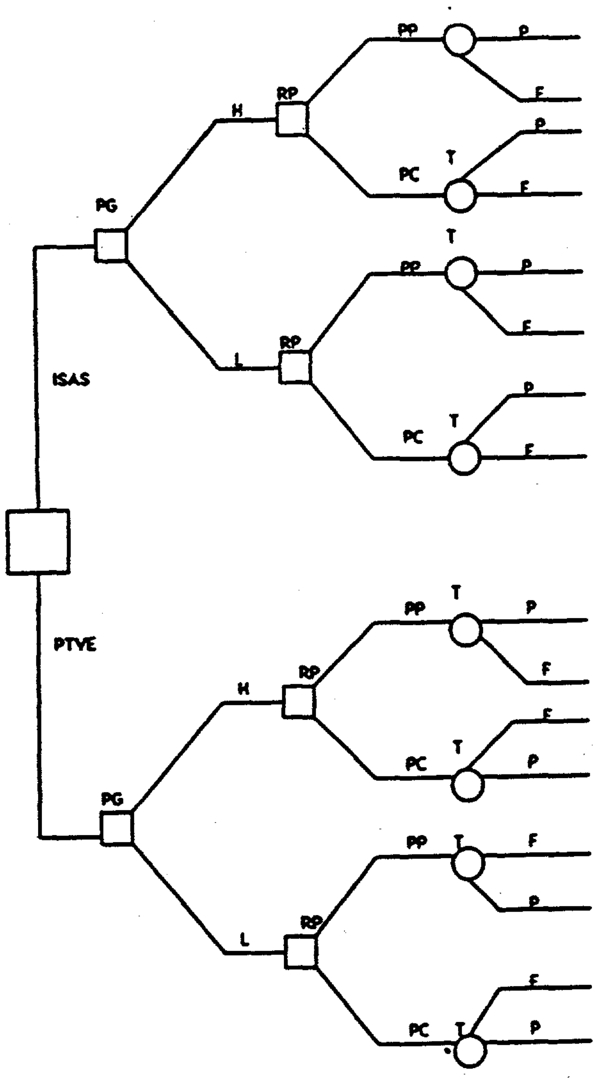
II. Empirical Implementation

A. Cost-Effectiveness Analysis of ISAS and Decision Theory

The groundwater remediation project occurs in a decision theoretic environment. The decision tree framework illustrates how choices are available over time. At each stage, the decision maker chooses whether to undertake an action or to do nothing. The choices are made in response to the state of nature, which may be described as good, bad, or unknown.

Since the outcome of each remediation technique is uncertain, the cost-effectiveness analysis should directly address the issue of uncertainty. A conventional cost-effectiveness analysis would consider a single branch of a decision tree, represents a unique branch of the ISAS technology to be studied (see Figure 2-II-A-1). A more comprehensive cost-effectiveness analysis would fully integrate an economic decision theory model, a groundwater model, and an engineering model. The usefulness of the groundwater and engineering modeling effort arises from their ability to provide information that complements field data. This enhanced cost-effectiveness analysis would allow evaluation of alternative implementations of ISAS, which appear as new paths in the decision tree. Both field-scale characterization and groundwater modeling should be used in the cost-effectiveness analysis.

The comprehensive cost-effectiveness analysis will outline an approach in which temporal decision points may be evaluated as new information is obtained regarding a remediation technique. As an example, monitoring and sampling the remediation activities may result in the acquisition of new information. This information should improve the understanding of the physical setting in which the groundwater remediation occurs.



Notation: Circles represent uncertain outcomes due to states of nature/ Boxes represent decisions.
ISAS - in situ air stripping/ PTVE - pump and treat with soil vapor extraction.
PG - pressure gradient. For ISAS it is the difference in pressure between the injection and the extraction well.
H - high pressure gradient; large difference in pressures/ L - low pressure gradient; small difference in pressures.
PP - pulse the pumping; vary PG/ PC - run the pumping continuously at the same PG.
T - test the groundwater to determine whether it meets the regulatory standard/ P - pass the standard/ F - fail the standard.

If the groundwater fails the test, the choices are to continue with the current facility or to modify the facility and continue. Under the current regulatory regime stopping the process entirely is not an option.

Figure 2-II-A-1. A decision tree.

Furthermore, this new information may be obtained some time after the initiation of remediation activity. Since much of the relevant information is unavailable as the groundwater remediation begins, the decision maker should be actively engaged in a process of learning and updating information. In this way the decision maker must evaluate the implications of this new information within the decision process; the more comprehensive cost-effectiveness analysis must also utilize a temporal sequence of decision points. This results in a series of decisions regarding the implementation of remediation that seeks to bring about cost minimization. In cost-effectiveness analysis all benefits are assumed to be derived from attainment of the standard. In the current case, the standard is predetermined at 5 parts per billion (ppb) for trichloroethylene (TCE) and tetrachloroethylene (PCE). The goal is to choose the groundwater remediation technology that satisfies the mandated standard at minimum cost.

Review of the ISAS history indicates that several choices were made during ISAS operation. These choices included the initiation/termination of events, flow rates or heating temperatures, and equipment maintenance (this resulted, of course, in a shutdown). The ISAS demonstration of horizontal well groundwater remediation illustrates how real-time decisions are made that inject uncertainty. Following are several examples that illustrate the choices that were made[3].

Vacuum extraction was initiated on day 1 and terminated on day 139. It was maintained at a flow rate of 550-600 scfm. Some equipment maintenance resulting in a

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[3] Similar choices were made for the PT-SVE technology.

shutdown occurred for vacuum extraction. The longest shutdown associated with vacuum extraction was 16 hours.

Air injection was initiated on day 16 and terminated on day 113. Air was first injected at a low rate (65 scfm) on day 16. This was increased to a medium rate (170 scfm) on day 28. The rate was increased again to a high rate (270 scfm) on day 69. Finally, the rate was decreased to a medium rate on day 112. Heating of injected air is another option available to the decision maker. The injected air heating temperature was increased on day 49. This temperature was maintained until shutdown on day 113. There also was some equipment maintenance that resulted in a shutdown. The longest shutdown associated with the air injection option was 21 hours.

Finally, some vacuum extraction and air injection decisions were joint decisions. This occurs with an equipment maintenance shutdown resulting from the joint use of vacuum extraction and air injection. The longest shutdown associated with this joint use was almost 42 hours.

B. Description of the Problem[4]

1. *In Situ* Air Stripping

The basic physics of ISAS consists of volatilizing contaminants into an air stream that is then extracted from the ground. Injected air bubbles contacting dissolved, adsorbed, and/or separate phase contaminants in the aquifer or vadose zone serve as the mechanism for this volatilization. In order for a contaminant to be removed from the subsurface in this

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[4] This section draws upon heavily from [54].

fashion, the contaminant must easily partition into the vapor phase. A Henry's Law constant (K_H) of greater than 10^{-5} atm-m^3/mole indicates a strippable volatile constituent [3]. The chlorinated solvent contaminants found at the SRID site are trichloroethylene (TCE) and tetrachloroethylene (PCE). K_H for TCE is 9.9×10^{-3} atm-m^3/mole, and K_H for PCE is 1.5×10^{-2} atm-m^3/mol [3]. Therefore, TCE and PCE are easily removed by air stripping.

Successful ISAS requires good contact between the injected air and the contaminated soils and groundwater. In the ideal situation, a homogeneous saturated zone would allow for even vertical migration of the injected air. Heterogeneities in the subsurface (e.g., clay layers or clay lenses) can cause variations in the movement of air or water. Sands generally have high permeability (under saturated conditions), whereas clays are relatively nonpermeable. Hence, less than optimum contact between air and contaminants may exist if the injected air preferentially follows high permeability paths.

The ISAS field demonstration at the SRID site is fully described in [34]. Throughout this report, reference is made to the "*in situ* air stripping" demonstration meaning "*in situ* air stripping using horizontal wells." The ISAS demonstration took place within the bounds of the Integrated Demonstration Site at Savannah River. This SRID site is a small part of a larger surrounding remediation site with an existing pump and treat system in place. As such, the ISAS demonstration at the SRID was set up to address a "hot spot" of this overall larger contaminant plume.

The characterization data of the SRID site are given in [13]. The characterization study provides baseline information on the geology, geochemistry, hydrology, and [illegible] of the demonstration site prior to the test. Following is a summary of the

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[4] This section draws upon heavily from [54].

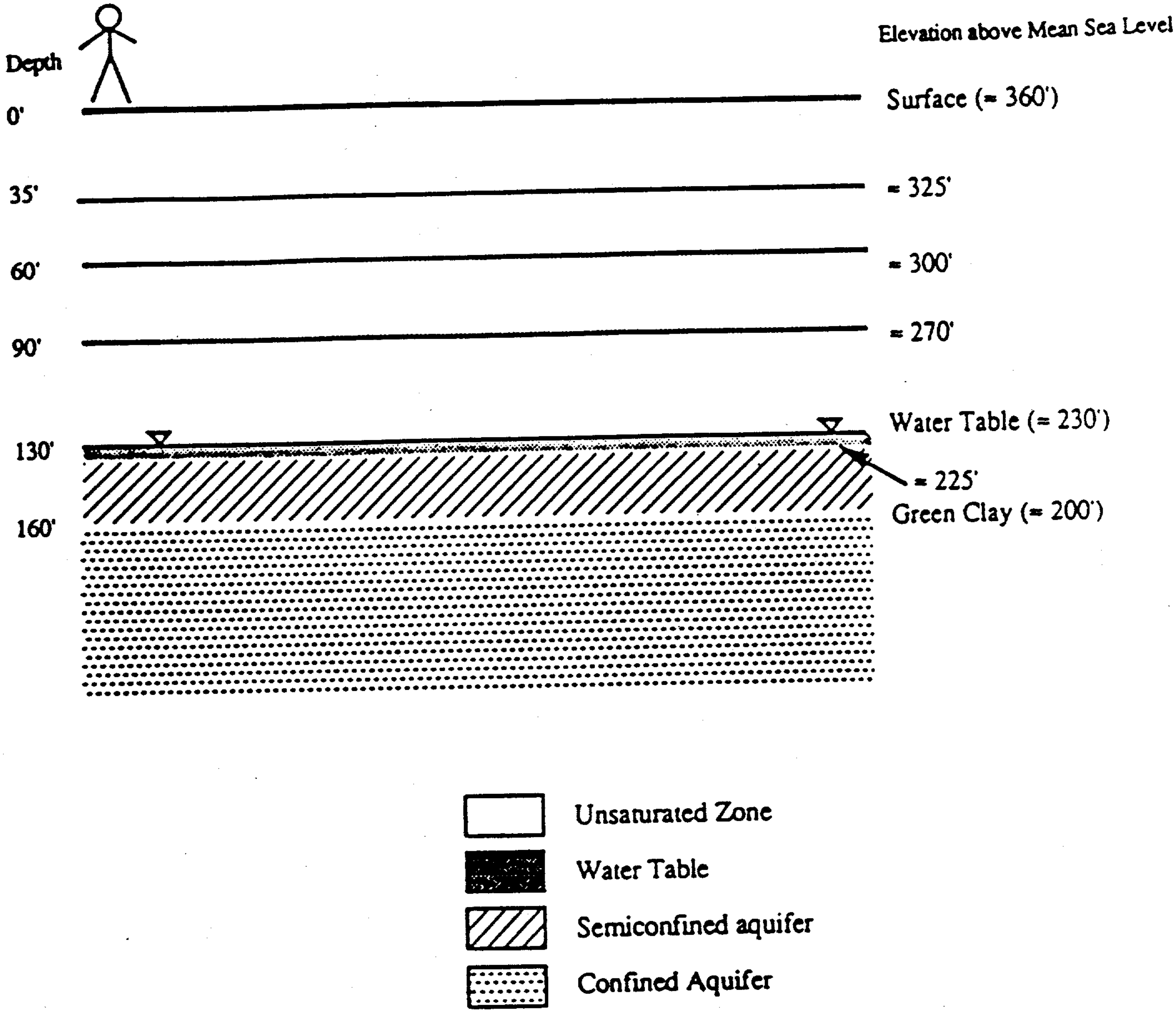

Figure 2-II-B-1. Schematic diagram showing relationship between clay layers and hydrologic features [13].

characterization data given in [13]: The sediments at the integrated demonstration (ID) site are composed of layers of sand, clay, and gravel. The hydrology of the subsurface is characterized by an approximately 130-foot-thick vadose zone, a relatively thin water table, an underlying semiconfined zone, and a deeper confined aquifer (see Figure 2-II-B-1). The clay layers are generally relatively thin or discontinuous with the exception of clay layers at an elevation of approximately 200 feet (depth ≈ 160 feet) and a thicker zone of interbedded clay and sand found at an elevation of approximately 270 feet (depth ≈ 90 feet). The water table is at an elevation of approximately 230 feet (depth ≈ 130 feet). Concentrations of volatile organic contaminants in the groundwater and sediments vary vertically and horizontally beneath the site: concentrations measured in groundwater collected from wells before the test (pre-1990) varied from approximately 400 to 1800 ppb trichloroethylene (TCE), and from 20 to less than 200 ppb tetrachloroethylene (PCE). Three-dimensional data visualization shows that most of the contamination in the vadose zone at the site is associated with the clay zone at and below the 270-foot elevation.

The ISAS demonstration showed the viability of the *in situ* air stripping process for removal of volatile organic compounds and demonstrated access to the subsurface through the use of directional drilling (e.g., horizontal wells) [34]. Technical details and results from the ISAS demonstration are summarized from [34]:

> The ISAS demonstration operated for 139 days. The field test operated at approximately 90% utility (i.e., the system was shut down for repairs or maintenance less than 10% of the time).
>
> A total of almost 16,000 pounds of chlorinated solvents were removed from the subsurface during the test. The extraction rate increased from approximately 109 pounds/day with vacuum extraction only, to approximately 130 pounds/day during the injection of air through the lower horizontal well.

> Substantial changes in groundwater VOC concentrations were measured during the test. Most of the monitoring wells at the site exhibited lower concentrations of contaminants and increases in microbial numbers and metabolic activity during the air injection period.
>
> Heterogeneities (both low permeability and high permeability zones) influenced the performance of the system. To evaluate the importance of these zones to mass transfer in subsurface remediations, data were collected from monitoring wells, vadose zone piezometers, etc. In addition, geophysical tomography data were collected to image the movement of fluid flow in the subsurface caused by the ISAS air injection and extraction.
>
> The removal rate of chlorinated solvents averaged 115 pounds/day over the 139-day ISAS demonstration. (See Figure 2-II-B-2.)

In addition to the above data collected to describe the performance of ISAS (i.e., extracted contaminants, monitoring well data, tomography data, etc.), there were extensive pretest and posttest data collected at the SRID site. Twelve cores were taken pre- and posttest (in side-by-side locations) to aid in evaluating the effectiveness of the ISAS demonstration. These data are fully described in a technical report [14].

The posttest sediment data indicate that more contaminants were destroyed than were simply extracted at the surface. Comparison of core data taken pre- and posttest from side-by-side boreholes typically show reductions in levels of contaminants of approximately 20% to 30% [14].

We summarize the data available for describing the effectiveness of the ISAS demonstration. Contaminant removal can be achieved by either withdrawal of contaminated vapors through the extraction well or by destruction of contaminants in place (e.g., bioremediation). Extracted contaminants are easily measured in the vapor extraction stream. Contaminants destroyed *in situ* are more difficult to measure. For this study we will focus

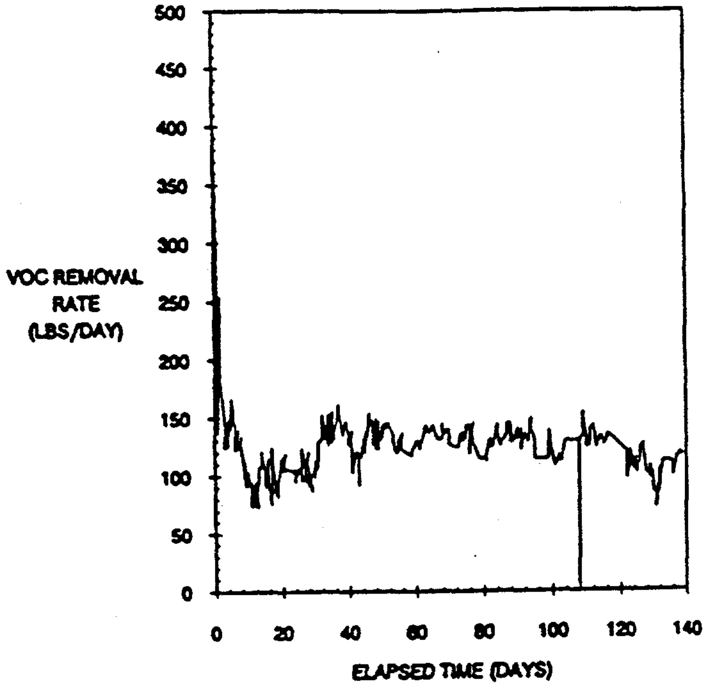

Figure 2-II-B-2. Removal rate of chlorinated solvents during the *in situ* air stripping test [13].

on the pounds of VOCs removed in the vapor extraction stream as the primary measure of ISAS system performance.

The amount of contaminants destroyed *in situ* can be estimated by taking the difference between an estimated pretest inventory and an estimated posttest inventory. Data presented in [14] do indicate that significant reductions in contaminant concentrations occurred in pretest versus posttest core data, which may be attributed to biodegradation. Because contaminant inventories are based on data interpolation and assumptions of geologic properties, they are not included in the quantitative scenario developed in Section E. Such inventory calculations have high uncertainties and large margins of error. Also, because pre- and posttest core data are not available for the baseline technologies (i.e., soil vapor extraction with vertical wells), only the number of pounds of VOCs extracted in the vapor stream at the surface is used as the measure of contaminant removal and cost-effectiveness. Total cost per unit of environment remediated and total cost per unit flow of air through the system are also reported and assessed.

2. Horizontal Wells

A major component of the ISAS demonstration was the use of horizontal wells, with the goal of improving access to the subsurface. The demonstration site was selected along an abandoned process sewer line that carried wastes to a seepage basin operated at the SRS between 1958 and 1985. The sewer line acted as a source of contamination and is known to have leaked at numerous locations along its length [13]. Because the source of contamination was linear at this particular location within the overall plume, horizontal wells were selected for the injection and extraction system [30].

Two horizontal wells were installed at the SRID site by Eastman Christensen, Inc. The lower horizontal well (used for air injection) is approximately 300 feet long and 165 feet in depth. Recall that the water table is approximately 130 feet in depth. The upper horizontal well (used for air extraction) is approximately 175 feet long and 75 feet in depth. Figure 2-II-B-3 shows map and cross-section views of the location of the horizontal wells at the SRID site.

3. Choice of Baseline Technology[5]

Because the ISAS system remediates both the vadose zone and the saturated zone (both groundwater and sediments below the water table), the baseline or conventional technology used for comparison comprises two techniques:

(1) Soil vapor extraction (SVE) using vertical wells is the baseline technology for remediation of the vadose zone.

(2) Pump and treat (PT) using vertical wells is the baseline technology for remediation of the saturated zone.

There is no assumption, however, that these conventional technologies achieve exactly the same performance or effect as ISAS with horizontal wells. They are simply technologies that are reasonably close to ISAS and address the same environmental contamination

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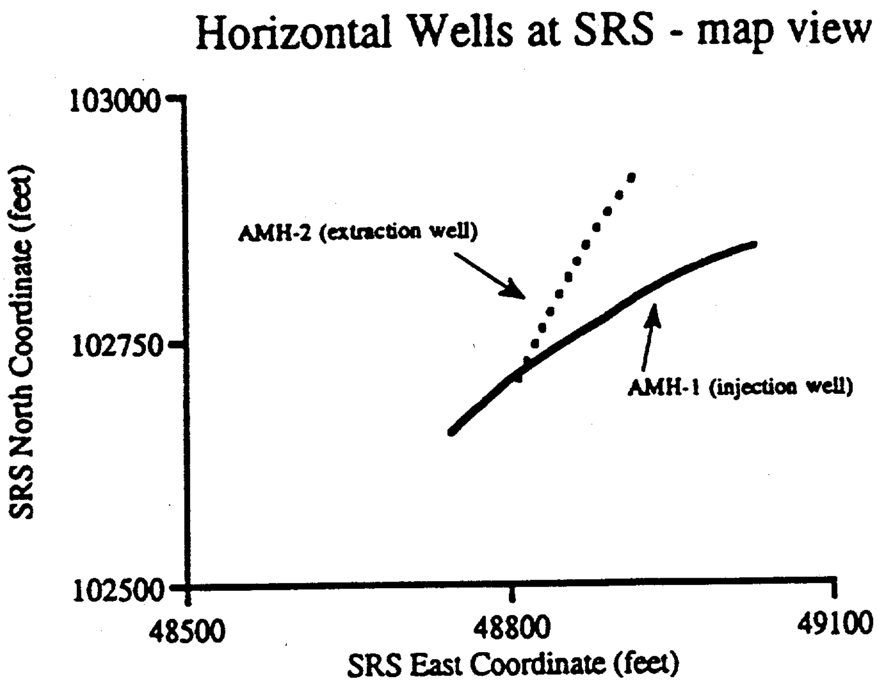
[5] In the empirical discussions that follow, some assumptions are made concerning the extrapolation of the data from the respective field studies.



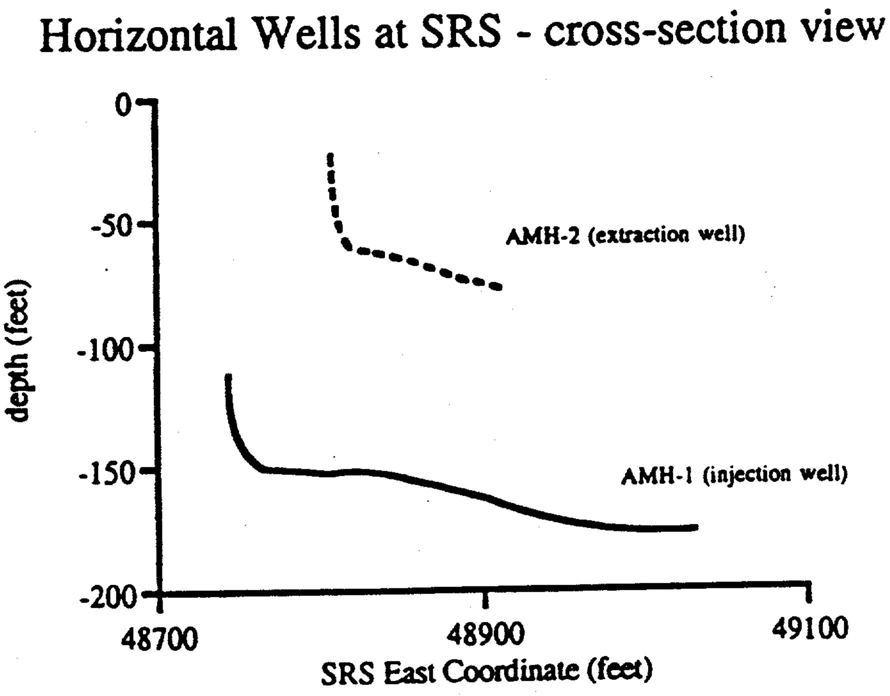


Figure 2-II-B-3. Map and cross-section views of horizontal wells at the SRID site [34].

problem. Differences in the effectiveness of ISAS versus the baseline technologies are addressed in Subsection II-B-3.

Other possibilities for the choice of baseline technologies exist. However, for reasons discussed below, these were not selected:

Pump and treat

> PT, by itself, is not a reasonable choice for the baseline technology. Contaminated soils in the vadose zone serve as a continuing source for contamination of the underlying groundwater. In practice, once contaminants have been found in the vadose zone, the vadose zone must be remediated. EPA is currently in the process of establishing soil standards for VOCs.

Excavation

> Given the depth and extent (over one square mile for the VOC plume in the A/M area) of contamination at the Savannah River Site, this is not a reasonable alternative.

In Situ Air Stripping with Vertical Wells

> A few examples exist in the literature of *in situ* air stripping with vertical wells: a vertical well extending below the water table is used for air injection, and a vertical well in the vadose zone is used for vapor extraction [3][38]. Various numbers and geometries of wells are proposed. Because this technology is relatively new, and not considered conventional or widely practiced, it was not considered for the baseline case in this study.

Both PT (using vertical wells) and SVE in the vadose zone (using vertical wells) are considered common practice in current remediation efforts [58][59]. Both of these baseline technologies have been used at the SRS. Thus, data exist relevant to the same hydrological and geological setting as the ID site. A full-scale PT groundwater remediation system has been ongoing at the SRS A/M area since 1984 [27]. (The ID site is within the A/M area.) Also, a pilot study of vertical soil vapor extraction wells was conducted at the ID site in

1987 [35]. Therefore, field data from the SRS exist for both the new and baseline technologies analyzed in this study.

4. Performance Comparison

a. Comparison of ISAS and Baseline Technologies

For remediation of the vadose zone, both ISAS and soil vapor extraction (SVE) employ essentially the same method. Contaminants are volatilized into a moving air stream and are transported to the surface through the extraction well. In the case of ISAS, air is actually injected into the subsurface below the vadose zone. Extraction takes place in a vadose zone well. SVE is a more passive system in the sense that no air is injected into the subsurface. Air enters the vadose zone from the ground surface, and vapors are extracted through the SVE well.

For remediation of the saturated zone (sediments and groundwater), the PT method is considered. Note that the ISAS demonstration suggested that more contaminants were pulled from the vadose zone than from the saturated zone (with vacuum extraction, only the removal rate was about 109 pounds/day; with the combination of air injection and vacuum extraction, the removal rate was about 130 pounds/day).

For purposes of selecting a conventional technology that remediates the saturated zone, PT is appropriate for this comparison. However, as a method for aquifer restoration, PT is considered to have significant limitations [36][12]. The remainder of this section describes how the historical long-term performance of PT systems influences the choice of how to set up a performance comparison with ISAS. Data from the SRS ongoing PT system are provided in Figure 2-II-B-4.

Results of a recent analysis suggest that PT is ineffective for permanently reducing levels of aquifer contamination to meet health-based goals for groundwater [12]:

> "The ideal scenario would be a steady decrease in contaminant concentrations until the target level is attained. Performance records suggest, however, that although concentrations may drop initially, this decline is followed by a leveling of concentrations with little or no further decrease in concentrations. At sites where the plume appears to be well contained, concentrations have leveled after average VOC concentration reductions of approximately 60% to 90% in on-site wells, with large masses of contamination (approximately 50%) remaining in the aquifer. At all sites where contamination concentrations have leveled, the concentrations remain well above the target levels, even at sites where cleanup goals were established above drinking water standards."

Briefly, the above behavior is due to contaminants in the saturated zone that are absorbed to aquifer material and act as slow, non-equilibrium, diffusion-limited [48], continuous sources for contamination of the groundwater. Because of kinetic limitations, residual saturation, and other subsurface sources such as dense non-aqueous phase liquids (DNAPLs), the rate of contaminant mass removal by pumping wells is exceedingly slow [22].

Given the inability to predict the time frame for a remediation to achieve "cleanup" (either because of poorly understood long-term physical processes in the subsurface, or the inability of the remediation method itself to actually achieve such a reduction in contaminants), this study refrains from making such estimates. Instead, it considers two approaches: (1) performance data from actual short-term field tests with each technology (ISAS, SVE, PT) will be used to calculate cost per pound of VOCs removed for the short time scale, and (2) performance curves will be estimated for the reduction in rate of

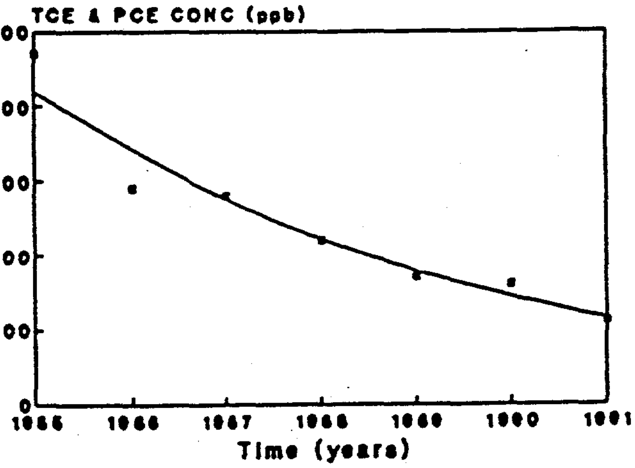


Figure 2-II-B-4. Decreasing concentration trend of solvents from pump and treat wells (SRS A/M area) in the air stripper influent [27].

contaminant removal with each technology, and long-term costs determined for a remediation time scale of 5 years. Some historical SRS data exist to guide estimates on the reduction in contaminant removal rates for SVE and PT. Of course, no such data exist for ISAS because the field test was only for 139 days. Simple cases of possible reduction levels in contaminant removal rate for the long-term performance of ISAS will be examined for their cost implications in Section II-G. The difficult part is to construct reasonable estimates of long-term performance curves based on extrapolation of short-term field experiments.

b. Basic Form of the Performance Scenario

In this section, the basis for a performance scenario is constructed in which the new ISAS technology as demonstrated at the SRID is compared to the "equivalent" conventional technologies. Here, an equivalent system is constructed such that it remediates roughly the same subsurface region treated by ISAS at the SRID. The basis of the performance comparison is the amount of contaminant removed from the subsurface.

This approach has its limits. Additional study is suggested to aid in extrapolating to further work at SRS and/or to remediation efforts at other sites. This study is based on field data from the SRID site. The difficulty lies in making extrapolations from short field-scale tests (e.g., 139 days) to performance over several years or more. Results are first presented based on field data only. Modeling studies based on the field data from the SRID would provide insight into the physical processes involved and support examination of a greater number of branches in the decision tree. This would aid in technology optimization and in determining what the effect of change in a parameter, such as site geology or the air injection rate, would have on performance.

First, the two plans used in this performance comparison are described, with focus on the actual field demonstration of the new ISAS technology at the SRID in the second half of 1990. The only exception is that for the purpose of the cost comparison, above ground processing of the extracted contaminants is considered, whereas in the actual demonstration the volatile organic contaminants were not treated before being released to the atmosphere. The above ground off-gas treatment used in this study is carbon absorption.

Next, the equivalent conventional technology is considered. Because the study uses equivalence in region remediated as the basis for constructing a competing groundwater remediation strategy, the first step is to define the extent and nature of the regions affected by the ISAS demonstration. The second step is to set up the conventional technologies described in Subsection II-B-2 to remediate an equivalent subsurface region and describe the details of the implementation of these technologies.

The estimate of the region affected by the ISAS test is based on the extensive monitoring data collected during the ISAS field demonstration. The vertical extent of the zone of groundwater affected by the ISAS is the distance between the lower horizontal well and the water table (about 35 feet). The areal extent of the zone of groundwater affected by the ISAS is estimated based on helium tracer tests [34], tomography data [15][47], and data from the groundwater monitoring wells [34]. Helium (an inert gas with a low molecular weight) was added to the air in the injection well as a tracer. Based on these data, the region of groundwater being affected by the air injection is estimated to be approximately 300 feet long by 60 feet wide by 35 feet deep. The field data that bear on the areal extent of the vadose zone affected by the ISAS are the vacuum levels measured in the vadose zone monitoring wells at the site [34]. Based on these data, the region of the vadose zone being affected by ISAS is estimated to be approximately 175 feet long by 150 feet wide by 100 feet deep.

The choice of conventional technologies to be used in the performance scenario was discussed in Subsection II-B-2; the details of the implementation of these technologies are described here and depicted in Figures 2-II-B-5 and 2-II-B-6. To remediate the groundwater, the study chose as the equivalent conventional technology a system of PT wells Field data from the PT system in place at the SRS A/M area, which surrounds the SRID site, was used to construct this plan. (Note that these systems are not exactly equivalent: the existing SRS A/M area PT system has been remediating a large plume area since 1984, whereas the ISAS field test was meant to address a "hot spot" or high contamination source area of this plume.) A network of vertical SVE wells was chosen to remediate the vadose zone, and data from a pilot test of vertical SVE wells [35] conducted at the SRID site is used.

To remediate a region of groundwater at the site that is approximately 300 feet long by 60 feet wide by 35 feet deep, one groundwater pumping well 175 feet deep and screened 35 feet at the bottom [52][27] is used.

To remediate a region of vadose zone at the site that is approximately 175 feet long by 150 feet wide by 100 feet deep, the study uses four vertical SVE wells. Field data are available from a pilot study of vertical vacuum wells in the A/M area at the SRS [35].

Plan 1: In Situ Air Stripping

- lower horizontal well for air injection
- upper horizontal well for vapor extraction

Plan 2: Baseline Technologies

(1) Pump and Treat
  - one pump and treat well
  - effluent is released to permitted outfall

(2) Soil Vapor Extraction
  - four soil vapor extraction wells

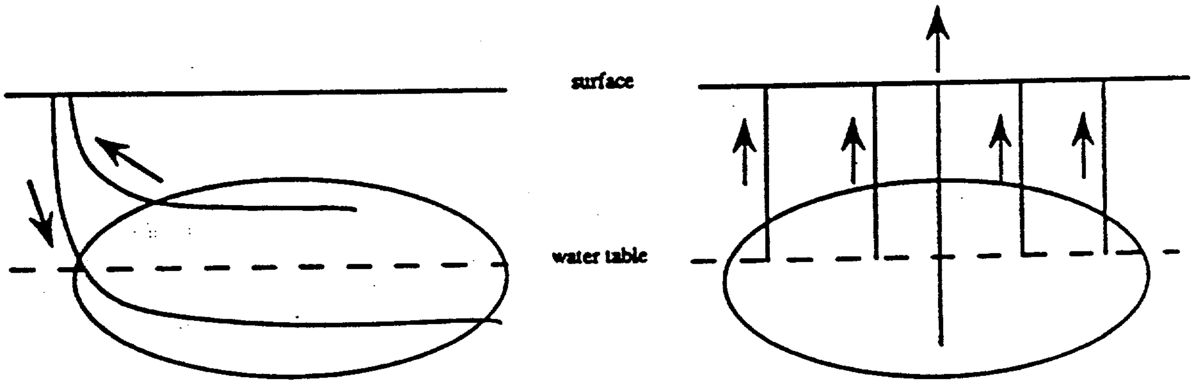


Figure 2-II-B-5. Schematic comparison of ISAS and baseline (conventional) technologies.

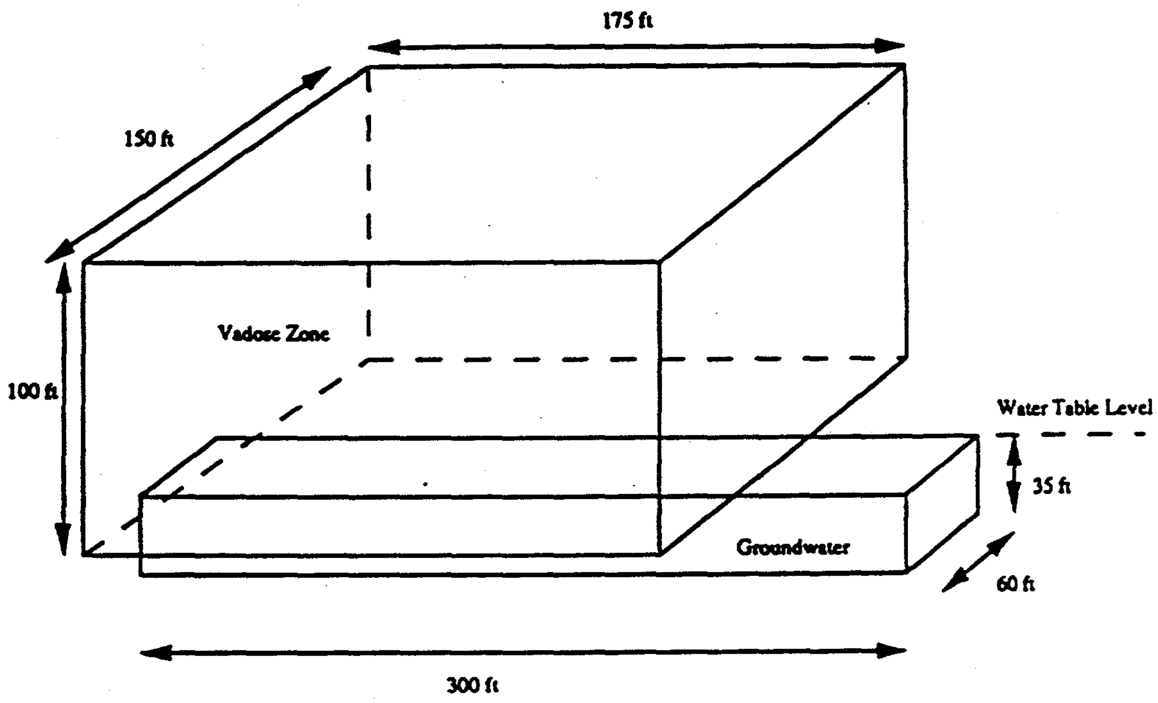


Figure 2-II-B-6. Schematic of ISAS zone of influence (based on field data only).

These data suggest that one of the wells screened over 100 feet of the vadose zone has a radius of influence of at least 75 feet.

The waste stream at the surface for both ISAS and SVE consists of a contaminant vapor stream that is passed through a carbon adsorption unit. For PT, groundwater is pumped to the surface and run through an air stripping tower that generates a contaminant vapor stream and clean effluent water. The contaminant vapor stream is passed through a carbon adsorption unit. The effluent water is assumed to be released to a National Pollutant Discharge Elimination System (NPDES) outfall. This is the current practice with the SRS M Area PT system [39].

For horizontal air stripping, the data from the innovative ISAS technology as demonstrated at the SRID is used. Nearly 16,000 pounds of volatile organic contaminants were removed during the 139-day demonstration. During the early portion of the demonstration (before air injection), soil vapor extraction alone removed contaminants at a rate of approximately 109 pounds/day. During the remainder of the demonstration, combined injection and extraction increased this rate to 130 pounds/day. Recall the branches of the decision tree and the choices a decision maker might have between ISAS air injection/no air injection, the air injection rate (low, medium, or high), heating of injected air/no heating, and equipment maintenance/no maintenance. A plot of the cumulative amount of contaminant removed from the subsurface versus time is given in Figure 2-II-B-7.

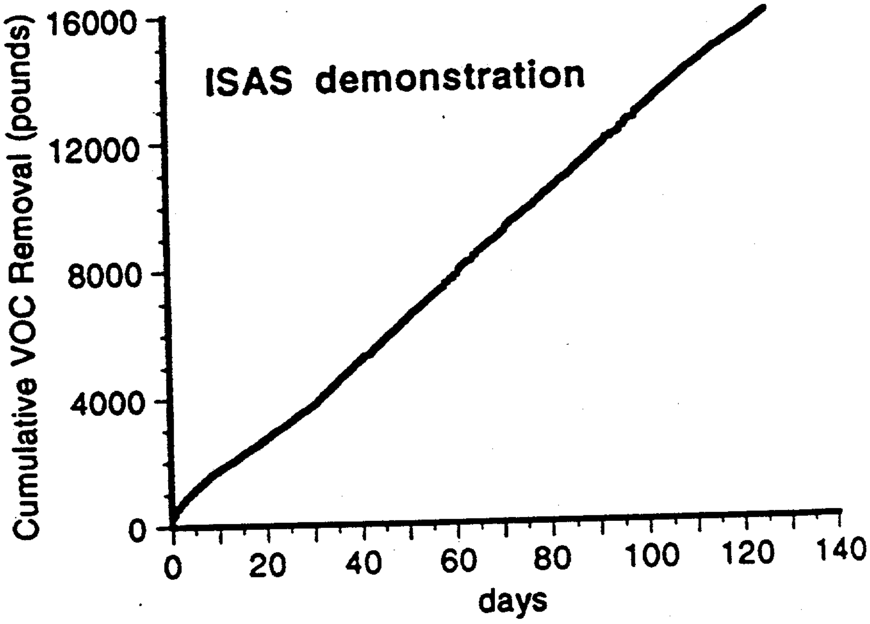


Figure 2-II-B-7. Cumulative removal of chlorinated solvents during the ISAS test [34].

C. Criteria for Cost-Effectiveness Evaluation

Three criteria are proposed to evaluate the cost-effectiveness of competing groundwater remediation technologies:

1) dollars per pound of contaminant removed
2) dollars per unit of environment remediated
3) dollars per standard engineering flow rate.

For the 5-year long-term costs, all three criteria are considered. Under the assumption of only a 139-day field test, only the first and third criteria are considered.

The first criterion utilizes the cost per pound of VOCs removed to compare the technologies. Since the measurement of VOCs obtained from the vapor extraction stream is fairly accurate, a strong argument is made to use the first criterion. This measure may also be justified on the basis of the mass balance approach. A difficulty with this measure, however, is the inclusion of contaminant removed underground. Information on the extent of this in-place removal is not available. This omission will bias the results for each of the competing technologies. However, if the underground removal is comparable for different technologies, then the use of dollars per pound of contaminant removed is valid for comparison.

The second criterion better represents the attainment of the regulatory standard -- actual removal of the contaminant. Unless the volume of original contaminant in place is known (an unlikely situation in most cases), this measure is difficult to apply and has considerable uncertainty associated with it. Estimates of the volume of the environment that is contaminated are rather imprecise. The volume of the study area, to be remediated by ISAS, vadose zone is 2,656,000 cubic feet (or 74,332 cubic meters), whereas the volume of the (ISAS) groundwater region (below the water table) is 630,000 cubic feet (or 17,849 cubic meters).[6] This amounts to 92,200 cubic meters. The PT-SVE system was constructed in such a way so that it remediates the same subsurface region as that treated by ISAS at the SRID. Given the amount of the original contaminant that has been removed, this criterion gives us an estimate of the cost per unit volume of the environment remediated.

The third criterion utilizes a measure of a standard engineering flow through the system. Total costs are compared to this engineering flow rate. These engineering flow rates are measured in terms of the volume of air or groundwater that flows through the system. Flow rates are useful for comparing engineering costs, although they do not address the efficiency of contaminant removal. That is, this approach assumes a perfect correlation between the level of remediation and the flow rate. ISAS uses one horizontal extraction well with a vapor extraction rate of 550-600 scfm. This study uses an average vapor extraction rate of 575 scfm. SVE uses four vertical wells with a vapor extraction rate of 250 scfm per well. The total SVE vapor extraction rate is assumed to be 1,000 scfm for the four wells.

D. Extrapolation of the Field Trial Data and Various Performance Scenarios

The field trials at the SRID project were conducted for relatively short durations. Useful cost-effectiveness evaluation requires extrapolation of the field data for the PT-SVE combined baseline technology. This allows a comparison with the results provided by the ISAS technology. In order to compare ISAS and PT-SVE, the study must place them on a common basis. Because the field trials differ in length, the options are to use only the data

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[6] Preliminary groundwater modeling results for ISAS, however, suggest that probably only 50% of the original contaminant will be removed over the 5-year time period.

for the period that is in common or to construct an extrapolation of the performance of the techniques that were run for the shorter time period. The study adopted both approaches.

The SVE field trial ran for only 21 days, so this provides the time frame that would be used to compare performance based on actual field data. Over the 21 days, ISAS extracted roughly 2,696 pounds. During the 21-day field trial, 1,496 pounds of VOCs were extracted via the single-well SVE. For the first 21 days, PT is assumed to remove 497 pounds. Four SVE wells are assumed to extract 5,984 pounds. The combined PT-SVE system is assumed to remove about 6,472 pounds. These data are used to construct Analysis Scenario A, "Actual PT-SVE." The comparison is thus made between the ISAS data for the initial 21 days and the combined PT-SVE system.

Extrapolation with short-term field data introduces the possibility of several errors.[7] The solution is to analyze two boundary scenarios. The actual results will lie within these boundaries. In Section II-E a short-term performance scenario for ISAS and the combined PT-SVE system is described. This performance scenario covers a period of 139 days and is constructed from actual field data and extrapolations. This scenario assumes that the greatly reduced SVE efficiency, following the 21 days of observation, follow from the kink in the field performance figures reported in [54]. The study reported that 16,000 pounds of VOC were removed by ISAS, and a projected 13,954 pounds of VOC were removed by the

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[7] We note that the 114-day PT field performance did not present the same type of extrapolation problem as the much shorter 21-day SVE field performance.

combined PT-SVE system (10,704 from SVE and 3,250 from PT). These extrapolations are used as the "Low PT-SVE Extrapolation" analysis scenario.[8]

To construct the "high PT-SVE" scenario, the study projects an SVE extraction rate that is 50% higher than the low extrapolation scenario (which was 10,704 pounds removed). This results in an SVE extraction of 16,056 pounds. Using this extrapolation leads to 19,306 pounds removed for the combined PT-SVE system, with 16,056 pounds from SVE and 3,250 pounds from PT. The PT extraction is the same 3,250 pounds that were reported under the "low PT-SVE" scenario. Results of this cost-effectiveness study are relatively sensitive to assumptions regarding SVE extraction rates. Although using more realistic assumptions regarding SVE extrapolation leads to higher carbon recharge and total site costs, these are offset by examining average costs. The much larger VOC extraction drives average cost per pound significantly lower.

E. Analysis Scenarios

A set of analysis scenarios are designed that should establish reasonable bounds on 139-day SVE performance. This was done in order to compare the 139-day ISAS field performance with a 139-day PT-SVE extrapolation. The study uses the following analysis scenarios that were developed in the previous section: 1) actual PT-SVE, 2) low PT-SVE extrapolation, and 3) high PT-SVE extrapolation.

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[8] It is of interest to note that the standard pump and treat system at the Savannah River A/M Area Site, which has been in operation since 1984, has removed approximately 230,000 pounds of solvents (Westinghouse Savannah River Company, 1991). This is approximately 33,000 pounds of solvents per year.

1. Actual PT-SVE

The "actual PT-SVE" analysis scenario uses the first 21 days of PT-SVE field data. (See Figure 2-II-E-1.) This is compared to the first 21 days of the ISAS field data. In this way, direct comparison is made between the first 21 days of performance for both the baseline technology and the innovative technology.

2. Low PT-SVE Extrapolation

The "low PT-SVE" extrapolation analysis scenario uses the PT and SVE extrapolation of VOC removal rates found in [54]. In this way, the 139-day ISAS field performance is compared to the 139-day low PT-SVE extrapolation. For the equivalent traditional remediation system, the removal of volatile organic contaminants from groundwater is based on data from the SRS A/M area PT network ([21], Table M-8.5). The mass of VOCs removed from one of the wells in this network (RWM-1) for the first few months of the PT operation is shown in Figure 2-II-E-2. Well RWM-1 is the closest recovery well to the SRID site. The removal of VOCs from the vadose zone is based on the vertical vacuum well pilot test. Field data [35] are shown for 21 days. These data are extrapolated to 139 days, as shown in Figure 2-II-E-3 by the dashed line. Again, the extrapolation is done to match the 139-day time frame of the ISAS test. The average rate of removal is about 20 pounds/day (per well) for the 139-day time period.

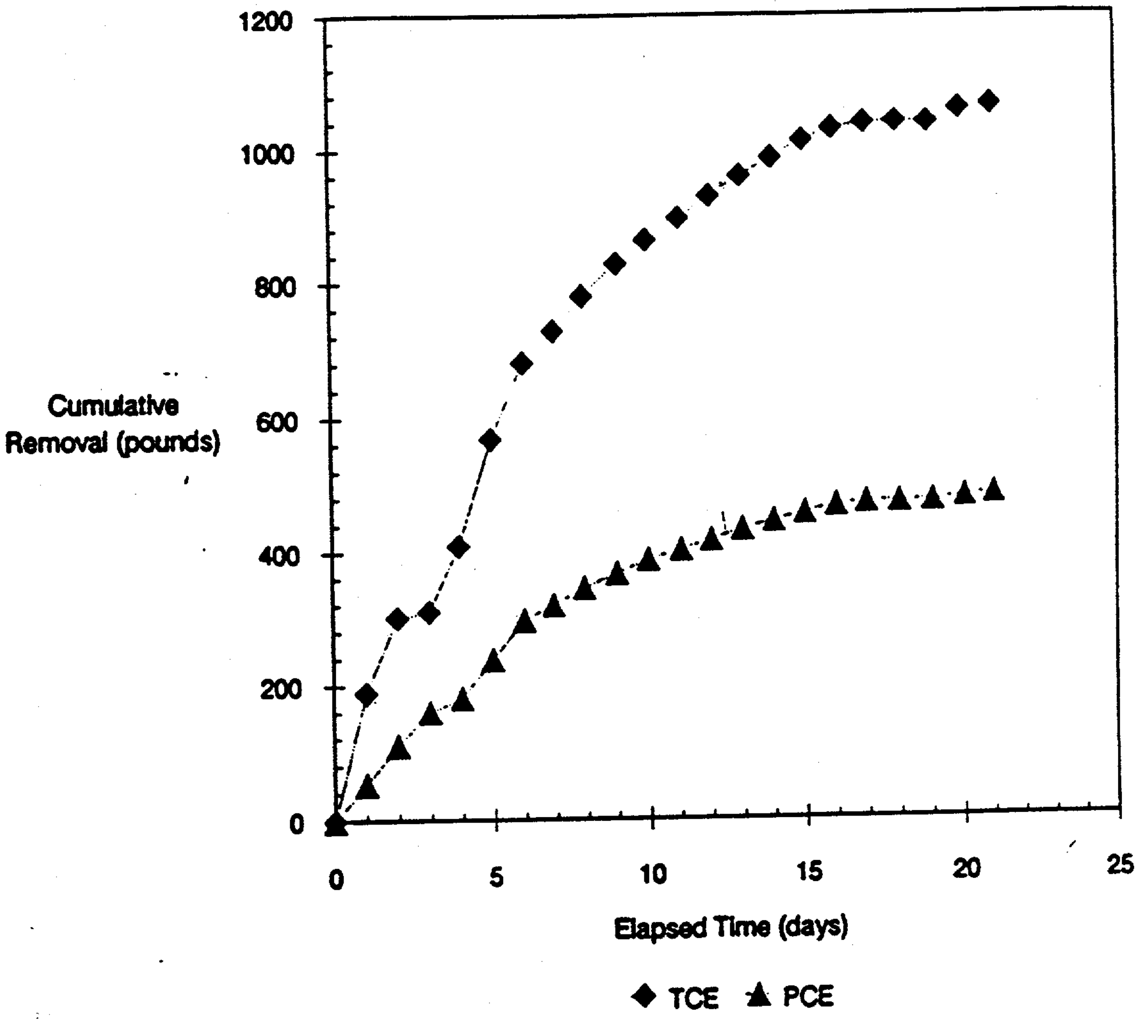

Figure 2-II-E-1. Total VOCs extracted by an SVE well during test [35].

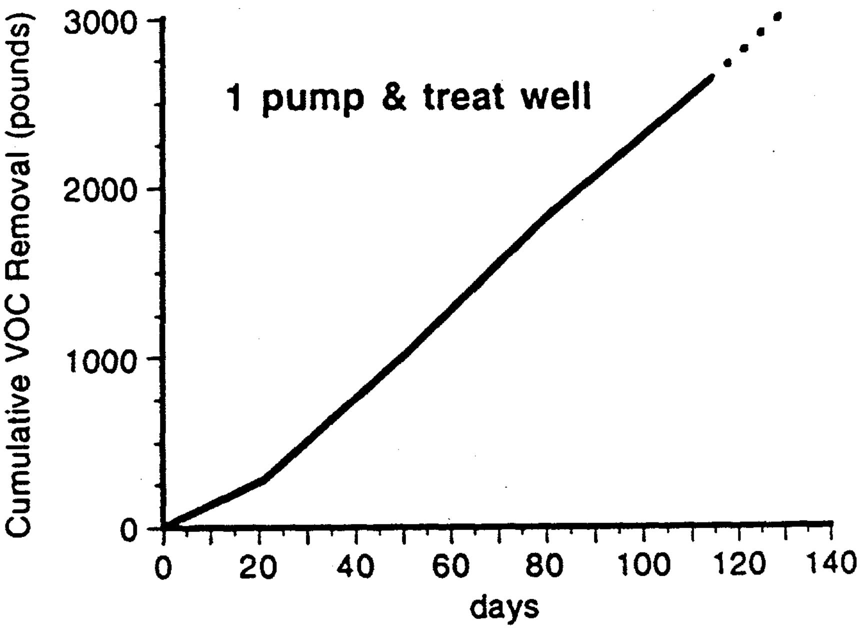

Figure 2-II-E-2. Cumulative removal of VOCs from PT well RWM-1 [48]. Solid line is field data. Dashed line indicates data extrapolation from day 114 to day 139.

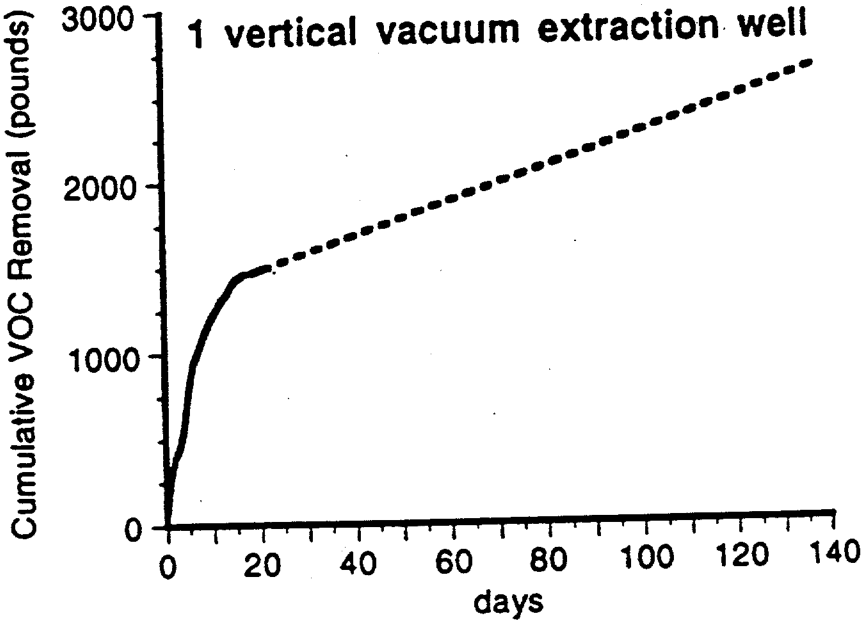

Figure 2-II-E-3. Cumulative removal of VOCs from SVE well VB-1 [35]. Solid line is field data. Dashed line indicates data the low extrapolation from day 21 to day 139.

3. High PT-SVE Extrapolation

The "high PT-SVE extrapolation" analysis scenario uses an SVE extraction rate that is 50% again as high as the "low SVE extrapolation" case. It is then compared to the actual 139-day ISAS field data.

4. Long-term Low PT-SVE Extrapolation

The "long-term low PT-SVE extrapolation" analysis scenario uses the PT and SVE extrapolation of VOC removal rates found in [54]. Earlier, this 139-day extrapolation was presented in analysis scenario B, "Low PT-SVE Extrapolation." VOC extraction is assumed to be maintained throughout the first year at the 139-day rate. This establishes the combined PT-SVE extraction of VOCs for the first year. The VOC extraction rate is assumed to be 75% in the second year and 50% for the third through fifth years. Combined PT-SVE extraction begins at 103 pounds per day for the first year, then falls to 77 pounds per day for the second year, and finally levels off at 51 pounds per day for the third through fifth years. Over the 5-year long-term period 121,545 pounds of VOCs are assumed to be removed. In comparison, ISAS removes a total of 135,780 pounds.

5. Long-term High PT-SVE Extrapolation

The "long-term high PT-SVE extrapolation" analysis scenario assumes the high PT-SVE extrapolation for the first year. Combined PT-SVE extraction begins at 139 pounds per day for the first year, then falls to 104 pounds per day for the second year, and finally levels off at 69 pounds per day for the third through the fifth years. Over the 5-year long-term period 164,761 pounds of VOCs are assumed to be removed. Again, ISAS removes 135,780 pounds.

F. Short-term Costs Comparison

Short-term costs over the field test time period are compared. Detailed cost tables for both technologies appear under the dollars per pound criterion for each analysis scenario. Costs are broken down into capital costs and those incurred during the operation and maintenance of the system (O&M costs). Capital cost components are site cost, equipment cost, and mobilization/demobilization cost. O&M cost components comprise monitoring and maintenance as well as consumable costs (e.g., fuel oil, lubricants, deionized water, chemical additives, maintenance supplies). Carbon recharge, a relatively large consumable cost incurred during the operation and maintenance of the system, is reported separately. Consumable costs and total O&M costs are reported both with and without carbon recharge. Finally, total site costs are the sum of capital cost and O&M costs. Again, total site costs are shown both with and without carbon recharge.

Carbon recharge costs depend upon assumptions regarding the VOC extraction rate. Because two performance scenarios were develped for the SVE, the actual costs for these scenarios with the carbon recharge costs included and without these costs will be reported. Until improved performance scenarios are available (such as from groundwater modeling), it has been suggested by reviewers to report the actual system costs both including and excluding carbon recharge expenses[9].

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[9] We are grateful to two reviewers for making this point.

The study intends to compare total costs over fixed operation periods rather than average costs. In general, it was found that ISAS had higher short-term costs due to the higher capital costs involved in horizontal well installation.[10] Once improved performance scenarios are available, such as from groundwater modeling, then unit costs may be more accurately represented.

1. Analysis Scenario A, "Actual PT-SVE"

The study investigates the three criteria for Analysis Scenario A, "Actual PT-SVE," which directly compares across the competing technologies the 21 days of field test data that are comparable.

a. Dollars per Pound Criterion

Short-term ISAS dollars per pound are $120.74/pound ($325,511/2,696 pounds), whereas short-term PT-SVE dollars per pound are $45.90/pound ($297,060/6,472 pounds). The study elected to leave carbon recharge costs in this criterion, because its basis is VOC pounds removed. With a direct comparison over the first 21 days to match the actual SVE field performance data, PT-SVE is considerably more cost-effective than ISAS.

Short-term costs for ISAS under Analysis Scenario A are displayed in Table 2-II-F-1, Short-term Costs for *In Situ* Air Stripping for Analysis Scenario A, "Actual PT-SVE." Short-term costs for the combined PT-SVE system under Analysis Scenario A are displayed in Table 2-II-F-2, Short-term Costs for PT-SVE for Analysis Scenario A, "Actual PT-SVE."

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[10] This raises the "learning by doing" issue, which will be taken up later.

Table 2-II-F-1. Short-term Costs for *In Situ* Air Stripping for Analysis Scenario A, "Actual PT-SVE"

Duration (days)	21
Pounds VOCs removed	2,696
VOC Extraction (lb/day)	115
CAPITAL COST	
Site Cost	$5,000
Equipment Costs	
Well Installation	$170,085
Other Equipment	$63,440
Design and engineering	$5,000
Mobile equipment (pickup)	$15,000
Total Equipment Costs	$253,525
Labor Cost	
Mobilize/demobilize	$37,600
Total Capital Cost	$296,125
OPERATION AND MAINTENANCE	
Labor Cost	
Monitoring/maintenance	$3,780
Carbon Recharge	$17,134
Consumable Costs	
(Excluding Carbon Recharge)	$8,471
(With Carbon Recharge)	$25,606
Total Operation and Maintenance	
(Excluding Carbon Recharge)	$12,251
(With Carbon Recharge)	$29,386
TOTAL SITE COST	
(Excluding Carbon Recharge)	$308,376
(With Carbon Recharge)	$325,511

Table 2-II-F-2. Short-term Costs for PT-SVE for Analysis Scenario A, "Actual PT-SVE"

Duration (days)	21
Pounds VOCs removed	6,472
VOC extraction (lb/day)	308
CAPITAL COST	
Site Cost	$7,500
Equipment Costs	
Well Installation	$8,110
Other Equipment	$132,466
Design and engineering	$7,500
Mobile equipment	$15,000
Total Equipment Costs	$163,076
Labor Cost	
Mobilize/demobilize	$56,400
Total Capital Cost	$226,976
OPERATION AND MAINTENANCE	
Labor Cost	
Monitoring/maintenance	$5,670
Carbon Recharge	$51,706
Consumable Costs	
(Excluding Carbon Recharge)	$12,707
(With Carbon Recharge)	$64,414
Total Operation and Maintenance	
(Excluding Carbon Recharge)	$18,377
(With Carbon Recharge)	$70,084
TOTAL SITE COST	
(Excluding Carbon Recharge)	$245,353
(With Carbon Recharge)	$297,060

b. Dollars per Standard Flow Rate Criterion

Short-term cost for ISAS as measured by a standard engineering flow rate is \$566.11/scfm (\$325,511/575 scfm). Short-term cost of PT-SVE as measured by this criterion is \$297.06/scfm (\$297,060/1,000 scfm). Combined PT-SVE is more cost-effective than ISAS when a standard engineering flow rate, such as dollars per scfm, is used as the criterion. This holds for the direct comparison of the first 21 days of field data.

c. Summary for Analysis Scenario A

Table 2-II-F-3 provides a summary for Analysis Scenario A. The ratio of the new technology to the baseline or traditional technology is also shown. This ratio may be deceptive, in that the smaller cost and the larger quantity are preferred. Therefore, when measuring dollars, percentages larger than 100% indicate that ISAS costs more than the baseline technology; when comparing pounds removed, percentages larger than 100% indicate that ISAS extracts more than the baseline technology.

Total costs are reported over fixed operating periods. The costs for the competing remediation technologies are shown both with and without carbon recharge. ISAS short-term costs, excluding carbon recharge costs are \$307,376, with \$296,125 (or 96.03%) for capital and \$12,251 (or 3.97%) for operation and maintenance. In contrast, PT-SVE short-term costs, with carbon recharge costs excluded, are \$245,353, with \$226,976 (or 92.51%) for

Table 2-II-F-3. Short-term Cost Summary Results

Analysis Scenario A, "Actual PT-SVE"

	ISAS	PT-SVE	Ratio
Dollars	$308,376	$256,353	125.69%
Dollars (with carbon recharge)	$325,511	$297,060	81.98%
Pounds Removed	2,696	6,472	41.66%
Days	21	21	--
Dollars/pound	$120.74	$45.90	263.05%
Dollars/scfm	$566.11	$297.06	190.57%

capital and $18,377 (or 7.49%) for operation and maintenance. Note that ISAS technology is somewhat more capital-intensive than the conventional PT-SVE system due to the initial capital cost involved in horizontal well drilling and installation.

When carbon recharge costs are included, ISAS short-term costs are $325,511, because carbon recharge adds $17,134 to ISAS consumable costs. Then capital is 90.97%, and operation and maintenance is 9.03%. And when carbon recharge costs are included for the combined PT-SVE system, consumable costs increase by $51,706, so PT-SVE short-term costs are $297,060. Capital is 76.41%, and operation and maintenance is 23.59%.

2. Analysis Scenario B, "Low Extrapolation"

The study investigates the three criteria for Analysis Scenario B, "Low PT-SVE Extrapolation." This analysis scenario assumes the extrapolation for SVE found in [53]. The actual 139-day ISAS field performance is compared to the 139-day (low) PT-SVE extrapolation case.

a. Dollars per Pound Criterion

Short-term ISAS dollars per pound are \$29.93/pound (\$478,906/16,000 pounds), and short-term PT-SVE dollars per pound are \$32.80/pound (\$457,735/13,954 pounds). These unit costs use the more conservative PT-SVE 139-day extrapolation for the quantity of VOC extracted and include carbon recharge costs. Even for the low extrapolation case, PT-SVE is almost as cost-effective at \$32.80/pound, compared to ISAS at \$29.93/pound. While this measure itself is close, it depends heavily on the amount extracted and on assumptions regarding extrapolation.

Short-term costs for ISAS are displayed in Table 2-II-F-4, Short-term Costs for *In Situ* Air Stripping for Analysis Scenario B, "Low PT-SVE Extrapolation." Short-term costs for the combined PT-SVE system under Analysis Scenario B are displayed in Table 2-II-F-5, Short-term Costs for PT-SVE for Analysis Scenario B, "Low PT-SVE Extrapolation."

b. Dollars per Standard Flow Rate Criterion

Short-term cost for ISAS as measured by a standard engineering flow rate is \$832.88/scfm (\$478,906/575 scfm). Short-term cost of PT-SVE is \$457.74/scfm (\$457,735/1,000 scfm). The combined PT-SVE system is more cost-effective than ISAS when a standard engineering flow rate, such as dollars per scfm, is used as the criterion. This holds even for the PT-SVE low extrapolation analysis scenario.

Table 2-II-F-4. Short-term Costs for In Situ Air Stripping for Analysis Scenario B, "Low PT-SVE Extrapolation"

Duration (days)	139
Pounds VOCs removed	16,000
VOC Extraction (lb/day)	115
CAPITAL COST	
Site Cost	$5,000
Equipment Costs	
Well Installation	$170,085
Other Equipment	$63,440
Design and engineering	$5,000
Mobile equipment (pickup)	$15,000
Total Equipment Costs	$253,525
Labor Cost	
Mobilize/demobilize	$37,600
Total Capital Cost	$296,125
OPERATION AND MAINTENANCE	
Labor Cost	
Monitoring/maintenance	$25,020
Carbon Recharge	$101,688
Consumable Costs	
(Excluding Carbon Recharge)	$56,073
(With Carbon Recharge)	$157,761
Total Operation and Maintenance	
(Excluding Carbon Recharge)	$81,093
(With Carbon Recharge)	$182,781
TOTAL SITE COST	
(Excluding Carbon Recharge)	$377,218
(With Carbon Recharge)	$478,906

Table 2-II-F-5. Short-term Costs for PT-SVE for Analysis Scenario B, "Low PT-SVE Extrapolation"

Duration (days)	139
Pounds VOCs removed	13,954
VOC extraction (lb/day)	100
CAPITAL COST	
Site Cost	$7,500
Equipment Costs	
Well Installation	$8,110
Other Equipment	$132,466
Design and engineering	$7,500
Mobile equipment	$15,000
Total Equipment Costs	$163,076
Labor Cost	
Mobilize/demobilize	$56,400
Total Capital Cost	$226,976
OPERATION AND MAINTENANCE	
Labor Cost	
Monitoring/maintenance	$37,530
Carbon Recharge	$109,119
Consumable Costs	
(Excluding Carbon Recharge)	$84,110
(With Carbon Recharge)	$193,229
Total Operation and Maintenance	
(Excluding Carbon Recharge)	$121,640
(With Carbon Recharge)	$230,759
TOTAL SITE COST	
(Excluding Carbon Recharge)	$348,616
(With Carbon Recharge)	$457,735

c. Summary for Analysis Scenario B

Excluding carbon recharge costs, of the ISAS $377,218 short-term cost, $296,125 (or 78.50%) is for capital and $81,093 (or 21.50%) is for operation and maintenance. In contrast, PT-SVE short-term costs, with carbon recharge costs excluded, are $348,616, with $226,976 (or 65.11%) for capital and $121,640 (or 34.89%) for operation and maintenance.

When carbon recharge costs are included (this uses the base case performance scenario found in [54]), ISAS short-term costs are $478,906, because carbon recharge adds $101,688 to ISAS consumable costs. Then capital is 61.83%, and operation and maintenance is 38.17%. When carbon recharge costs are included for the combined PT-SVE system, consumable costs increase by $109,119, so PT-SVE short-term costs are $457,735. Capital is 49.59%, and operation and maintenance is 50.41%.

Table 2-II-F-6 provides a summary for Analysis Scenario B. The ratio of ISAS to PT-SVE costs is also shown.

Table 2-II-F-6. Short-term Cost Summary Results

Analysis Scenario B, "Low PT-SVE Extrapolation"

	ISAS	PT-SVE	Ratio
Dollars	$377,218	$348,616	108.20%
Dollars (with carbon recharge)	$478,906	$457,735	104.63%
Pounds Removed	16,000	13,954	114.63%
Days	139	139	--
Dollars/pound	$29.93	$32.80	91.25%
Dollars/scfm	$832.88	$457.74	188.18%

3. Analysis Scenario C, High PT-SVE Extrapolation

The study investigates the three criteria for Analysis Scenario C, "High PT-SVE Extrapolation." This analysis scenario compares the 139-day ISAS field performance data with a higher SVE extrapolation (it is 50% again as high as the low extrapolation scenario).

a. Dollars per Pound Criterion

Short-term ISAS dollars per pound are $29.93/pound ($478,906/16,000 pounds), and short-term PT-SVE dollars per pound are $25.95/pound ($500,901/19,306 pounds). These unit costs use the more optimistic PT-SVE 139-day extrapolation for the quantity of VOC extracted and include carbon recharge costs. With the optimistic extrapolation of SVE extraction, which results in 19,306 pounds removed for the combined PT-SVE system, PT-SVE is more cost-effective at $25.95/pound, compared to ISAS at $29.93/pound.

Short-term costs for ISAS are displayed in Table 2-II-F-7, Short-term Costs for *In Situ* Air Stripping for Analysis Scenario C, "High PT-SVE Extrapolation." Short-term costs for the combined PT-SVE system under Analysis Scenario C are displayed in Table 2-II-F-8, Short-term Costs for PT-SVE for Analysis Scenario C, "High PT-SVE Extrapolation."

b. Dollars per Standard Flow Rate Criterion

Short-term cost for ISAS as measured by a standard engineering flow rate is $832.88/scfm ($478,906/575 scfm). Short-term cost of PT-SVE is $500.90/scfm

Table 2-II-F-7. Short-term Costs for *In Situ* Air Stripping for Analysis Scenario C, "High PT-SVE Extrapolation"

Duration (days)	139
Pounds VOCs removed	16,000
VOC Extraction (lb/day)	115
CAPITAL COST	
Site Cost	$5,000
Equipment Costs	
Well Installation	$170,085
Other Equipment	$63,440
Design and engineering	$5,000
Mobile equipment (pickup)	$15,000
Total Equipment Costs	$253,525
Labor Cost	
Mobilize/demobilize	$37,600
Total Capital Cost	$296,125
OPERATION AND MAINTENANCE	
Labor Cost	
Monitoring/maintenance	$25,020
Carbon Recharge	$101,688
Consumable Costs	
(Excluding Carbon Recharge)	$56,073
(With Carbon Recharge)	$157,761
Total Operation and Maintenance	
(Excluding Carbon Recharge)	$81,093
(With Carbon Recharge)	$182,781
TOTAL SITE COST	
(Excluding Carbon Recharge)	$377,218
(With Carbon Recharge)	$478,906

Table 2-II-F-8. Short-term Costs for PT-SVE for Analysis Scenario C, "High PT-SVE Extrapolation"

Duration (days)	139
Pounds VOCs removed	19,306
VOC extraction (lb/day)	139
CAPITAL COST	
Site Cost	$7,500
Equipment Costs	
Well Installation	$8,110
Other Equipment	$132,466
Design and engineering	$7,500
Mobile equipment	$15,000
Total Equipment Costs	$163,076
Labor Cost	
Mobilize/demobilize	$56,400
Total Capital Cost	$226,976
OPERATION AND MAINTENANCE	
Labor Cost	
Monitoring/maintenance	$37,530
Carbon Recharge	$152,285
Consumable Costs	
(Excluding Carbon Recharge)	$84,110
(With Carbon Recharge)	$236,395
Total Operation and Maintenance	
(Excluding Carbon Recharge)	$121,640
(With Carbon Recharge)	$273,925
TOTAL SITE COST	
(Excluding Carbon Recharge)	$348,616
(With Carbon Recharge)	$500,901

($500,901/1,000 scfm). As in the other analysis scenarios, combined PT-SVE is more cost-effective than ISAS when a standard engineering flow rate, such as dollars per scfm, is used as the criterion. This is especially true for the optimistic PT-SVE analysis scenario.

c. Summary for Analysis Scenario C

Excluding carbon recharge costs, of the ISAS $377,218 short-term cost, $296,125 (or 78.50%) is for capital and $81,093 (or 21.50%) is for operation and maintenance. In contrast, PT-SVE short-term costs, with carbon recharge costs excluded, are $348,616, with $226,976 (or 65.11%) for capital and $121,640 (or 34.89%) for operation and maintenance.

When carbon recharge costs are included, ISAS short-term costs are $478,906, because carbon recharge adds $101,688 to ISAS consumable costs. Then capital is 61.83%, and operation and maintenance is 38.17%. When carbon recharge costs are included for the combined PT-SVE system, consumable costs increase by a considerable $152,285 (due to the high extraction rate assumption), so PT-SVE short-term costs are $500,901. Capital is 45.31%, and operation and maintenance is 54.69%.

Table 2-II-F-9 provides a summary for Analysis Scenario C. The ratio of ISAS to PT-SVE costs is also shown.

G. Long-term Cost Comparison

Long-term costs over the 5-year period are compared. Detailed cost tables for both technologies appear under the dollars per pound criterion for each analysis scenario. Again, as with the tables presented in Section F, "Short-term Cost Comparison," costs are broken

Table 2-II-F-9. Short-term Cost Summary Results

Analysis Scenario C, "High PT-SVE Extrapolation"	ISAS	PT-SVE	Ratio
Dollars	$377,218	$348,616	108.20%
Dollars (with carbon recharge)	$478,906	$500,901	95.61%
Pounds Removed	16,000	19,306	82.88%
Days	139	139	--
Dollars/pound	$29.93	$25.95	115.34%
Dollars/scfm	$832.88	$500.90	166.28%

down into capital costs and O&M costs. However, now the operation and maintenance of the system occurs over 5 years. Capital as well as O&M cost components remain the same. Carbon recharge, an especially large consumable cost incurred during the lifetime operation and maintenance of the system, is shown separately. Consumable costs and total O&M costs are shown both with and without carbon recharge. Again, total site costs are shown both with and without carbon recharge. Net present value per VOC pound and per scfm are reported. Finally, discounted and undiscounted total annual dollars are shown.

1. Analysis Scenario D, "Long-term Low PT-SVE Extrapolation"

This study investigates the three criteria for Analysis Scenario D, "Long-term Low PT-SVE Extrapolation." This analysis scenario assumes the extrapolation for SVE for the 5-year long-term period found in [54]. Over this period, the combined PT-SVE system is assumed to remove 121,545 pounds of VOCs, and ISAS is assumed to remove 135,780 pounds of VOCs.

a. Dollars per Pound Criterion

To evaluate net present value, a discount rate of 7% is used for the base case. Results are also shown for low and high discount rates of 4% and 10%. Long-term ISAS dollars per pound are $15.63/pound ($2,122,705/135,780 pounds), and long-term PT-SVE dollars per pound are $21.51/pound ($2,614,863/121,545 pounds). These unit costs use the more conservative PT-SVE 139-day extrapolation as the basis for the initial year's quantity of VOC extracted. The net present value calculations include carbon recharge costs. Even for the long-term low extrapolation case, PT-SVE is almost as cost-effective at $21.51/pound, compared to ISAS at $15.63/pound. This ratio of ISAS to combined PT-SVE net present value per pound of VOC is 72.66%.

Long-term costs for ISAS are displayed in Table 2-II-G-1, *In Situ* Air Stripping Long-term Costs (5 years) for Analysis Scenario D, "Low PT-SVE Extrapolation." Long-term costs for the combined PT-SVE system are displayed in Table 2-II-G-2, Combined PT-SVE Long-term Costs (5 years) for Analysis Scenario D, "Long-term Low PT-SVE Extrapolation."

b. Dollars per Unit of Environment Remediated Criterion

Anticipating the results of groundwater modeling, the study calculates an estimate of cubic meters remediated and dollars per unit of environment remediated. Groundwater modeling results show that about 50% of the initial VOC contaminant mass in place would be removed after 5 years. From the groundwater modeling results, over 5 years, about

Table 2-II-G-1. *In Situ* Air Stripping Life-cycle Costs (5 years) for Analysis Scenario D, "Low PT-SVE Extrapolation"

Years	1	2	3	4	5
CAPITAL COST					
Site Cost	$5,000				
Equipment Costs					
Well Installation	$170,085				
Other Equipment	$63,440				
Design and engineering	$5,000				
Mobile equipment (pickup)	$15,000				
Total Equipment Costs	$253,525				
Labor Cost					
Mobilize/demobilize	$37,600				
Total Capital Cost	$296,125				
OPERATION AND MAINTENANCE					
Escalation Rate	1.00	1.04	1.04	1.04	1.04
Labor Cost					
Monitoring/maintenance	$65,700	$68,328	$71,061	$73,904	$76,860
VOC Extraction* (lb/day)	115	86	57	57	57
Carbon Recharge	$267,022	$207,076	$143,791	$149,799	$156,074
Consumable Costs					
(Excluding Carbon Recharge)	$147,242	$153,132	$159,257	$165,627	$172,252
(With Carbon Recharge)	$414,264	$360,208	$303,048	$315,426	$328,326
Total Operation and Maintenance					
(Excluding Carbon Recharge)	$212,942	$221,460	$230,318	$239,531	$249,112
(With Carbon Recharge)	$479,964	$428,536	$374,109	$389,330	$405,186

Table 2-II-G-1. *In Situ* Air Stripping Life-cycle Costs (5 years) for Analysis Scenario D, "Low PT-SVE Extrapolation" (concluded)

	Years	1	2	3	4	5
TOTAL ANNUAL COST						
(Excluding Carbon Recharge)		$509,067	$221,460	$230,318	$239,531	$249,112
(With Carbon Recharge)		$776,089	$428,536	$374,109	$389,330	$405,186
Excluding Carbon Recharge						
Discounted (4%)		$509,067	$212,776	$212,610	$212,445	$212,279
Discounted (7%)		$509,067	$206,488	$200,229	$194,160	$188,275
Discounted (10%)		$509,067	$200,385	$188,568	$177,449	$166,985
With Carbon Recharge						
Discounted (4%)		$776,089	$411,733	$345,346	$345,305	$345,277
Discounted (7%)		$776,089	$399,564	$325,235	$315,585	$306,233
Discounted (10%)		$776,089	$387,755	$306,295	$288,423	$271,604
Excluding Carbon Recharge						
Discount Rate		NPV			$/scfm**	scfm**/$
	0.04	$1,359,178			$2,364	0.000423
	0.07	$1,298,218			$2,258	0.000443
	0.10	$1,242,454			$2,161	0.000463
With Carbon Recharge						
Discount Rate		NPV	$/lb VOC*		$/scfm**	scfm**/$
	0.04	$2,223,749	$16.38		$3,867	0.000259
	0.07	$2,122,705	$15.63		$3,692	0.000271
	0.10	$2,030,166	$14.95		$3,531	0.000283

*Total VOC extraction is assumed to be 135,780 pounds.

**Standard cubic feet per minute is assumed to be 575 scfm.

Table 2-II-G-2. Combined PT-SVE Life-cycle Costs (5 years) for Analysis Scenario D, "Long-term Low PT-SVE Extrapolation"

Years	1	2	3	4	5
CAPITAL COST					
Site Cost	$7,500				
Equipment Costs					
Well Installation	$8,110				
Other Equipment	$132,466				
Design and engineering	$7,500				
Mobile equipment (pickup)	$15,000				
Total Equipment Costs	$163,076				
Labor Cost					
Mobilize/demobilize	$56,400				
Total Capital Cost	$226,976				
OPERATION AND MAINTENANCE					
Escalation Rate	1.00	1.04	1.04	1.04	1.04
Labor Cost					
Monitoring/maintenance	$98,550	$102,492	$106,592	$110,855	$115,290
VOC Extraction* (lb/day)	103	77	51	51	51
Carbon Recharge	$286,536	$222,208	$154,300	$160,747	$167,480
Total Consumable Costs					
(Excluding Carbon Recharge)	$220,864	$229,699	$238,887	$248,442	$258,380
(With Carbon Recharge)	$507,400	$451,907	$393,187	$409,189	$425,860
Total Operation and Maintenance					
(Excluding Carbon Recharge)	$319,414	$332,191	$345,479	$359,298	$373,670
(With Carbon Recharge)	$605,950	$554,399	$499,779	$520,045	$541,150

Table 2-II-G-2. Combined PT-SVE Life-cycle Costs (5 years) for Analysis Scenario D, "Long-term Low PT-SVE Extrapolation" (concluded)

	Years	1	2	3	4	5
TOTAL ANNUAL COST						
(Excluding Carbon Recharge)		$546,390	$332,191	$345,479	$359,298	$373,670
(With Carbon Recharge)		$832,926	$554,399	$499,779	$520,045	$541,150
Excluding Carbon Recharge						
Discounted (4%)		$546,390	$319,166	$318,917	$318,669	$318,420
Discounted (7%)		$546,390	$309,733	$300,345	$291,241	$282,413
Discounted (10%)		$546,390	$300,579	$282,854	$266,174	$250,478
With Carbon Recharge						
Discounted (4%)		$832,926	$532,661	$461,354	$461,238	$461,137
Discounted (7%)		$832,926	$516,918	$434,487	$421,540	$408,992
Discounted (10%)		$832,926	$501,641	$409,184	$385,259	$362,743
Excluding Carbon Recharge						
Discount Rate		NPV			$/scfm**	scfm**/$
	0.04	$1,821,562			$1,822	0.000549
	0.07	$1,730,122			$1,730	0.000578
	0.10	$1,646,476			$1,646	0.000607
With Carbon Recharge						
Discount Rate		NPV	$/lb VOC*		$/scfm**	scfm**/$
	0.04	$2,749,316	$22.62		$2,749	0.000364
	0.07	$2,614,863	$21.51		$2,615	0.000382
	0.10	$2,491,754	$20.50		$2,492	0.000401

*Total VOC extraction is assumed to be 121,545 pounds.

**Standard cubic feet per minute is assumed to be 1,000 scfm.

110,230 pounds of VOCs are assumed to be removed. Doubling this amount, the study assumes a total of 220,000 pounds of VOCs originally in place. Note that there is a considerable amount of uncertainty associated with this estimate. A one-to-one correspondence between VOC pounds extracted and units of environment remediated is assumed. Units of environment permanently remediated is the new, long-term metric. Then the study converts VOC pounds extracted to cubic meters remediated.

In Analysis Scenario D, "Long-term Low PT-SVE Extrapolation," ISAS removed 135,780 pounds, whereas the combined PT-SVE system removed 121,545 pounds. For ISAS an estimate of 56,904 cubic meters remediated was made from (135,780 long-term pounds removed/220,000 initial pounds) x 92,200 initial cubic meters = 56,904 cubic meters. This results for ISAS in an estimate of dollars per unit of the environment remediated as $37.30/cubic meter ($2,122,705/56,904 cubic meters). For PT-SVE an estimate of 50,938 cubic meters remediated was made from (121,545 long-term pounds removed/220,000 initial pounds) x 92,200 initial cubic meters = 50,938 cubic meters. This results, for the combined PT-SVE system, in an estimate of $51.33/cubic meter ($2,614,863/50,938 cubic meters).

c. Dollars per Standard Flow Rate Criterion

Long-term cost for ISAS as measured by a standard engineering flow rate is $3,691.66/scfm ($2,122,705/575 scfm). Long-term cost of PT-SVE is $2,614.86/scfm ($2,614,863/1,000 scfm). The combined PT-SVE system is more cost-effective than ISAS when a standard engineering flow rate, such as dollars per scfm, is used as the long-term criterion. This holds even for the PT-SVE low extrapolation analysis scenarios for both the short term and the long term.

d. Summary for Analysis Scenario D

For the net present value calculations, a discount rate of 7% was used for the base case, but the study also reports low and high discounts rates of 4% and 10%. Excluding carbon recharge costs, the ISAS long-term net present value is $1,298,218. In contrast, PT-SVE long-term costs, with carbon recharge costs excluded, are $1,730,122.

When carbon recharge costs are included using the low extrapolation case, ISAS long-term costs are $2,122,705. When carbon recharge costs are included for the combined PT-SVE system, long-term costs are $2,614,863.

Table 2-II-G-3 provides a summary for Analysis Scenario D. The ratio of ISAS to PT-SVE costs is also reported.

Under the assumptions of Analysis Scenario D, "Long-term Low PT-SVE Extrapolation," ISAS is more cost-effective in the long-term analysis when using the criteria of dollars per pound removed and dollars per cubic meter remediated. In contrast, PT-SVE is more cost-effective in the long-term analysis when using the dollars per scfm criterion.

Table 2-II-G-3. Long-term Cost Summary Results

Analysis Scenario D, "Long-term Low PT-SVE Extrapolation"

	ISAS	PT-SVE	Ratio
Dollars	$1,298,218	$1,730,122	75.04%
Dollars (with carbon recharge)	$2,122,705	$2,614,863	81.18%
Pounds Removed	135,780	121,545	111.07%
Years	5	5	--
Dollars/pound	$15.63	$21.51	72.66%
Dollars/cubic meter	$37.30	$51.33	72.71%
Dollars/scfm	$3,691.66	$2,614.86	141.19%

2. Analysis Scenario E, "Long-term High PT-SVE Extrapolation"

The study investigates the three criteria for Analysis Scenario E, "Long-term High PT-SVE Extrapolation." This analysis scenario assumes the high extrapolation for SVE for the 5-year long-term period. Over this period, the combined PT-SVE system is assumed to remove 164,761 pounds of VOCs.

a. Dollars per Pound Criterion

To evaluate net present value, a discount rate of 7% is used in the summary tables. Results are also shown for low and high discount rates of 4% and 10%. Long-term ISAS dollars per pound are $15.63/pound ($2,122,705/135,780 pounds), and long-term PT-SVE dollars per pound are $17.58/pound ($2,896,654/164,761 pounds). These unit costs use a more optimistic PT-SVE 139-day extrapolation as the basis for the initial year's quantity of VOC extracted. The net present value calculations include carbon recharge costs. ISAS remains more cost-effective at $15.63/pound, compared to PT-SVE at $17.58/pound. This is due to the large carbon recharge costs for the combined PT-SVE system. This ratio of ISAS to combined PT-SVE net present value per pound of VOC is 88.91%.

Long-term costs for ISAS are displayed in Table 2-II-G-4, *In Situ* Air Stripping for Long-term Costs (5 years) for Analysis Scenario E, "Long-term High PT-SVE Extrapolation." Long-term costs for the combined PT-SVE system under Analysis Scenario E are displayed in Table 2-II-G-5, Combined PT-SVE Long-term Costs (5 years) for Analysis Scenario E, "Long-term High PT-SVE Extrapolation."

b. Dollars per Unit of Environment Remediated Criterion

For ISAS, this criterion is calculated as $37.30/cubic meters ($2,122,705/56,904 cubic meters). For the combined PT-SVE system, this is $41.95/cubic meter ($2,896,654/69,050 cubic meters). An estimate of 69,050 cubic meters remediated for the combined PT-SVE system was made from (164,761 long-term pounds removed/220,000 initial pounds) x 92,200 initial cubic meters = 69,050 cubic meters.

c. Dollars per Standard Flow Rate Criterion

Long-term cost for ISAS as measured by a standard engineering flow rate is $3,691.66/scfm ($2,122,705/575 scfm). Long-term cost for PT-SVE is $2,896.65/scfm ($2,896,654/1,000 scfm). PT-SVE is more cost-effective than ISAS when Analysis Scenario E, "Long-term High PT-SVE Extrapolation," is evaluated with the dollars per scfm criterion.

Table 2-II-G-4. *In Situ* Air Stripping Life-cycle Costs (5 years) for Analysis Scenario E, "Long-term High PT-SVE Extrapolation"

Years	1	2	3	4	5
CAPITAL COST					
Site Cost	$5,000				
Equipment Costs					
Well Installation	$170,085				
Other Equipment	$63,440				
Design and engineering	$5,000				
Mobile equipment (pickup)	$15,000				
Total Equipment Costs	$253,525				
Labor Cost					
Mobilize/demobilize	$37,600				
Total Capital Cost	$296,125				
OPERATION AND MAINTENANCE					
Escalation Rate	1.00	1.04	1.04	1.04	1.04
Labor Costs					
Monitoring/maintenance	$65,700	$68,328	$71,061	$73,904	$76,860
VOC Extraction* (lb/day)	115	86	57	57	57
Carbon Recharge	$267,022	$207,076	$143,791	$149,799	$156,074
Consumable Costs					
(Excluding Carbon Recharge)	$147,242	$153,132	$159,257	$165,627	$172,252
(With Carbon Recharge)	$414,264	$360,208	$303,048	$315,426	$328,326
Total Operation and Maintenance					
(Excluding Carbon Recharge)	$212,942	$221,460	$230,318	$239,531	$249,112
(With Carbon Recharge)	$479,964	$428,536	$374,109	$389,330	$405,186

Table 2-II-G-4. *In Situ* Air Stripping Life-cycle Costs (5 years) for Analysis Scenario E, "Long-term High PT-SVE Extrapolation" (concluded)

	Years	1	2	3	4	5
TOTAL ANNUAL COST						
(Excluding Carbon Recharge)		$509,067	$221,460	$230,318	$239,531	$249,112
(With Carbon Recharge)		$776,089	$428,536	$374,109	$389,330	$405,186
Excluding Carbon Recharge						
Discounted (4%)		$509,067	$212,776	$212,610	$212,445	$212,279
Discounted (7%)		$509,067	$206,488	$200,229	$194,160	$188,275
Discounted (10%)		$509,067	$200,385	$188,568	$177,449	$166,985
With Carbon Recharge						
Discounted (4%)		$776,089	$411,733	$345,346	$345,305	$345,277
Discounted (7%)		$776,089	$399,564	$325,235	$315,585	$306,233
Discounted (10%)		$776,089	$387,755	$306,295	$288,423	$271,604
Excluding Carbon Recharge						
Discount Rate		NPV			$/scfm**	scfm**/$
	0.04	$1,359,178			$2,364	0.000423
	0.07	$1,298,218			$2,258	0.000443
	0.10	$1,242,454			$2,161	0.000463
With Carbon Recharge						
Discount Rate		NPV	$/lb VOC*		$/scfm**	scfm**/$
	0.04	$2,223,749	$16.38		$3,867	0.000259
	0.07	$2,122,705	$15.63		$3,692	0.000271
	0.10	$2,030,166	$14.95		$3,531	0.000283

*Total VOC extraction is assumed to be 135,780 pounds.

**Standard cubic feet per minute is assumed to be 575 scfm.

Table 2-II-G-5. Combined PT-SVE Life-cycle Costs (5 years) for Analysis Scenario E, "Long-term High PT-SVE Extrapolation"

Years	1	2	3	4	5
CAPITAL COST					
Site Cost	$7,500				
Equipment Costs					
Well Installation	$8,110				
Other Equipment	$132,466				
Design and engineering	$7,500				
Mobile equipment (pickup)	$15,000				
Total Equipment Costs	$163,076				
Labor Cost					
Mobilize/demobilize	$56,400				
Total Capital Cost	$226,976				
OPERATION AND MAINTENANCE					
Escalation Rate	1.00	1.04	1.04	1.04	1.04
Labor Cost					
Monitoring/maintenance	$98,550	$102,492	$106,592	$110,855	$115,290
VOC Extraction* (lb/day)	139	104	69	69	69
Carbon Recharge	$399,886	$299,915	$199,943	$199,943	$199,943
Total Consumable Costs					
(Excluding Carbon Recharge)	$220,864	$229,699	$238,887	$248,442	$258,380
(With Carbon Recharge)	$620,751	$529,614	$438,830	$448,385	$458,323
Total Operation and Maintenance					
(Excluding Carbon Recharge)	$319,414	$332,191	$345,479	$359,298	$373,670
(With Carbon Recharge)	$719,301	$632,106	$545,422	$559,241	$573,613

Table 2-II-G-5. Combined PT-SVE Life-cycle Costs (5 years) for Analysis Scenario E, "Long-term High PT-SVE Extrapolation" (concluded)

	Years	1	2	3	4	5
TOTAL ANNUAL COST						
(Excluding Carbon Recharge)		$546,390	$332,191	$345,479	$359,298	$373,670
(With Carbon Recharge)		$946,277	$632,106	$545,422	$559,241	$573,613
Excluding Carbon Recharge						
Discounted (4%)		$546,390	$319,166	$318,917	$318,669	$318,420
Discounted (7%)		$546,390	$309,733	$300,345	$291,241	$282,413
Discounted (10%)		$546,390	$300,579	$282,854	$266,174	$250,478
With Carbon Recharge						
Discounted (4%)		$946,277	$607,320	$503,488	$496,002	$488,801
Discounted (7%)		$946,277	$589,371	$474,167	$453,312	$433,527
Discounted (10%)		$946,277	$571,953	$446,554	$414,296	$384,504
Excluding Carbon Recharge						
Discount Rate		NPV			$/scfm**	scfm**/$
	0.04	$1,821,562			$1,822	0.000549
	0.07	$1,730,122			$1,730	0.000578
	0.10	$1,646,476			$1,646	0.000607
With Carbon Recharge						
Discount Rate		NPV	$/lb VOC*		$/scfm**	scfm**/$
	0.04	$3,041,887	$18.46		$3,042	0.000329
	0.07	$2,896,654	$17.58		$2,897	0.000345
	0.10	$2,763,583	$16.77		$2,764	0.000362

*Total VOC extraction is assumed to be 164,761 pounds.

**Standard cubic feet per minute is assumed to be 1,000 scfm.

d. Summary for Analysis Scenario E

For the net present value calculations, a discount rate of 7% was used for the base case, but the study also reports low and high discounts rates of 4% and 10%. Excluding carbon recharge costs, the ISAS long-term net present value is $1,298,218. In contrast, PT-SVE long-term costs, with carbon recharge costs excluded, are $1,730,122.

When carbon recharge costs are included for the high extrapolation case, ISAS long-term costs are $2,122,705. When carbon recharge costs are included for the combined PT-SVE system, long-term costs are $2,896,654.

Table 2-II-G-6 provides a summary for Analysis Scenario E. The ratio of ISAS to PT-SVE costs is also reported.

Table 2-II-G-6. Long-term Cost Summary Results

Analysis Scenario E, "Long-term High PT-SVE Extrapolation"

	ISAS	PT-SVE	Ratio
Dollars	$1,298,218	$1,730,122	75.04%
Dollars (with carbon recharge)	$2,122,705	$2,896,654	73.28%
Pounds Removed	135,780	164,761	81.94%
Years	5	5	--
Dollars/pound	$15.63	$17.58	88.91%
Dollars/cubic meter	$37.30	$41.95	88.92%
Dollars/scfm	$3,691.66	$2,896.55	127.44%

As in Analysis Scenario D, ISAS is more cost-effective in the long-term analysis when using the criteria of dollars per pound and dollars per cubic meter remediated. PT-

SVE is more cost-effective in the long-term analysis when using the dollars per scfm criterion.

H. Summary of Results

Results are summarized for both short-term (21 and 139 days) and long-term (5 years) costs. First, the short-term costs are considered. Under Analysis Scenario A, "Actual PT-SVE," PT-SVE is more cost-effective using the criteria of dollars per pound removed and dollars per scfm. The ratios of ISAS/PT-SVE costs using these two criteria are 263.05% and 190.57%, respectively. Under Analysis Scenario B, "Low PT-SVE Extrapolation," ISAS is slightly more cost-effective than PT-SVE using the dollars per pound criterion. However, PT-SVE is more cost-effective when considering the dollars per scfm criterion. The ratios of ISAS/PT-SVE using these two criteria are 91.25% and 188.18%, respectively. Finally, under Analysis Scenario C, "High PT-SVE Extrapolation," PT-SVE is again more cost-effective than ISAS using both the dollars per pound and the dollars per scfm criteria. The ratios of ISAS/PT-SVE using these two criteria are 115.34% and 166.28%, respectively. Table 2-II-H-1 is a compilation of the three short-term summary tables for each analysis scenario.

Note that these measures are most sensitive to assumptions regarding the rate of VOC extraction. An attempt was made to establish reasonable bounds within which to consider VOC extraction. The 139-day ISAS field performance provided a fairly lengthy short-term

Table 2-II-H-1. Short-term Cost Summary Results

Analysis Scenario A, "Actual PT-SVE"

	ISAS	PT-SVE	Ratio
Dollars	$308,376	$245,353	125.69%
Dollars (with carbon recharge)	$325,511	$297,060	81.98%
Pounds Removed	2,696	6,472	41.66%
Years	21	21	--
Dollars/pound	$120.74	$45.90	263.05%
Dollars/scfm	$566.11	$297.06	190.57%

Analysis Scenario B, "Low PT-SVE Extrapolation"

	ISAS	PT-SVE	Ratio
Dollars	$377.218	$348,616	108.20%
Dollars (with carbon recharge)	$478,906	$457,735	104.63%
Pounds Removed	16,000	13,954	114.63%
Years	139	139	--
Dollars/pound	$29.93	$32.80	91.25%
Dollars/scfm	$832.88	$457.54	188.18%

Analysis Scenario C, "High PT-SVE Extrapolation"

	ISAS	PT-SVE	Ratio
Dollars	$377,218	$348,616	108.20%
Dollars (with carbon recharge)	$478,906	$500,901	95.61%
Pounds Removed	16,000	19,306	82.88%
Years	139	139	--
Dollars/pound	$29.93	$25.95	115.34%
Dollars/scfm	$832.88	$500.90	166.28%

data set on VOC concentration levels. Extrapolation of SVE extraction of VOCs from the 21-day field test is problematic, given the short field trial. The three analysis scenarios provided reasonable bounds for SVE extraction.

Turning to the long-term cost comparison, under Analysis Scenario D, "Long-term Low PT-SVE Extrapolation," ISAS is somewhat more cost-effective than PT-SVE using the criteria of dollars per pound removed and dollars per cubic meter remediated. However, PT-SVE is again more cost-effective when considering the dollars per scfm criterion. The ratios of ISAS/PT-SVE using these three criteria are 72.66%, 72.71%, and 141.19%, respectively. Finally, under Analysis Scenario E, "Long-term High PT-SVE Extrapolation," the results are the same. ISAS is again more cost-effective if the criteria of dollars per pound removed and dollars per cubic meters remediated are used. The ratios of ISAS/PT-SVE using these three criteria are 88.91%, 88.92%, and 127.44%, respectively. Table 2-II-H-2 is a compilation of the two long-term summary tables for each analysis scenario.

Note that these measures are most sensitive to assumptions regarding the rate of VOC extraction. An attempt was made to establish reasonable bounds within which to consider VOC extraction. Groundwater modeling also was used to establish a performance scenario.

Table 2-II-H-2. Long-term Cost Summary Results

Analysis Scenario D, "Long-term Low PT-SVE Extrapolation"

	ISAS	PT-SVE	Ratio
Dollars	$1,298,218	$1,730,122	75.04%
Dollars (with carbon recharge)	$2,122,705	$2,614,863	81.18%
Pounds Removed	135,780	121,545	111.07%
Years	5	5	--
Dollars/pound	$15.63	$21.51	72.66%
Dollars/cubic meter	$37.30	$51.33	72.71%
Dollars/scfm	$3,691.66	$2,614.86	141.19%

Analysis Scenario E, "Long-term High PT-SVE Extrapolation"

	ISAS	PT-SVE	Ratio
Dollars	$1,298,218	$1,730,122	75.04%
Dollars (with carbon recharge)	$2,122,705	$2,896,654	73.28%
Pounds Removed	135,780	164,761	81.94%
Years	5	5	--
Dollars/pound	$15.63	$17.58	88.91%
Dollars/cubic meter	$37.30	41.95$	88.92%
Dollars/scfm	$3,691.66	$2,896.65	127.44%

III. Groundwater Modeling

Groundwater modeling is capable of provided more sophisticated performance scenarios for both short-term and long-term cost comparison. Ultimately, groundwater modeling could be extended to such issues as "technology optimization," in which different operating conditions and strategies could be examined. This relates back to the decision tree approach and reinforces the decision theoretic environment, in which the decision maker has available an array of alternatives. Technology optimization includes management choices such as pulse, cyclic, or continuous pumping. The use of modeling should guide the design of future ISAS systems as well as other remediation technologies.

A. Background

Preliminary groundwater modeling results exist for three plume geometries. Preliminary groundwater modeling, using a homogeneous medium, in which remediation by a single vertical well was compared to remediation by a single horizontal well was summarized by Birdsell and Rosenberg [6]. Plume geometries are symmetric, linear, and box. For each plume geometry, a model run for horizontal and vertical wells may be compared. In the case of the box plume geometry, vertical well case, both a box plume with a cap and a box plume without a cap have been run. It is thought that capping of the well may improve contaminant removal. The study focuses on the linear plume geometry, because it is the more appropriate description of the SRID site. (The assumption is made that a plume generated by a line source such as a leaking pipe may be represented by a linear plume geometry.) Preliminary modeling assumptions are hydraulic properties of homogeneous sand and a porous medium. Contaminant properties of TCE and a given concentration level are also assumed. (Additional assumptions are a well screened interval of 30 meters; withdrawn contaminated air at a rate of 100 ft^3/min; and simulated extraction for 30 days.)

The study focuses on the comparison of horizontal and vertical wells for the linear plume geometry. The vertical well remediation is initially considerably more successful in removing the contaminant, although over time the horizontal well removes more of the contaminant. For the simulated extraction of 30 days, the vertical well left approximately 5.8% of the original contaminant in the ground, whereas the horizontal well removed virtually all of the contaminant. If the environmental standard is zero contaminant remaining in the ground, then the vertical well technology fails to remove a significant amount. Recall, however, that this result was for a homogeneous medium.

In Section II-G, five-year long-term estimates were based on short-term 21-day and 139-day field-scale tests in order to develop long-term 5-year performance scenarios. Groundwater modeling is capable of providing the information necessary for a more comprehensive analysis, as well as providing better information concerning environmental remediation performance than field studies by themselves. This cost-effectiveness analysis of the ISAS groundwater remediation demonstration will also investigate groundwater modeling to simulate the performance of various scenarios.

"History-matching" of the actual ISAS field test data was presented in [49]. This better illustrates the effect of site heterogeneity. Numerical simulations were then made from the "history-matching" of TCE concentration data from the ISAS demonstration. In the modeling results that follow, it is assumed that TCE and PCE each account for about 50% of the VOC mass. Total VOC mass is estimated by doubling the TCE amount. This technique may be refined. ISAS combined stripping/extraction was compared to ISAS extraction only. No results are available for the competing PT-SVE system.

The preliminary results for the length of time required to remove a given fraction of the initial TCE inventory are shown below.

Table 2-III-A-1. Years Required to Achieve Removal of a Given Persent of TCE

Amount Removed	Stripping/ Extraction	Extraction Only
50%	4.3	5.1
75%	8.9	11.4
90%	15.3	22.6
95%	20.6	>27.4

With both air injection and vacuum extraction, only 50% of the original TCE is removed after 4.3 years. This illustrates the difficulty of obtaining large removal fractions for a heterogeneous site such as this. The history-matching analysis in [49] noted that "air injection has a very small long-term benefit in these predictions because the accessible TCE has been extracted at early time." (p. 5)

B. Long-term Modeling Results

Long-term simulation modeling of the ISAS field demonstration data is another potential analysis scenario. It is referred to as "long-term ISAS modeling." Estimates from history-matching of the ISAS demonstration (Robinson and Rosenberg in [49]) suggest a downward revision in total VOC removal for ISAS for the first year and for each of the following years. ISAS modeling of VOC removal is calculated as 91 pounds per day for the first year, followed by 67, 58, 48, and 38 pounds per day, respectively, for the second through fifth years. The first year extraction of 91 pounds per day was calculated as a weighted average of 115 pounds per day (from the 139-day actual extraction) and 76 pounds per day (for the remaining 226 days of the first year) from the long-term modeling projections. (Robinson, et al. [49], Figure 3.16.) Over the 5-year modeling long-term period, 110,230 pounds of VOCs are assumed to be removed. This compares to the 135,780 pounds removed by ISAS found in [54] and used in long-term analyses (Analysis Scenarios D and E).

1. Long-term ISAS modeling cost comparison

Long-term costs over the 5-year long-term period are compared for the ISAS performance found in the long-term Analysis Scenarios D and E and an ISAS modeling performance scenario. A detailed cost table for the ISAS modeling analysis scenario appears under the dollars per pound criterion. Carbon recharge costs are an especially large consumable cost incurred during the lifetime operation and maintenance of the system. Under the modeling performance scenario, ISAS is assumed to remove 110,230 pounds of

VOCs, which is a more conservative total extraction estimate for ISAS than reported in the long-term Analysis Scenarios D and E. This long-term total extraction estimate also provides a means to calculate an estimate of the initial contaminant mass in place. With the 5-year modeling total extraction of 110,230 pounds and a removal percentage of 50%, 220,000 pounds were assumed to be originally in place. This was discussed previously in Section II-G.

a. Dollars per Pound Criterion

Again, a net present value of 7% is used for the base case. Results are also shown for low and high discount rates of 4% and 10%. Long-term ISAS dollars per pound are $17.48/pound ($1,926,438/110,230 pounds). Long-term costs for ISAS are displayed in Table 2-III-B-1, *In Situ* Air Stripping Modeling Long-term Costs (5 years).

b. Dollars per Unit of Environment Remediated Criterion

A cost of $41.79/cubic meter is reported for long-term ISAS modeling. This was calculated from $1,926,438/46,100 cubic meters. It should be compared to the ISAS 5-year long-term estimate of $37.30/cubic meter reported in the long-term Analysis Scenarios D and E. The estimate of 46,100 cubic meters remediated was calculated from 50% removal after 5 years from the original 92,200 cubic meters.

Table 2-III-B-1. *In Situ* Air Stripping Modeling Life-cycle Costs (5 years)

Years	1	2	3	4	5
CAPITAL COST					
Site Cost	$5,000				
Equipment Costs					
Well Installation	$170,085				
Other Equipment	$63,440				
Design and engineering	$5,000				
Mobile equipment (pickup)	$15,000				
Total Equipment Costs	$253,525				
Labor Cost					
Mobilize/demobilize	$37,600				
Total Capital Cost	$296,125				
OPERATION AND MAINTENANCE					
Escalation Rate	1.00	1.04	1.04	1.04	1.04
Labor Cost					
Monitoring/maintenance	$65,700	$68,328	$71,061	$73,904	$76,860
VOC Extraction* (lb/day)	91	67	58	48	38
Carbon Recharge	$211,098	$154,728	$133,850	$110,652	$88,383
Consumable Costs					
(Excluding Carbon Recharge)	$147,242	$153,132	$159,257	$165,627	$172,252
(With Carbon Recharge)	$358,340	$307,860	$293,107	$276,280	$260,635
Total Operation and Maintenance					
(Excluding Carbon Recharge)	$212,942	$221,460	$230,318	$239,531	$249,112
(With Carbon Recharge)	$424,040	$376,188	$364,168	$350,183	$337,495

Table 2-III-B-1. *In Situ* Air Stripping Modeling Life-cycle Costs (5 years) (concluded)

ANNUAL TOTAL COST					
(Excluding Carbon Recharge)	$509,067	$221,460	$230,318	$239,531	$249,112
(With Carbon Recharge)	$720,165	$376,188	$364,168	$350,183	$337,495
Excluding Carbon Recharge					
Discounted (4%)	$509,067	$212,776	$212,610	$212,445	$212,279
Discounted (7%)	$509,067	$206,488	$200,229	$194,160	$188,275
Discounted (10%)	$509,067	$200,385	$188,568	$177,449	$166,985
With Carbon Recharge					
Discounted (4%)	$720,165	$361,437	$336,170	$310,585	$287,594
Discounted (7%)	$720,165	$350,755	$316,593	$283,853	$255,073
Discounted (10%)	$720,165	$340,389	$298,156	$259,422	$226,230

Excluding Carbon Recharge

Discount Rate	NPV	$/lb VOC*	$/scfm**	scfm**/$
0.04	$1,359,178	$12.33	$2,364	0.000423
0.07	$1,298,218	$11.78	$2,258	0.000443
0.10	$1,242,454	$11.27	$2,161	0.000463

With Carbon Recharge

Discount Rate	NPV	$/lb VOC*	$/scfm**	scfm**/$
0.04	$2,015,950	$18.29	$3,506	0.000285
0.07	$1,926,438	$17.48	$3,350	0.000298
0.10	$1,844,361	$16.73	$3,208	0.000312

*Total VOC extraction is assumed to be 110,230 pounds.

**Standard cubic feet per minute is assumed to be 575 scfm.

c. Dollars per Standard Flow Rate Criterion

Long-term cost for ISAS modeling as measured by a standard engineering flow rate of $3,350.33/scfm ($1,926,438/575 scfm). This compares to the ISAS long-term cost under Analysis Scenarios D and E, which was $3,691.66/scfm.

d. Summary for Long-term ISAS Modeling Results

Results for a discount rate of 7% are discussed, but low and high discount rates of 4% and 10% are also reported. Excluding carbon recharge costs, the ISAS long-term modeling net present value is $1,298,218. This is the same as the long-term ISAS long-term cost reported in the long-term Analysis Scenarios D and E. When carbon recharge costs are included, the ISAS long-term modeling net present value is $1,926,438. This compares to the long-term ISAS long-term cost of $2,122,705 reported in the long-term Analysis Scenarios D and E.

Table 2-III-B-2 presents a summary of long-term ISAS modeling results and compares them to the costs from the long-term Analysis Scenarios D and E. The ratio of ISAS modeling/ISAS is also shown.

Table 2-III-B-2. Long-term ISAS Modeling Summary Results

	ISAS Modeling	ISAS	Ratio
Dollars	$1,298,218	$1,298,218	100.00%
Dollars (with carbon recharge)	$1,926,438	$2,122,705	90.75%
Pounds Removed	110,230	135,780	81.18%
Years	5	5	--
Dollars/pound	$17.48	$15.63	111.84%
Dollars/cubic meter	$41.79	$37.30	112.04%
Dollars/scfm	$3,350.33	$3,691.66	90.75%

Under the assumptions of the ISAS modeling performance scenario, total 5-year VOC extraction is lower. This results in a lower net present value but slightly higher dollars per pounds removed and dollars per cubic meter remediated. The third criterion, dollars per scfm, is slightly lower, given the long-term modeling assumptions.

C. Technology Optimization

With technology optimization modeling, the study examines the effect of different operating conditions and strategies in order to develop a performance scenario. This use of modeling should guide the design of future ISAS systems. This performance scenario is referred to as ISAS technology optimization modeling, although it is sometimes shortened to simply "ISAS technology optimization."

1. Short-term Cost Comparison

The study investigates the potential that technology optimization modeling offers for reducing ISAS short-term costs. Cyclic injection and extraction are compared with continuous operation. The cyclic operating strategy uses a 30-days-on, 30-days-off remediation scheme. The study assesses the effect on operating costs. Robinson and Rosenberg in [49] found that the TCE mass removed decreased by only 25% when the system was operated for one-half the time. The study uses a reduction in VOC removal of 25%. Under the technology optimization assumptions, ISAS removes 12,000 pounds. This is compared to the 139-day ISAS field removal of 16,000 pounds.

a. Dollars per Pound Criterion

Short-term ISAS dollars per pound under the technology optimization assumption are \$36.53/pound (\$438,360/12,000 pounds). Earlier, short-term ISAS dollars per pound were \$29.93/pound (\$478,906/16,000 pounds). Carbon recharge costs are included in this criterion, because its basis is VOC pounds removed.

Short-term costs for ISAS technology optimization modeling are displayed in Table 2-III-C-1, Short-term Costs for *In Situ* Air Stripping Technology Optimization. This table reports both the 139-day short-term ISAS costs (seen earlier in Analysis Scenarios B and C) and the 139-day ISAS technology optimization modeling costs.

Table 2-III-C-1. Short-term Costs for *In Situ* Air Stripping Technology Optimization

Duration (days)	139	139
Pounds VOCs removed	16,000	12,000
VOC Extraction (lb/day)	115	86
CAPITAL COST		
Site Cost	$5,000	$5,000
Equipment Costs		
Well Installation	$170,085	$170,085
Other Equipment	$63,440	$63,440
Design and engineering	$5,000	$5,000
Mobile equipment (pickup)	$15,000	$15,000
Total Equipment Costs	$253,525	$253,525
Labor Cost		
Mobilize/demobilize	$37,600	$37,600
Total Capital Cost	$296,125	$296,125
OPERATION AND MAINTENANCE		
Labor Cost		
Monitoring/maintenance	$25,020	$12,510
Carbon Recharge	$101,688	$76,266
Consumable Costs		
(Excluding Carbon Recharge)	$56,073	$28,037
(With Carbon Recharge)	$157,761	$104,303
Total Operation and Maintenance		
(Excluding Carbon Recharge)	$81,093	$40,547
(With Carbon Recharge)	$182,781	$116,813
TOTAL SITE COST		
(Excluding Carbon Recharge)	$377,218	$336,672
(With Carbon Recharge)	$478,906	$412,938

b. Dollars per Standard Flow Rate Criterion

Short-term cost for ISAS technology optimization modeling as measured by a standard engineering flow rate is \$718.15/scfm (\$412,938/575 scfm). Short-term 139-day cost for ISAS was reported earlier (in Analysis Scenarios B and C) as \$832.88/scfm (\$478,906/575 scfm).

c. Summary for Short-term ISAS Technology Optimization Modeling Results

Table 2-III-C-2 provides a summary for short-term ISAS technology optimization modeling. The ratio of ISAS technology optimization/ISAS 139-day field data is also shown.

Table 2-III-C-2. Short-term ISAS Technology Optimization Summary Results

	ISAS Technology Optimization	ISAS 139-day Field Data	Ratio
Dollars	\$336,672	\$377,218	89.25%
Dollars (with carbon recharge)	\$412,938	\$478,906	86.22%
Pounds Removed	12,000	16,000	75.00%
Days	139	139	--
Dollars/pound	\$34.41	\$29.93	114.97%
Dollars/scfm	\$718.15	\$832.88	86.22%

Excluding carbon recharge costs, for the ISAS technology optimization cost of $336,672, once again $296,125 (or 87.96%) is for capital, but now only $40,547 (or 12.04%) is for operation and maintenance. Excluding carbon recharge costs, the ISAS technology optimization O&M costs are 50% of the actual ISAS 139-day field test, because the system is running one-half the time. However, carbon recharge costs, even with a reduction of 25% in the VOC removal rate (from 16,000 to 12,000 pounds), are still large. Comparing ISAS 139-day short-term field data to the ISAS 139-day technology optimization modeling results, carbon recharge costs decline from $101,688 to $76,266. In contrast, ISAS 139-day short-term costs (which were reported in Analysis Scenarios B and C) excluding carbon recharge costs, are $377,218, with $296,125 (or 78.50%) for capital and $81,093 (or 21.50%) for operation and maintenance.

When carbon recharge costs are included, short-term ISAS technology optimization costs are $412,938, because carbon recharge adds $76,266 to consumable costs. Because the VOC removal rate is 75% of the 139-day field test, the carbon recharge costs will be 75% as well. Then capital is 71.71%, whereas operation and maintenance is 28.29%. Earlier, when carbon recharge costs were included for the 139-day ISAS short-term data, consumable costs increased by $101,688. ISAS 139-day short-term costs were $478,906. Capital was 61.83%, whereas operation and maintenance was 38.17%.

2. Long-term Cost Comparison

To evaluate long-term technology optimization, ISAS technology optimization is compared with ISAS modeling. ISAS technology optimization uses a cyclic 30-days-on, 30-days-off operating strategy. A reduction in VOC removal of 25% is used.

a. Dollars per Pound Criterion

A net present value of 7% is used for the base case, but the study also reports discount rates of 4% and 10%. Long-term ISAS dollars per pound are \$17.48/pound (\$1,926,438/110,230 pounds). Long-term costs for ISAS are displayed in Table 2-III-C-3, *In Situ* Air Stripping Technology Optimization Modeling Long-term Costs (5 years).

b. Dollars per Unit of Environment Remediated Criterion

An estimate of \$36.61/cubic meter remediated is reported for the long-term ISAS technology optimization. This was calculated from \$1,268,337/34,648 cubic meters. An estimate of 34,648 cubic meters remediated was made from (82,673 long-term pounds removed/220,000 initial pounds) x 92,200 initial cubic meters = 34,648 cubic meters. It should be compared to the ISAS 5-year long-term estimate of \$37.30/cubic meter remediated, which was reported in the long-term Analysis Scenarios D and E.

Table 2-III-C-3. *In Situ* Air Stripping Technology Optimization Modeling Life-cycle Costs (5 years)

Years	1	2	3	4	5
CAPITAL COST					
Site Cost	$5,000				
Equipment Costs					
Well Installation	$170,085				
Other Equipment	$63,440				
Design and engineering	$5,000				
Mobile equipment (pickup)	$15,000				
Total Equipment Costs	$253,525				
Labor Cost					
Mobilize/demobilize	$37,600				
Total Capital Cost	$296,125				
OPERATION AND MAINTENANCE					
Escalation Rate	1.00	1.04	1.04	1.04	1.04
Labor Cost					
Monitoring/maintenance	$32,850	$34,164	$35,531	$36,952	$38,430
VOC Extraction* (lb/day)	68	50	43	36	29
Carbon Recharge	$158,323	$116,046	$100,388	$82,989	$66,287
Consumable Costs					
(Excluding Carbon Recharge)	$73,621	$76,566	$79,628	$82,814	$86,126
(With Carbon Recharge)	$231,944	$192,612	$180,016	$165,803	$152,413
Total Operation and Maintenance					
(Excluding Carbon Recharge)	$106,471	$110,730	$115,159	$119,765	$124,556
(With Carbon Recharge)	$264,794	$226,776	$215,547	$202,755	$190,843

Table 2-III-C-3. *In Situ* Air Stripping Technology Optimization Modeling Life-cycle Costs (5 years) (concluded)

	Years	1	2	3	4	5
ANNUAL TOTAL COST						
(Excluding Carbon Recharge)		$402,596	$110,730	$115,159	$119,765	$124,556
(With Carbon Recharge)		$560,919	$226,776	$215,547	$202,755	$190,843
Excluding Carbon Recharge						
Discounted (4%)		$402,596	$106,388	$106,305	$106,222	$106,140
Discounted (7%)		$402,596	$103,244	$100,114	$97,080	$94,137
Discounted (10%)		$402,596	$100,193	$94,284	$88,724	$83,492
With Carbon Recharge						
Discounted (4%)		$560,919	$217,884	$198,975	$179,827	$162,626
Discounted (7%)		$560,919	$211,444	$187,387	$164,350	$144,236
Discounted (10%)		$560,919	$205,195	$176,475	$150,204	$127,926
Excluding Carbon Recharge						
Discount Rate		NPV	$/lb VOC*		$/scfm**	scfm**/$
	0.04	$827,651	$5.63		$1,439	0.000695
	0.07	$797,172	$5.42		$1,386	0.000721
	0.10	$769,290	$5.23		$1,338	0.000747
With Carbon Recharge						
Discount Rate		NPV	$/lb VOC*		$/scfm**	scfm**/$
	0.04	$1,320,231	$8.98		$2,296	0.000436
	0.07	$1,268,337	$8.63		$2,206	0.000453
	0.10	$1,220,720	$8.31		$2,123	0.000471

*Total VOC extraction is assumed to be 82,673 pounds.

**Standard cubic feet per minute is assumed to be 575 scfm.

c. Dollars per Standard Flow Rate Criterion

Long-term cost for ISAS technology optimization as measured by a standard engineering flow rate is $2,205.80/scfm ($1,268,337/575 scfm). This compares to the ISAS long-term cost under Analysis Scenarios D and E, which was $3,691.66/scfm.

d. Summary for Long-term ISAS Technology Optimization Modeling Results

Results for a discount rate of 7% are discussed but the study also reports low and high discount rates of 4% and 10%. Excluding carbon recharge costs, the ISAS long-term technology optimization modeling net present value is $797,172. When carbon recharge costs are included, the ISAS long-term modeling net present value is $1,268,337. This compares to the ISAS long-term cost of $2,122,705 found in the long-term Analysis Scenarios D and E.

Table 2-III-C-4 provides a summary for long-term ISAS technology optimization modeling. The ratio of ISAS technology optimization/ISAS modeling is also shown.

ISAS technology optimization modeling has been comparaed to ISAS base case modeling. VOC pounds removed has been reduced by 25%. It is interesting to observe the ratio column in the summary table above. All percentages are less than 100%. ISAS technology optimization significantly reduces total costs, both with and without carbon recharge costs. Dollars per VOC pound removed has been reduced to one half. Dollars per cubic meter remediated is lower. Finally, dollars per scfm is lower by one third. It appears that the modeling of technology optimization shows promising results that could guide the design and construction of future ISAS systems.

Table 2-III-C-4. Long-term ISAS Modeling Summary Results

	ISAS Technology Optimization	ISAS Modeling	Ratio
Dollars	$797,172	$1,298,218	61.41%
Dollars (with carbon recharge)	$1,268,337	$1,926,438	65.84%
Pounds Removed	82,673	110,230	75.00%
Years	5	5	--
Dollars/pound	$8.63	$17.48	49.37%
Dollars/cubic meter	$36.61	$37.30	98.15%
Dollars/scfm	$2,205.80	$3,350.33	65.85%

IV. Conclusion

The task addressed in this report has been to assess the cost-effectiveness of ISAS as an environmental remediation technology. This new technology was demonstrated at the SRID test site in 1990 to be a technically effective new remediation technology for the removal of chlorinated solvents from contaminated soil and groundwater. ISAS was compared to a baseline groundwater remediation technology combining PT with soil vapor extraction to assess the cost-effectiveness of ISAS. A technique was developed and presented for conducting comprehensive cost-effectiveness analyses of competing technologies for remediation of groundwater contamination at various types of sites. The approach allows several different technologies to be compared. The decision maker may wish to compare several methods that have not yet been applied in the field. Alternatively one can compare a particular field trial, such as the SRID implementation of ISAS, to a projection of how ISAS would perform under ideal implementation.

To compare the cost-effectiveness of ISAS to the baseline combined PT-SVE system, three metrics were used: dollars per pound of contaminant removed, dollars per unit of environment remediated, and dollars per standard engineering flow rate. For the short-term cost comparison of 21 days and 139 days, only the first and third criteria are reported. An estimate of the second criterion, dollars per unit of environment remediated, is more problematic. It is reported only for the 5-year long-term time frame.

Using the dollars/pound of contaminant removed criterion, the study draws several conclusions. In the very short field trial comparison (21 days), ISAS is not as cost-effective as the baseline (PT-SVE) technology. For the 139-day trial, ISAS is likely to be as cost-effective as the PT-SVE baseline. That is, compared to the Low Extrapolation scenario for the PT-SVE technology, ISAS is superior. With the High Extrapolation scenario, ISAS fares less well against the PT-SVE baseline. In the long-term (5 year) comparison, ISAS appears to be superior to PT-SVE using the dollars/pound criterion.

It is worth noting that the ISAS field trial analyzed in this report was a demonstration project. As such, it encountered numerous technical problems in the implementation, and these problems may have raised the capital costs significantly. One would expect that additional experience with ISAS would lead to lower construction and installation costs in future applications. ISAS would appear to be a viable technology for future environmental restoration projects.

Groundwater modeling expands the role of cost-effectiveness analysis by allowing analysts to consider other performance scenarios. Because field-scale tests are costly and restricted by physical circumstances, the results of groundwater modeling have much to offer. The role of modeling was assessed by comparing the long-term analysis scenarios to a modeling performance scenario. Furthermore, groundwater modeling contributed to an estimate of the original contaminant mass in place. Groundwater modeling may be extended as well to such areas as technology optimization. Also considered was the trade-off that technology optimization offers: does the penalty of decreased average mass removal justify the decrease in operating costs? For the short term, ISAS technology optimization was compared to the actual ISAS 139-day field-scale test, whereas for the long term, it was more appropriate to compare ISAS technology optimization long-term costs with ISAS base case modeling long-term costs.

Because this approach integrates economic decision making and groundwater modeling, it has the advantage of being able to provide complete evaluation of the competing technologies under a wide variety of implementation and performance scenarios. Field data alone is not sufficient because field implementations are unique and provide no data on alternate implementations.

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Appendix A. Basic Building Blocks: Decision Problems and the Value of Information

1. Introduction

The value of new information in a decision making task may be derived by evaluating the losses avoided from making incorrect decisions with the original information[1] or by evaluating the payoffs obtained from making better decisions with the new information.[2] Conceptually both methods yield identical results for the value of new information in a decision process. The choice is based largely on analytical tractability for the application at hand. In both cases, the analysis proceeds through formal decision theory and the basic building blocks are the event tree and the decision tree. The construction and application of the decision tree will first be discussed and then the calculation of the value of new information that may become available during the decision process will be demonstrated.

The uncertainty inherent in decision making is represented in the form of an event tree (Figure A-1) where each of the draws are denoted by chance nodes (circles) and the probabilities of each of the outcomes is shown on the branches of the tree.[3]

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[1] See the approach taken by Gates and Kisiel [1974] in evaluating the value of additional sample data.

[2] See Lave [1963] for an example applied to the forecasts generated by the National Weather Service and Bernknopf, Brookshire, McKee, and Soller [1991] for an application to the geologic information produced by U.S. Geologic Survey.

[3] The probabilities represented in the event tree are derived using Bayes' Rule. This rule is used to update prior evaluation of the probability of an event when new information becomes available. Some notation will be useful: let E = event, E' = not the event, and D = data. We are concerned with updating the prior estimate of the probability of the event with the observed data and we have the following relationships defined:

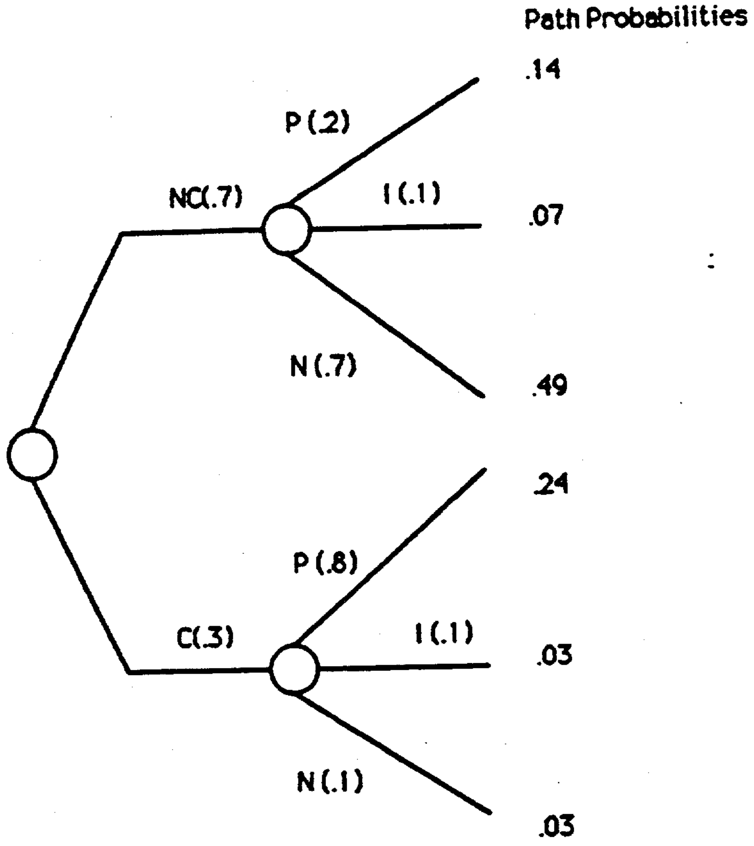
$$P(D,E) = P(E|D)*P(D) = P(D|E)*P(E)$$
$$P(E|D) = [P(D|E)*P(E)]/P(D)$$
$$P(E|D) = [P(D|E)*P(E)]/[P(D|E)*P(E) + P(D|E')*P(E')]$$

Although an event tree is based on Bayes's Theorem, it offers several advantages over the arithmetic application of Bayes's Rule such as a more graphic presentation and greater ease in addressing complex settings which cannot be characterized as only producing outcomes event, E, and not the event, E'. When the event tree is employed solutions are found by a process known as "tree flipping" [Raiffa, 1968] to obtain the path probabilities which summarize the probability of the series of chance events occurring that are shown on each of the branches of the tree. These are joint probabilities since they apply to the accumulated series of events described on the path.

In the example shown in Figure A-1, there is a testing process to determine which of two possible events has occurred. Beginning with Figure A-1, it is the case that that the groundwater may be uncontaminated (denoted as NC) or contaminated (denoted as C) and the condition that actually exists is referred to as the resulting state of nature. The true state is unknown. The groundwater may be tested, but the test does not always reveal the true state of nature. The test may indicate positive for contamination (denoted as P), negative for no contamination (N) or it may be inconclusive (I). The probabilities of the states of nature and the test outcomes are denoted in parentheses in Figure A-1. The path, or joint, probabilities are denoted at the ends of the paths in the decision tree.

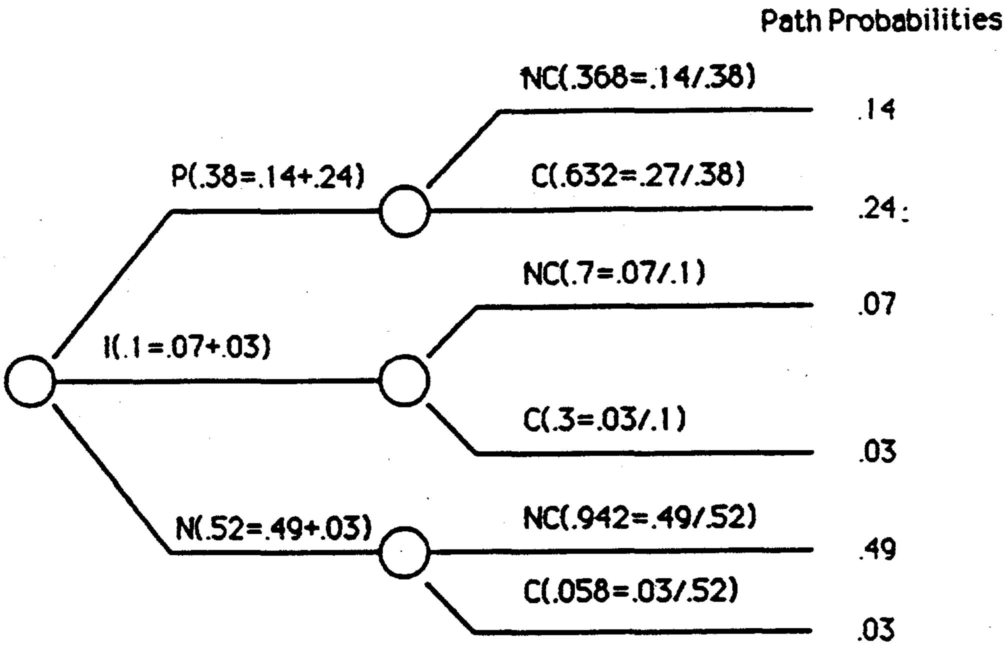
It is useful to view the decision tree from the perspective of the sequence undertaken by the decision maker. That is, the test is undertaken and then the state of nature is evaluated by the decision maker. This structure of the problem is shown in Figure A-2 which also denotes the calculation of the decision maker path probabilities. These calculations may be briefly described by means of an illustration from the tree. A P observation from the test may be obtained under two conditions as seen in Figure A-2. Thus the probability of observing a Positive is the sum of these probabilities (0.38). Since all possible events have been depicted in the tree the path probabilities must sum to 1.0.

Figure A-1 - Event Tree: Nature's Perspective



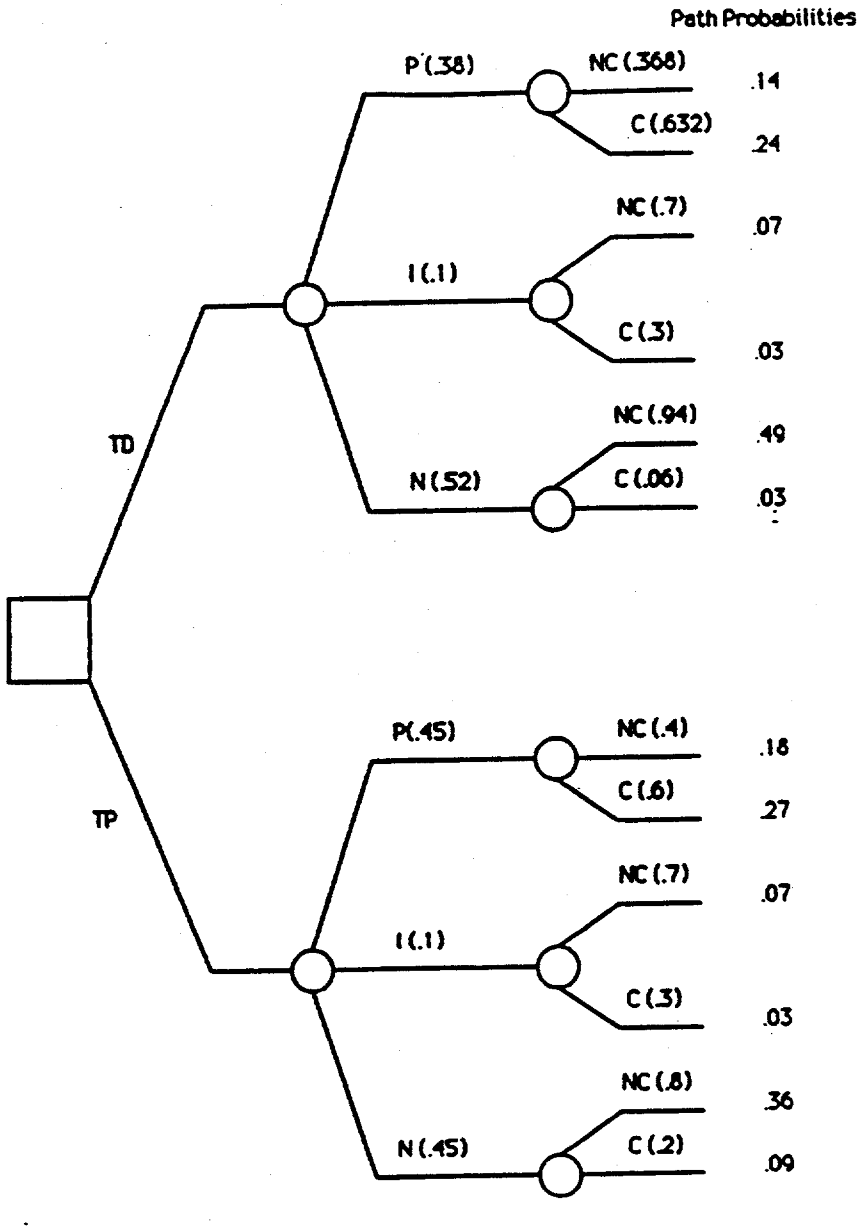
Notation:
Circles represent uncertain outcomes due to states of nature.
Probabilities are shown in parentheses.
C - groundwater is contaminated (a state of nature).
NC - groundwater is not contaminated (a state of nature).
P - groundwater sample passes the test; is contaminated.
F - groundwater sample fails the test; is not contaminated.
I - test result is inconclusive.

Figure A-2 - Event Tree: Decision Maker's Perspective



Notation:
Circles represent uncertain outcomes due to states of nature.
Probabilities are shown in parentheses.
C - groundwater is contaminated (a state of nature).
NC - groundwater is not contaminated (a state of nature).
P - groundwater sample passes the test; is contaminated.
F - groundwater sample fails the test; is not contaminated.
I - test result is inconclusive.

Figure A-3 - Decision Tree



Notation:
Circles represent uncertain outcomes due to states of nature/ Probabilities are shown in parentheses/ Boxes represent decisions/ TD - to test the groundwater by drilling test wells/ TP - to test the groundwater by using a penetrometer.
Remaining notation is the same as Figure A-1.

A decision tree augments the event tree to include the choice nodes of the decision maker. As in Figure A-3, decision nodes are shown as squares and chance nodes as circles. In the current example, the decision is whether to test by drilling on the site (TD) or by means of a penetrometer (TP). From the data reported in the decision tree it is clear that these tests have different probabilities of predicting that the site is contaminated or not, or the test is inconclusive. The decision maker's choice of testing method is determined by balancing the relative costs of false predictions and of the testing procedures. For example, TP may be less expensive than TD yet it may yield more false positive predictions; that is, predicting contamination (P) when the true state of nature is non-contamination (NC).[4] The decision maker would choose TD over TP if the costs of these false predictions was greater than the savings from the use of the less expensive method.

The decision tree is a flow diagram that shows the logical and temporal structure of the decision problem and it contains four elements [see Stokey and Zeckhauser, 1978]:[5]

1. Decision nodes - indicate the possible courses of action open to the decision maker;
2. Chance nodes - show the intervening uncertain events and all possible outcomes (the event tree);

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[4] The probability of a false prediction for TP is 0.18 + 0.09 = 0.27. For TD this probability is 0.14 + 0.03 = 0.17.

[5] Stokey and Zeckhauser (p. 203) note, "... we have found with almost every type of model, the foremost advantage is the discipline imposed by the model. It requires us to structure the problem, break it into manageable pieces, and get all its elements down on paper - ..."

3. Probabilities - for each possible outcome of a chance event;
4. Payoffs - summarize the consequences of each possible combination of choice and chance.

The tree also indicates areas where additional information will or will not be useful (cf. Stokey and Zeckhauser, p 213) and the value of this information.

2. The Value of Information

It is only worthwhile collecting information if the cost of obtaining the information is less than the potential benefits, for example, losses avoided with the information available. To make informed decisions regarding the production of new information, the decision maker will wish to calculate the value of new information. The value of perfect information will be addressed first since it will serve as a benchmark from which to gauge the value of imperfect or incomplete information.

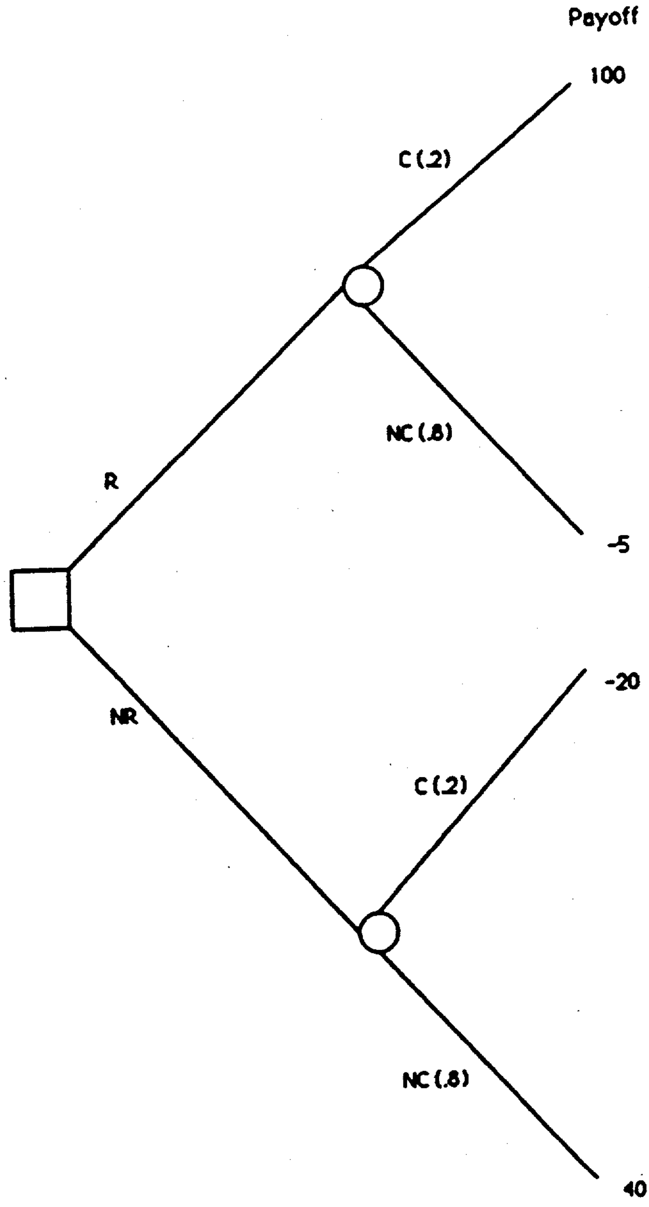
Consider the data in Table A-1 where NC and C refer to the respective states of nature (non-contaminated and contaminated) and NR and R refer to the respective actions that could be taken (no remediation and remediation). The data in the table refer to the payoffs given the action and the state of nature. With the existing level of information (commonly referred to as priors), as represented by the probabilities of the respective states of nature, the decision maker selects to not remediate (NR) since its expected payoff is greatest. The question here is what would the individual be willing to pay for perfect information concerning the true probabilities of the states of nature. If she learns, before making a decisions, that the true state of nature is that the groundwater is not contaminated (NC) then her decision will still be to select NR and there will be no benefit to be derived from having this information. If she learns that the true state of nature is that the groundwater is contaminated (C) she will change her action from NR to R. In this case the payoff to having the information is $120 (the payoff from choosing R when that state is known to be C ($100) plus the loss avoided from not making the inappropriate choice, NR (-$20).

It is informative to proceed with the demonstration of the value of information in the context of a decision tree representation of the problem reported in Table A-1. The above argument is demonstrated in Figure A-4 with the parameters that appear in Table A-1. In Figure A-4 the original probabilities, and the resulting expected values, are shown. With prefect information these priors are revised and since the information is perfect the decision maker now knows that the probability of state NC <u>or</u> C is 1.0. This revised probability is termed the posterior since it has been updated through the use of the new information. In this example, the value of perfect information is 0.2*120 + 0.8*0 = 24. That is, a risk neutral decision maker would be willing to pay $24 to learn the true state of nature <u>prior</u> to making a decision. In this example the primary component of the expected value of perfect information is the loss avoided from choosing action NR when the true state is C.

Table A-1. Value of Information and the States of Nature

	Action Taken		
State of Nature	NR	R	Probability of the state of nature
NC	40	-5	0.8
C	-20	100	0.2
Expected Value of payoff	28	16	

Figure A-4 - The Value of Information



Notation:
Circles represent uncertain outcomes due to states of nature.
Probabilities are shown in parentheses.
Boxes represent decisions.
R - to remediate the groundwater contamination.
NR - to not remediate the groundwater contamination.
Payoffs in $.

As noted above, perfect information allows updating of the priors to certainty. Thus, instead of estimating P(NC) = 0.8, with perfect information the decision maker knows that P(NC) is either 0.0 or 1.0. The value of perfect information is a useful benchmark but in most cases perfect information cannot be obtained and one must make do with sample information which will be used to imperfectly update priors concerning the states of nature. Suppose it is possible to take one observation and this results in a change of the probabilities of the states of nature such that P(NC) is 0.64 and P(C) is 0.36. Alternatively, the data may lead one to revise these probabilities to P(NC) = 0.96 and P(C) = 0.04. These possibilities are summarized in Table A-2 below. Prior to conducting the test, the expected value of the test information is .5(4.80) + .5(28.80) = 16.80. That is, the new information would allow losses of 28.80 to be avoided (if it was learned that the probability of NC is 0.64) or 4.80 (if it was learned that the probability of NC is 0.96). Since both outcomes of the testing process are equally likely, ex ante, the expected value of the test information is 16.80. From Table A-1 the expected value of perfect information is 24.00. Thus, the expected value of sample information (EVSI) is the residual reduction in uncertainty and is 24.00 - 16.80 = 7.20. An expected value maximizer would be willing to pay $7.20 for the sample information. This analysis may also be shown via a decision tree in the same manner as was done with Figure A-4, above.

Table A-2. Expected Value of Sample Information

	Act		$P(S_i \mid D_1)$	Opportunity Loss		
State	NR	R		NR	R	
NC	40.00	-5.00	0.64	0.00	45.00	
C	-20.00	100.00	0.36	120.00	0.00	
EV	18.40	32.80		43.20	28.80	EOL

	Act		$P(S_i \mid D_1)$	Opportunity Loss		
State	NR	R		NR	R	
NC	40.00	-5.00	0.96	0.00	45.00	
C	-20.00	100.00	0.04	120.00	0.00	
EV	37.60	0.80		4.80	43.20	EOL

Note: $P(S_i \mid D_1)$ denotes the probability of state i (C or NC) given the new data.

3. The Case of Biased or Imperfect Information

The sample information in the above discussion did not reveal with certainty which outcome would occur but the information itself was unbiased. A different situation arises when the data are biased or imperfect. At the simplest level, the imperfect information can be analyzed as another chance node in an event tree and this is depicted in Figure A-5 below where the information takes the form of observing that the test has shown the presence or absence of groundwater contamination. The first chance node of Figure A-5 describes the observation obtained from the test. The second node denotes the predicted true state of nature.

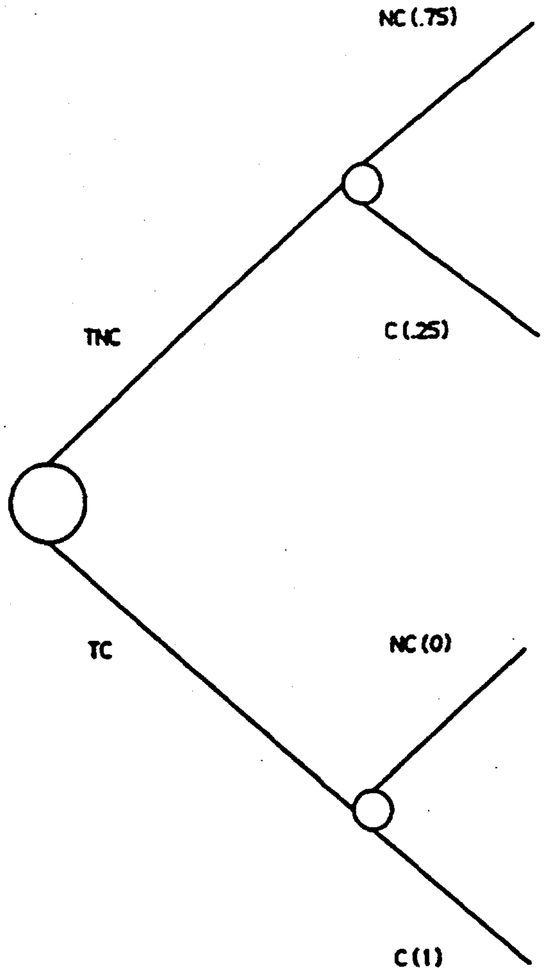
Thus, the results of the test are indicated on the figure as C or NC. Let it be assumed that a test showing the presence of contamination (test says C) is unambiguous; the groundwater is contaminated. But, if it is observed that the test indicated no contamination (test says NC), it is known only that this is true, in practice, with probability 0.75. Thus, the information is biased and the bias depends on whether the observation is that the test was passed or failed.

If the decision maker is risk neutral, then biased or imperfect information is employed in the same manner as the sample information above. The probabilities are weighted by the known errors in the data. The case of risk averse decision makers is taken up now.

4. Non-expected Value Maximizer - Risk Aversion

To this point the discussion has been based on the assumption that the decision makers are risk neutral - that is, the individual is attempting to maximize expected value of the monetary payoff. In most cases, decision makers are risk averse; they have diminishing marginal utility in payoffs. The source of the risk aversion may be due to the fact that many public policy decisions may generate catastrophic and/or irreversible consequences if they fail. Groundwater contamination is a timely example of such a decision setting. Risk averse decision makers can be easily incorporated into the analysis presented above by replacing the payoffs at the ends of the branches with the utility equivalents.

Figure A-5 - Imperfect Information



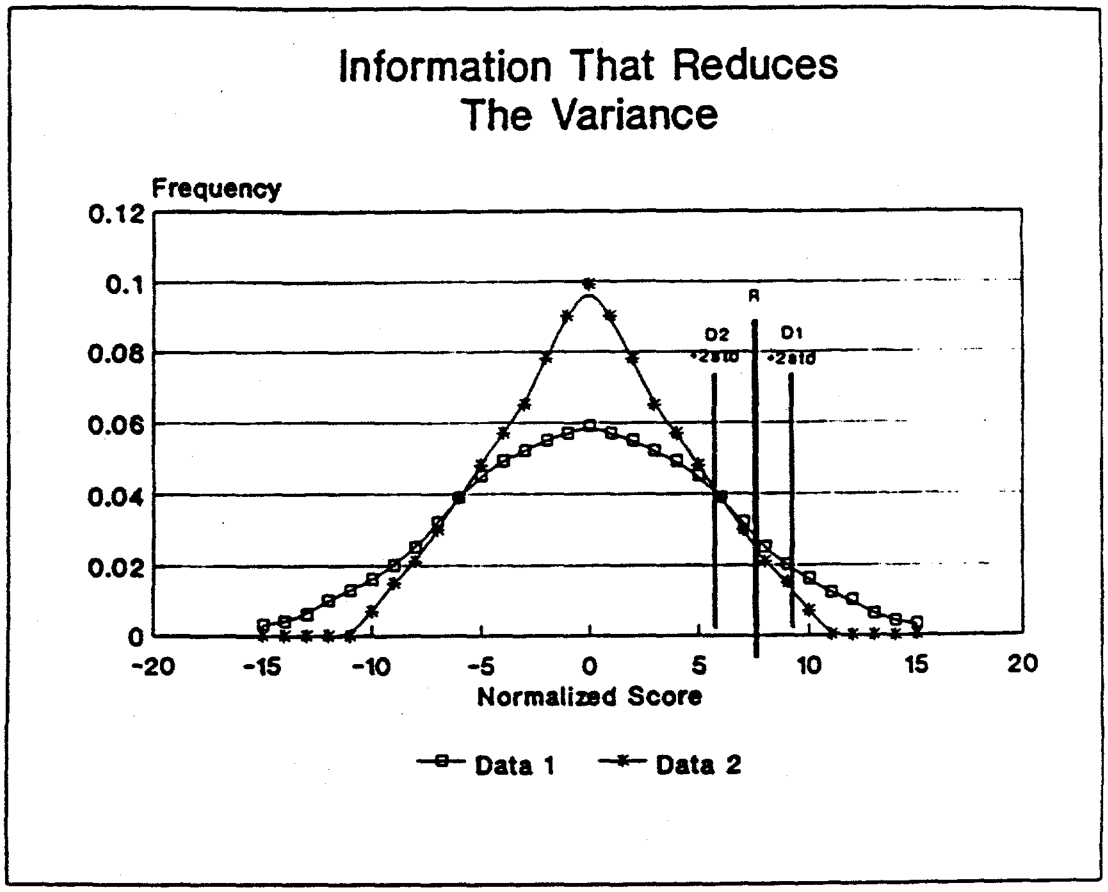
Notation:
Circles represent uncertain outcomes due to states of nature.
Probabilities are shown in parentheses.
TNC - test shows no contamination of the groundwater.
TC - test shows contamination of groundwater.
NC - groundwater is predicted to be not contaminated.
C - groundwater is predicted to be contaminated.

The value of information may be extended when risk averse decision makers are introduced. For an expected value maximizer there is no return to reducing the variance, σ^2, in the estimate of either probabilities or payoffs. The reason is simple, the expected value maximizer is concerned only with the mean of the distribution. A risk averse individual is concerned with the variance since utility is not linear in payoffs and the "downside risk" is weighted more heavily. Thus, a mean-preserving spread (higher variance) is associated with increasing risk. Rothschild and Stiglitz [1971, 1972] demonstrate the implications of this definition of increasing risk for a variety of economic problems. In this situation new information that reduces the variance of the estimates will be valued even if the expected value is unaffected.

That is, a risk averse individual will have a utility function of the form $U = U(y,\sigma^2)$ where $\partial U/\partial\sigma^2 < 0$. Decreasing variance will increase utility. Thus, if two outcomes have the same expected payoff but one has a higher variance the risk averse individual will select the outcome with the lower variance.

The institutional setting may also introduce a role for the variance of the distribution in the policy decisions. In Figure A-6, two probability distributions are depicetd reporting a statistic of concern to the decision maker (eg, the probability of groundwater contamination). The distribution available prior to systematic testing is labelled Data1 while Data2 describes the situation after the testing is done. R denotes the required level of the statistic to meet the conditions for exposure to risk. If the decision maker must select according to the rule that $R < \mu+2\sigma$, where R is the required standard, then the particular site or technique giving rise to this statistic would be accepted under distribution Data1 but not under Data2. Thus, the new information will lead to more socially efficient remediation being undertaken.

Figure A-6



Notation:
Data1 (also D1) - probability distribution based on the initial data.
Data2 (also D2) - probability distribution based on the new data.
R - denotes the regulated standard on which to accept or reject the use of the groundwater for human consumption.
std - standard deviation.

5. Summary of Decision Theory

In any decision process, timing is critical and this is no less the case when the value of information is being considered. Wagner et al note (p. 239), "The value of information ... depends on when in the decision-making process the information is obtained and to what extent this information can affect further decisions". The payoff to the groundwater modeling activity arises from several sources. Field trials are costly and consequently field data will always be incomplete. Computational costs of search over the entire grid of feasible solutions is also very costly and thus the entire set of feasible decisions will not be investigated. The use of groundwater modeling enables us to omit some possible applications of remediation technologies from further consideration.

6. Towards an Analytical/Computational Method

The remediation decision problem has been represented in extensive form in a decision tree approach. This is very useful for illustration of the principles of decision theory[6] and for representing the intricacies of particular decision problems including capturing the temporal aspects and the fact that decisions may be revisited during the life of the project. However, in most applications the tree approach is intractable due to the inherent complexity of the decision problem. The actual groundwater remediation problem faced at a contaminated site is a good example of the complex settings often encountered by decision makers. Here there are many decision stages with potentially many decisions available at each stage. To completely specify the problem in tree form would probably obscure as much as it would illuminate. Therefore it will be convenient to adopt the alternate representation to be developed in this section. This representation is referred to as the normal form in which the decision tree is represented by means of a matrix relating the transitions between states that occur as the outcome of a decision on the part of the decision maker.

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[6] Such as the calculation of path probabilities and payoffs via the "averaging out" and "folding back" techniques (see [46]).

This section formalizes the previous discussion for the purpose of laying the groundwork for the programming of the decision problems. This development of the formal model will show how and where groundwater modeling provides the necessary information for the decision process.

The decisions to be made in the groundwater remediation problem arise at intervals and involve making decisions concerning the steps to be undertaken in the site characterization phase, the construction of the remediation technology, and the operation of the facility. At each stage of the decision process there is a (unique) set of decisions that may be made. At each stage there is a level of groundwater contamination that is known with some degree of certainty depending on the amount of information currently available.

The task facing the analyst is to optimize the set of decisions (choose a policy to follow) for each of the available technologies. The objective for the optimization is to minimize costs subject to achieving the mandated level of groundwater contamination (and soil contamination, if required) within the time frame that is specified. The analyst's task is to conduct a comprehensive assessment of each technology including accounting for all potential risks such as cost overruns, contaminant spread, and failure to completely remediate. The decision maker selects from among the competing technologies according to an objective function, which might include weights to be attached to the noted risks.

The advantage of the modeling approach to be described is that the complexity of the model is not materially increased as the dimensionality of the problem (number of states and policy options) increases. The further advantage of applying groundwater and decision modeling to the remediation problem is that the decision maker is able to make comparisons of technologies in a consistent manner since they can be analyzed as if a specified level of potential implementation was actually applied. Field studies alone cannot do this since the data collected are specific to a particular implementation of the remediation technology.

Adopting the normal form to analyze the groundwater decision problem facilitates sensitivity analysis since it is comparatively easy to incorporate additional information through modifying the transition probability matrix[7] on the basis of the groundwater and engineering models. It is also fairly straightforward to accommodate an increase in the number of decisions that could be faced if the problem were to become more complex.

Finally, the policy-iteration algorithm at the heart of the decision problem is solved by linear (or non-linear) programming ensures that the decision maker/analyst will not find the problem intractable. Well-developed computer algorithms exist for solution of large dimension linear and non-linear programming problems.

2. The Model Framework

There is considerable uncertainty in groundwater remediation and the decision maker is, in effect, engaged in a game against nature. A useful concept for solving such games is a sequence of moves in which decision maker chooses and then nature "chooses". It is the combination of these moves that yields a new state of nature. At a stage a state of nature is observed and either the decision maker or nature may "move" by choosing an action. The state of nature determines the payoff to the decision maker. For the groundwater remediation problem, the relevant state of nature is the current level of contamination and the history of the decision process.

The game proceeds over time and the time intervals are denoted as "periods." "Stages" are those periods in which a decision must be taken. Recall that the principle steps and sub-steps to represent the real-time aspect of the process. There are three stages to the remediation problem: the site characterization phase, the design and construction of the physical facility, and the operation of the remediation facility. At each stage one of several "states" of nature may arise. These states are the result of interaction between the decision maker's previous actions and the outcomes of the chance events. This interaction between decisions and moves by nature has been referred to as a sequence. This interaction is defined as a transition probability.

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[7] This matrix describes the transition from the current state (defined as a particular level of contamination) to a new state (a different level of contamination). This concept will be developed in detail below.

Payoffs, in the form of the level of groundwater remediation, are the result of the decisions taken and the state that eventuates arise at the end of a stage period. The decision maker chooses a strategy that defines the decision that will be taken for each possible state of nature that may arise. Such a fully specified strategy may be referred to as a policy. In order to present the decision problem sufficiently precisely that a programming model for cost-effectiveness analysis may be developed, the following notation is adopted.

t - denotes a period or unit of real time (say, hours or days), $t = 1,....,T$. Decisions are made at the beginning of <u>some</u> of these periods.

n - denotes those time periods at which decisions are made and these will be referred to as stages. The number of stages is finite, so $n = 1,...,N$ and $N < T$ (see [10]). The stages may be represented as decision nodes with the decision tree approach.

i - denotes a state of nature that is determined by the past moves of nature and the decisions undertaken by the decision maker. The state will describe the current level of groundwater contamination. It is indexed as $i = 0,1,...,M$.

(n,i) - denotes a state of nature i exists at stage n. One of several states will be manifest within a single stage, n. The decision problem is a Markov process and the history is defined by the ordered pair (n,i). This pair will fully define the state facing the decision maker in the subsequent analysis. The number of states and stages is finite as is the set of ordered pairs (n,i).

D(n,i) - denotes the (non-empty) set of decisions that may be made at state (n,i).

k - denotes a particular decision taken at (n,i) and k is an element of D(n,i). It is indexed as $k = 1,2,...K$.

Δ - denotes the set of all policy rules.

δ - denotes a policy, essentially a decision rule which defines a k to be taken anytime the agent is at a particular (n,i). Decision $k = \delta(n,i)$, δ is an element of Δ, and $\delta(n,i)$ is an element of D(n,i).

$P_{ij}^{k}(n)$ - denotes the transition probability which is the probability that the state observed next stage is (n+1,j) if the state observed now is (n,i) and decision k is selected.

$R_i^k(n)$ - denotes the payoff to the decision maker from taking decision k at (n,i).

$v^\delta(n,i)$ - denotes the consequence function of a policy, δ. This value is the expectation of the summed consequences over stages n through N if the decision maker occupies state (n,i) and chooses policy δ.

The transition from state to state is governed by the <u>transition probabilities</u>. These probabilities are determined by the technical relationships such as the groundwater flow and solute transport relations. The transition probabilities are also affected by the state, which means that the history is a factor. Another way to think of the game against nature that the decision maker faces is to note that nature's moves are stochastic and the decision maker is able to obtain information regarding the probability distribution over the set of possible moves available to nature. This information is derived from sophisticated groundwater models, field investigations, and expert judgement. Each time nature is able to move the decision maker treats the situation as a lottery over the possible outcomes. The probabilities of the individual outcomes, as well as the exact nature of the outcomes, are provided as the output of the groundwater models.

The decision problem may be represented as a Markov decision model. This model presumes the decision maker knows the transition probabilities or is able to form a prior to be updated in Bayesian fashion. The role of groundwater modeling is to provide these probabilities to the decision maker. If the ending stage is N, then for all states (n,i) with $n < N$ and for all decisions k in D(n,i) it is the case that $\sum_j P_{ij}^k(n) = 1$. That is, all possible transitions can be defined and probabilities be assigned in accordance with the laws of probability.

Decisions produce consequences comprised of the payoffs, $R_i^k(n)$, which are also a function of the state of nature at the stage the decision is taken and $R_i^k(N)$ is the consequence of the decision made at the final stage. Consequences may take the form of rewards or costs depending on the problem being addressed. For all possible states, (n,i), a decision policy, δ, denotes a particular decision that will be chosen each time a specified state arises; thus δ(n,i) is fully specified by δ. Only admissible policies are considered so δ(n,i) is an element of D(n,i). Δ represents the policy space which is the set of all policies that may be undertaken over the life of the decision problem. The consequence function of a policy, δ, is defined as $v^{\delta}(n,i)$. This value is the expectation of the summed consequences over stages n through N if the decision maker is in state (n,i) and chooses policy δ. $v^{\delta}(n,i)$ is the sum of the consequences earned in period n and the expectation of the consequences for periods n+1 through N. A simple recursive relation defines v^{δ}:

$$v^{\delta}(N,i) = R_i^k(N), \text{ with } k=\delta(N,i); \text{ when } n=N$$

and, $v^{\delta}(n,i) = R_i^k(n) + \sum_j P_{ij}^k(n) v^{\delta}(n+1,j), \text{ with } k=\delta(n,i), \ n < N.$

By construction, the groundwater remediation problems will have finite state space and finite decision space and so this value can be computed.

The decision maker is presumed to choose a policy to maximize the payoff to the groundwater remediation program - in this case minimize the (risk adjusted) costs of remediating contamination. Regardless of the facilities currently in place (ISAS or pump and treat with soil vapor extraction) the optimal policy yields the least cost of proceeding with that facility. The policy choice rule can be expressed as:

$$f(n,i) = \min_{\delta}[v^{\delta}(n,i)];$$

where $f(n,i)$ is the decision maker's objective at the current state (n,i). That is, the decision maker chooses the policy δ which minimizes the total costs summed from the current stage to the end of the remediation program.

When the decision problem spans a long time frame it is appropriate to apply a discount factor to the payoffs and this introduces a necessary modification to the problem formulation presented above. Let $\beta=1/(1+r)$ be the discount factor where r is the rate of interest. To make comparisons across different technologies and implementations requires a common criteria for evaluation. This requires that all payoff streams be converted to present values via the use of the discount factor. Now, the optimal vector of decisions is given by the solution to the set of equations:

$$f_i = \min_{k \in D(n,i)} [R_i^k + \textstyle\sum_{j=1}^{N} \beta P_{ij}^k f_j] \qquad (1)$$

The solution to the following linear program yields the optimal f in the equation above (see [11]):

Program A: Minimize $\{\sum_{i=1}^{N} f_i\}$ subject to the constraints

$$f_i - \textstyle\sum_{j=1}^{N} \beta P_{ij}^k f_j \geq R_i^k, \text{ all i,k}$$

f_i unrestricted, all i.

This is an extremely useful result since the alternative solution technique is to determine the optimal policy by enumerating all of the policies in Δ to find the vector f that maximizes (minimizes) the objective function. For most applications the number of potential policies is extremely large and a crude case by case evaluation would be a nearly impossible task. Linear programming algorithms are not hampered by increases in the dimensionality of the problem and so the number of stages to the decision tree and the number of decisions that may be made at each stage can be expanded to include complexities that can be addressed using the data from the groundwater modeling.

Denardo in [11] shows that the linear programming approach implements the policy- iteration algorithm that solves the Markov decision problem faced in groundwater remediation.[8] As usual, either the primal or the dual problem can be solved (the choice is made for purposes of interpretation of the results). It is also the case that the decisions, k, that are taken will determine the transition from state (n,i) to (n+1,j) via the transition probabilities, p_{ij}^{k}. The analytical pieces are now in place to conduct an integrated decision theory based cost-effectiveness analysis of groundwater remediation. The next section discusses the implementation of the above framework in groundwater remediation applications.

3. Application of the Decision Model to Groundwater Remediation

The contamination levels that are permitted are specified by regulatory fiat. The objective of the decision maker is to meet these standards at minimum cost and the result is that the decision maker will choose a policy that yields the lowest cost while meeting the standard. The returns (costs) of decisions, denoted by R_i^k in the above objective function, are provided by the groundwater and engineering models.

A key element of the linear programming representation of the decision problem is the matrix of transition probabilities, p_{ij}^{k}. To generate this matrix requires knowledge of the technical conditions governing transitions between states (contamination levels) including the effects of decisions undertaken at stage n that will affect the resulting state at stage n+1. Groundwater models are capable of providing estimates of the transition probabilities via simulations of alternative remediation programs. The transition probabilities provide the constraints necessary for the linear programming model presented above. Some adjustments are required to implement these probabilities since what the real concern is with ensuring a level of input (or effort) that will result in meeting the standard mandated by the regulations. At a

---

[8] The policy iteration algorithm involves a three step iterative process. Step 1, pick any policy δ in Δ. Step 2, evaluate this policy by computing the payoff, v^{δ}, for alternative policies. Step 3, alter the policy to the policy yielding the highest payoff in step 2. Repeat until no improvement can be found. The solution to the policy iteration process may be found by the use of Howard's Algorithm (see Howard [1960]).

minimum there is a three-dimensional representation involving the decisions, k, and the transition probabilities between states n and n+j; j runs from 1 to N-n.

Once these estimates have been produced, the analyst applies a linear programming algorithm to Program A immediately above and the optimal implementation of the remediation technology is found. At this point the decision maker is in a position to choose between competing technologies for remediation of groundwater contamination.

The groundwater information allows the decision maker to calculate the reward that would result from different groundwater remediation techniques, as well as different implementations of these techniques. The information produced by the groundwater modeling and applied to decision making has value from two sources. First, losses from making incorrect decisions over the known range of available decisions are avoided. Second, the range of available decisions is expanded since the groundwater models permit us to investigate different facility and operating configurations that were not available with field data only.

4. Methodology

The methodology used to evaluate the cost effectiveness of a new environmental technology is composed of both a performance evaluation and an economic evaluation. The new environmental technology will be compared to some baseline or more conventional technology currently in use. The question be addressed is: "For the remediation of soils and groundwater contaminated by chlorinated solvents, how much money can be saved by using ISAS with horizontal wells instead of conventional technologies?"

In particular, the importance of the performance evaluation and groundwater modeling must be emphasized in this methodology. The performance issues are critical in establishing some sort of balanced comparison from which the economic cost savings of the two (or more) alternative technologies will be calculated.

A fundamental issue in evaluating a new environmental technology is to address the question, "What does one compare the new technology to?" It is important to note that in many cases a new environmental technology does not specifically replace some current technology or practice on a one-to-one basis. Thus, a range of baseline technologies may be investigated, if necessary, to reasonably consider the actual role of the new environmental remediation technology. The challenge is to analyze information on diverse techniques in a fashion that will lead to a fair and reasonable assessment of the cost effectiveness of the new technology. Given this goal, the major components of the methodology are:

> Identify major performance characteristics of the new environmental technology.
>
> Identify appropriate conventional technologies to serve as the baseline for performance comparisons with the new technology.
>
> Compare performance between the new technology and the conventional alternatives.
>
> Use analysis scenarios to provide a realistic context for the performance comparison.
>
> Perform an economic comparison of the new technology and the conventional alternatives. Use analysis scenarios for detailed cost-savings analysis on a life-cycle basis.
>
> Assess uncertainty in cost, performance, and regulatory permitting.

The reader will need to pay careful attention to caveats discussed in this report, such as applicable geologic setting, to determine how this technology can best be utilized at a particular integrated demonstration site or environmental restoration site.

Appendix B. Linear Programming Implementation

1. Overview

A Markov decision process and its solution is described and documented. Examples from the possible states and decisions involved in groundwater remediation are used for the actual demonstration. The goal is defining a groundwater remediation policy. A policy, then, is a rule that prescribes a decision in a specific state. This decision problem may be solved using well-known linear programming techniques. GAUSS code for several aspects of the decision problem are included and described.

The topics discussed in this appendix cover the transition probability matrix; converting a transition probability matrix; the calculation of steady-state probabilities; the formulation of the linear programming problem and its solution; a linear programming example; the example written in GAUSS code; and the policy-improvement and dynamic programming algorithms. Both Howard's [1960] policy iteration and policy-improvement routines, as well as dynamic programming formulations, result in the same solution as the linear programming problem.

2. Transition Probabilities

The behavior of a system operating over time suggests a stochastic process with a Markovian structure. At time t the system is in exactly one of a finite number of exclusive states or categories. A state transition matrix is used to describe this stochastic process.

The transition probability matrix, $P_{ij}(k)$, has the following interpretation: given alternative k, the element p_{ij} is the probability of going from state i to state j. The usual convention is to number the states 0,1,...,M, so that there are M+1 states. Decisions or alternatives are numbered k = 1,2,...,K, and there are K decisions. An example of a transition matrix is

for alternative 1,

and for alternative 2,

$$P_{k=1} = \begin{bmatrix} 0.6 & 0.4 \\ 0.4 & 0.6 \end{bmatrix}$$

$$P_{k=2} = \begin{bmatrix} 0.7 & 0.3 \\ 0.5 & 0.5 \end{bmatrix}.$$

Of course, each element of P must be $0 \leq p_{ij} \leq 1$. The rows of the transition matrix sum to unity. P is referred to as a stochastic matrix. The transition probabilities are assumed known to the decision maker. The sequence of states and decisions is a Markov decision process.

Given this sequence of states and decisions, the problem then is to choose the optimal decision. It is substantially easier to solve this problem by rearranging the transition probability matrix by state. The discussion employs the following standardized notation: $P_{ij}(k)$ is organized by state i, i = 0,1,...,M, and for each state is an associated decision k = 1, 2,..., K. This notation and ordering was used by Howard [1960] in his work on Markov processes. In effect, transition <u>row</u> probabilities $P_{ij}(k)$ are created. To do so, another matrix is created, which for each state, 0,1,...,M, the <u>rows</u> of the matrix are associated with each alternative or decision k. Consider the groundwater remediation problem:

state 0 = meet standard

alternative 1 pulse
alternative 2 continuous

state 1 = fail standard

alternative 1 pulse
alternative 2 continuous.

Assume the transition probabilities for each state and each possible action are given by

for state = 0,

for state = 1,

$$P_0 = \begin{bmatrix} 0.6 & 0.4 \\ 0.7 & 0.3 \end{bmatrix}$$

$$P_{i=1} = \begin{bmatrix} 0.4 & 0.6 \\ 0.5 & 0.5 \end{bmatrix}$$

Here there are two states, groundwater concentration levels that satisfy the standard and concentration levels that fail the standard. (The states may be interpreted as groundwater quality that is acceptable or unacceptable.) The rows of a transition matrix should each sum to unity. Transpose the transition row probabilities, $P_i(k)$, into column vectors and use the SUMC command in GAUSS, which sums the elements of a column vector. Sample GAUSS code is shown below.

```
psum = sumc(p1);
if psum = 1;
        continue;
elseif psum not=1;
        print "psum not=1"; psum;
endif;
```

Along with the transition probability matrix there is a reward or cost structure. Reward matrixes are shown below. These "rewards" are the costs associated with the states and alternatives. The rows of the reward matrixes are associated with each alternative.

for state = 0,

$$R_0 = \begin{bmatrix} 5 & 1 \\ 7 & 3 \end{bmatrix}$$

for state = 1,

$$R_1 = \begin{bmatrix} 5 & 2 \\ 6 & 4 \end{bmatrix}$$

Markov processes with rewards were introduced by Howard [1960]. The "optimal" decision is found by maximizing the reward. For the two-state, two-alternative Markov decision problem there are two transition matrices and two reward matrices. This leads to four decision variables in the linear programming formulation of the problem.

3. Converting Transition Matrixes

Occasionally the state transition matrix, $P_{ij}(k)$ is given by alternative k, and the element p_{ij} is the probability of going from state i to state j, given the alternative. This is the notation used by many authors, including Nemhauser [1966] and Denardo [1982]. While the transition probability matrix is easily understood for a given decision, it must be rearranged for the linear programming formulation and solution. From a problem in Nemhauser [1966], given the selection of alternative k, the transition probability matrix for this problem is

for alternative 1,

$$P_{k=1} = \begin{bmatrix} 0.5 & 0.5 \\ 0.75 & 0.25 \end{bmatrix}$$

for alternative 2,

$$P_{k=2} = \begin{bmatrix} 1 & 0 \\ 0.5 & 0.5 \end{bmatrix}$$

It is necessary, however, to order the transition probabilities by state. In doing so, another matrix is created, in which the rows are associated with an alternative or decision k. This is shown as

$$P_{i=0} = \begin{bmatrix} 0.5 & 0.5 \\ 1 & 0 \end{bmatrix}$$

The GAUSS sample code below converts transition matrixes given by alternative

$$P_{i=1} = \begin{bmatrix} 0.75 & 0.25 \\ 0.5 & 0.5 \end{bmatrix}$$

to transition matrixes arranged by state. The transition and reward matrixes from Nemhauser [1966] are converted for this example. There are, for a given alterative k,

```
np1 = { 0.5 0.5, 0.75 0.25 };
nr1 = { 0 6, -3 8 };
np2 = { 1 0, 0.5 0.5 };
nr2 = { 2 4, 1 -1 };

p1 = np1[1,.]¦np2[1,.];
p2 = np1[2,.]¦np2[2,.];
r1 = nr1[1,.]¦nr2[1,.];
r2 = nr1[2,.]¦nr2[2,.];
p = p1¦p2;
ptrans = p';

psum = sumc(p1);
if psum = 1;
    continue;
if psum NOT= 1;
    print "psum NOT= 1";
    psum;
endif;
```

4. Steady-State Probabilities

Each state i has an associated steady-state probability. The linear programming formulation of the Markov decision process is based on this steady-state probability. Of course, the transition probability matrix need not be 2x2.

Consider the 4x4 transition probability matrix

$$P = \begin{bmatrix} 0 & 0.875 & 0.625 & 0.0625 \\ 0 & 0.75 & 0.125 & 0.125 \\ 0 & 0 & 0.5 & 0.5 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

For an MxM transition matrix, a generalized GAUSS program to calculate the steady-state probabilities follows below.

```
ptrans = p';
a = ptrans - eye(rows(p));
a = a¦ones(1,cols(p));
a = a[2:rows(a),.];
b = zeros(rows(p),1);
b = b¦1;
b = b[2:rows(b)];
print "p-matrix, a-matrix, and b-vector"; p; a; b;
x = inv(a)*b; x;
xsum = sumc(x);
if xsum = 1;
   continue;
if xsum not= 1;
   print "xsum not= 1";
   xsum;
endif;
```

This sample code may be used for any size transition matrix. In the GAUSS program, the solution vector x contains the steady-state probabilities. A good error-check for the steady-state probabilities is that they each sum to unity.

5. Linear Programming Solution

A Markov decision process may be formulated as a linear programming problem. The linear programming solution was proposed by Manne [1960]. The goal is to find the policy that minimizes the expected (long-run) average cost.

A new decision variable is created,

$$y_{ik} = P\{\text{state is } i\} \text{ and the decision is } k,$$

which may be interpretated as the steady-state unconditional probability that the system is in state i and decision k is made. There is also a decision matrix,

$$D_{ik} = P\{\text{ decision is } k, \text{ given that state is } i\},$$

for $i = 0,1,\dots,M$ and $k = 1,2,\dots,K$.

Results in more usable form can be obtained by computing the steady-state distribution and the decision probabilities,

$$y_{ik} = \pi_i D_{ik}$$

$$\pi_i = \sum_{k=1}^{K} y_{ik} \; for \; i = 0,1,\dots,M.$$

$$D_{ik} = \frac{y_{ik}}{\pi_i} \; for \; i = 0,1,\dots,M \; , \; k = 1,2,\dots K.$$

Associated with each decision variable is a decision cost C_{ik}, which is the cost incurred during the next step if the system is in state i and decision k is made.

a. Statement of Linear Programming Problem

The following constraints on y_{ik} are required,

$$\sum_{i=0}^{M} \pi_i = 1 \; such \; that \; \sum_{i=0}^{M} \sum_{k=1}^{K} y_{ik} = 1,$$

$$\sum_{k=1}^{K} y_{jk} = \sum_{i=0}^{M} \sum_{k=1}^{K} y_{ik} p_{ij}(k) \; for \; j = 0,1,\dots,M,$$

$$y_{ik} > 0, i = 0,1,\dots,M \; , \; k = 1,2,\dots,K.$$

The first constraint can be interpreted as the steady-state probabilities must sum to 1. Following Hillier and Liebermann [1986], the long-run expected average cost per unit time is given by

$$E(C) = \sum_{i=0}^{M}\sum_{k=1}^{K}\pi_i C_{ik} D_{ik} = \sum_{i=0}^{M}\sum_{k=1}^{K} C_{ik} y_{ik}.$$

So the problem is to choose the y_{ik} that

$$\min \sum_{i=0}^{M}\sum_{k=1}^{K} C_{ik} y_{ik},$$

subject to the constraints

$$\sum_{i=0}^{M}\sum_{k=1}^{K} y_{ik} = 1,$$

$$\sum_{k=1}^{K} y_{jk} - \sum_{i=0}^{M}\sum_{k=1}^{K} y_{ik} P_{ij}(k), \text{ for } j = 0,1,\ldots,M,$$

Once the decision variables y_{ik} are found, the decision matrix, D_{ik}, may be obtained from

$$D_{ik} = \frac{y_{ik}}{\pi_i},$$

which relates the optimal alternative for each state.

b. Example

The linear programming solution is to "stack" the row transition probabilities as

$$P = \begin{bmatrix} P_1 \\ P_2 \end{bmatrix} = \begin{bmatrix} 0.6 & 0.4 \\ 0.7 & 0.3 \\ 0.4 & 0.6 \\ 0.5 & 0.5 \end{bmatrix},$$

and define $P_i(k)$ as row i of the transition matrix when decision k is selected.

From this, then P' is

$$P' = \begin{bmatrix} 0.6 & 0.7 & 0.4 & 0.5 \\ 0.4 & 0.3 & 0.6 & 0.5 \end{bmatrix},$$

If P_1 and P_2 are each 2x2 matrixes, then P is 4x2. The P' matrix, that is, the transpose of the stacked transition matrixes, is the key to the linear programming solution. The importance of organizing the transition matrixes by states, with the row vectors, $P_i(k)$, associated with the alternatives, cannot be stressed enough. The example illustrates the constraints on the decision variables, y_{ik},

$$y_{01}+y_{02}+y_{11}+y_{12}=1$$

$$y_{01}+y_{02}-(p_{00}y_{01}+p_{00}y_{02}+p_{10}y_{11}+p_{10}y_{12})=0$$

$$y_{11}+y_{12}-(p_{01}y_{01}+p_{01}y_{02}+p_{11}y_{11}+p_{11}y_{12})=0$$

It is important to reduce the number of state variables to a manageable size. However, even if the number of state variables is large, no greater numerical difficulty is encountered (except for keeping track of variables and data storage), because of the linear programming solution. While this may be true, it will very likely be the case that some interpretation is lost.

As another example, consider the running procedure/pressure gradient problem, in which there are three states (no failure, one failure, and two failures) and two alternatives (continuous and pulse),

1. Choose alternative 1 (continuous)
2. Choose alternative 2 (pulse)

with the following states,

0. No failure
1. One failure

2. Two failures.

There are six decision variables,

y_{01} = P{ no failure, continuous }
y_{02} = P{ no failure, pulse }
y_{11} = P{ one failure, continuous }
y_{12} = P{ one failure, pulse }
y_{21} = P{ two failures, continuous }
y_{22} = P{ two failures, pulse }.

It is important to first inspect for impractical or nonsensical alternatives. This problem was constructed so that all alternatives are meaningful, although occasionally Markov decision problems have impractical alternatives that need to be deleted. An example of an impractical alternative would be a Markov decision process with two alternatives (do nothing, repair equipment) and three states (no failure, possible failure, failure). The y_{ik} combination (no failure, repair equipment) may be rejected as impractical.

c. Example in GAUSS Code

Sample GAUSS code for the linear programming solution is shown below for an example. The objective is cost minimization.

```
library simplex;
lpset;
p = { 0.6 0.4, 0.7 0.3, 0.4 0.6, 0.5 0.5 };
r = { 5 1, 7 3, 5 2, 6 4 };

c = ones(1,4);
c[1,1] = p[1,.]*r[1,.]';
c[1,2] = p[2,.]*r[2,.]';
c[1,3] = p[3,.]*r[3,.]';
c[1,4] = p[4,.]*r[4,.]';

b = { 1, 0, 0 };
ptrans = p';
a = ones(3,4);

i = 2;
do while i <= rows(a);
```

```
        j = 1;
        do while j <= cols(ptrans)/2;
                a[i,j] = 1 - ptrans[1,j];
                print "column index j"; j;
                print "a[i,j] element"; a[i,j];
                j = j + 1;
        endo;
        j = 3;
        do while j <= cols(ptrans);
                a[i,j] = -ptrans[1,j];
                print "column index j"; j;
                print "a[i,j] element"; a[i,j];
                j = j + 1;
        endo;
        i = i + 1;
endo;

a[.,.] = -a[.,.];

/* non-negativity restrictions are set with l and u */
l = 0;
u = 1e200;
_output = 1;
_lprule[1] = 3;
_lpmin = 1;
_lpcnst = 3;

_title = "LP1.INP";
output file = LP1.OUT reset;
{ x, optval, retcode } = lpprt(simplex(a,b,c,l,u));
```

Several comments are in order. The non-negativity restriction on the decision variables y_{ik} is provided by the lower limit, l = 0, and the upper limit, u = 1e200. An important global variable that needs to be declared is _lpmin. If _lpmin = 0, the maximization problem will be solved. If _lpmin = 1, the minimization problem will be solved. The default is 0. Equality and inequality restrictions are set by the global variable _lpcnst. If _lpcnst = 1, the constraint is a less than or equal to inequality. If _lpcnst = 2, the constraint is a greater than or equal to inequality. Use _lpcnst = 3 for the strict equality. The default is 1 (since the maximization problem is the default.) Of course _lpcnst may be either a scalar or a Mx1 vector that describes each equation type. For the appropriate problem, one might use _lpcnst = { 2, 1, 3, 2 }. In the GAUSS input code above, global variables _lpmin = 1 (minimization) and _lpcnst = 2 were set. These Markov decision problems required a "tie-breaking" rule to be used. In practice, the global variable _lprule[1] was set for 3, the "largest increase rule." The GAUSS manual (see p. 392) provides good documentation on the "entering tie-breaking rule," which is _lprule[1], and the "leaving tie-breaking rule," which is _lprule[2]. In addition, the global variable _lpname was declared. The default is "X." Occasionally, the maximum number of iterations for the simplex algorithm must be declared. This is controlled by the global variable _lpmaxit. Its default is 300.

d. Interpretation of the Solution

The solution to the example cost minimization problem is $y_{01} = 0.5$ and $y_{11} = 0.5$, that is, the first alternative is the best choice if the state = 0 and, again, the first alternative is the best choice if the state = 1.

Calculation of the steady-state probabilities proceeds by arranging a transition matrix that contains the rows associated with the first alternative for each state. This is shown below with

$$P_{k=1} = \begin{bmatrix} 0.6 & 0.4 \\ 0.4 & 0.6 \end{bmatrix}$$

The steady-state probabilities are, not surprisingly, 0.5 and 0.5. The next step is to construct the decision matrix, D_{ik}. It is clear that

$$D_{ik} = \begin{bmatrix} 1 & 0 \\ 1 & 0 \end{bmatrix}$$

The decision matrix, D_{ik}, is a matrix representation of the choice of alternatives.

6. Policy-Improvement and Dynamic Programming Algorithms

Howard [1960] demonstrated that the policy-improvement algorithm was capable of solving the Markov decision problem. Manne [1960] later showed the similarity between linear programming and dynamic programming formulations of the problem. Both of these iterative techniques are addressed because of their historical importance in Markov sequential decision problems. Brief examples of GAUSS input code are also provided for these two techniques.

The policy-improvement algorithm is capable of finding the optimal policy rapidly. Howard described two steps for this procedure. The first, value determination, evaluates an arbitrarily chosen policy. The second, policy improvement, finds an alternative policy that minimizes the objective. This continues until two successive policies are equal. This is the optimal policy.

Return to the decision cost, which was given by

C_{ik} = (expected) cost in state i and decision k is made.

Let $q_{ij}(k)$ be the (expected) cost when in state i and decision k is made, and the system evolves to state j next time period. Then

$$C_{ik} = \sum_{j=0}^{M} q_{ij}(k) P_{ij}(k).$$

When policy R is chosen, there are values $g(R)$, $v_0(R)$, $v_1(R),\ldots,v_M(R)$ that satisfy

$$g(R)+v_i(R) = C_{ik}+\sum_{j=0}^{M} p_{ij}(k)v_j(R) \text{ for } i=0,1,\ldots,M.$$

for $i = 0,1,\ldots,M$. From this, the recursive relationship,

$$v_i^n(R) = C_{ij}+\sum_{j=0}^{M} p_{ij}(k)v_j^{n-1}(R)$$

for $i = 0,1,\ldots,M$ may be obtained. Howard [1960] provides a proof of the properties of the policy-iteration method. The sample GAUSS input file PI.INP for a reward maximization 2x2 problem is provided. The policy-improvement routine proceeds as follows: 1) assume no a priori knowledge, so set $v_1 = v_2 = 0$; 2) enter policy-improvement routine, which will select an initial policy that maximizes the expected immediate reward in each state. (In the examples, this policy is alternative $k = 1$ for both states 1 and 2; 3) next, use value-determination to evaluate the initial policy; 4) set $v_2 = 0$; 5) again enter policy-improvement routine. The value-determination equations are

$$g+v_1 = q_1+p_{11}v_1+p_{12}v_2$$

or, in matrix notation

$$g + v_2 = q_2 + p_{21}v_1 + p_{22}v_2$$

$$g+v = q+P_1v$$

This system of equations is solved by first setting $v_2 = 0$ and solving for two unknowns, g and v_1. Sample GAUSS code follows below.

```
        /* use p1 and p2 transition matrixes and r1 and r2 reward matrixes from above
*/
        q1 = p1.*r1; transq1 = q1'; m1 = sumc(transq1);
        q2 = p2.*r2; transq2 = q2'; m2 = sumc(transq2);
        /* Howard refers to m1 and m2 vectors as the expected immediate reward */
        d = maxindc(m1~m2);

        i = 1;
        do while i <= 3;
                newp = p1[d[1],.]|p2[d[2],.];
                newr = r1[d[1],.]|r2[d[2],.];
                newq = newp.*newr;
                tnewq = newq';
                qvector = sumc(tnewq);
                v1_coeff = (1 - newp[1,1])|(-newp[2,1]);
                A_mat = ones(2,1)~v1_coeff;
```

```
        x = inv(A_mat)*qvector;
        g = x[1];
        v1 = x[2];
        v2 = 0;
        /* now enter policy-improvement routine */
        v_vector = x[2]|v2;
        n1 = m1 + p1*v_vector; tn1 = n1';
        b1 = sumc(tn1);
        n2 = m2 + p2*v_vector; tn2 = n2';
        b2 = sumc(tn2);
        d = maxindc(b1~b2);
        i = i + 1;
endo;
```

Howard's value-iteration solution can also be formulated as a dynamic programming problem.

Appendix A and B - References

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