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COST/BENEFIT ANALYSIS COMPARING EX SITU TREATMENT
TECHNOLOGIES FOR REMOVING CARBON TETRACHLORIDE
FROM HANFORD GROUND WATER

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MASTER

SUMMARY

Pacific Northwest Laboratory conducted a cost/benefit and performance analysis to compare ex situ technologies that can be used to destroy the carbon tetrachloride (CCl_4) in the ground water of Hanford's 200 West Area. The objective of this work was to provide a direct quantitative and qualitative comparison of competing technologies. The technologies examined included a biological system, the Thermochemical Environmental Energy System II (TEES II), and a UV/oxidation system. The factors examined included key system operation parameters, impact on inorganic contaminants in the ground water, and secondary waste production. The cost effectiveness of these destruction technologies was also compared to the cost for an air stripping/granular activated carbon (AS/GAC) system. While the AS/GAC system appeared to be more cost effective at many levels than the CCl_4 destruction technologies, the secondary waste produced by this system may lead to significant cost and/or regulatory problems. The factors with the greatest influence on cost for each destruction technology are as follows: nutrient requirements for both of the biological systems, electricity requirements and the type of unit operations for the TEES II process, and electricity requirements for UV/oxidation.

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1.0 INTRODUCTION

Past waste disposal practices at the U. S. Department of Energy's (DOE) Hanford sit has resulted in carbon tetrachloride and nitrate contamination in the ground water. As part of the DOE's VOC Arid Site Integrated Demonstration, technologies are currently being investigated to determine cost-effective means to destroy these ground water contaminants. A cost/benefit and performance analysis was conducted by the Pacific Northwest Laboratory (PNL)^(a) to compare ex situ technologies that can be used to destroy the carbon tetrachloride (CCl_4) in the ground water of Hanford's 200 West Area. Specifically, a biological system, the Thermochemical Environmental Energy System II (TEES II), and a UV/Oxidation system for CCl_4 destruction were analyzed to determine their cost effectiveness and assessed qualitatively in terms of key system operation parameters, impact on inorganic contaminants in the ground water, and secondary waste production. The cost effectiveness of these destruction technologies was also compared to the cost for an air stripping/granular activated carbon (AS/GAC) system, a standard organics removal technology. Assumptions regarding the ground-water constituents, design parameters, and costing parameters for the comparison were developed to provide a fair comparison of the technologies. System cost sensitivities to CCl_4 concentration and influent flow rate were also assessed.

As used in this study, the TEES process is considered in two configurations: as a noncatalytic, ground-water treatment system (TEES II) and as a catalytic, biological sludge treatment system. Each configuration has specific applications to the technologies described in the subsequent sections.

Sections 2 and 3 of this report describe the methods and assumptions, respectively, used in this study. Section 4 describes the cost/benefit and

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performance analysis of the technologies, and section 5 presents the economic analysis. Section 6 describes the conclusions of the analysis.

2.0 METHODS

The framework for this study was developed to provide a direct quantitative and qualitative comparison of competing technologies. All technologies were required to meet the same effluent standards so that cost could be used as the quantitative measure of system effectiveness. Although the same effluent conditions with respect to the chosen constituents were assumed, the performance of each system was different in terms of qualitative measures. For each technology, the production of secondary waste, system flexibility, and the effect on inorganic constituents in the ground water are all important parameters that must be assessed as part of a comprehensive comparison of technology effectiveness. Thus, qualitative system performance parameters were included in this analysis. The following specific items describe the approach of this study:

- Some assumptions were developed from data and assumptions in the documents "Hanford Past Practice Site Cleanup and Restoration Conceptual Study: Integrated Study and Summary" (WHC 1991) (hereafter, "Hanford Study") and "Purge Water Characterization and Treatment Summary" (Garrett and Olson 1990) (hereafter, "Water Summary"). Other assumptions were made to enable direct comparison between options.
- Ground-water constituents were chosen as a mix of estimates from the Hanford Study and actual ground-water analyses from the Water Summary. Three simulated plumes were defined to examine treatment effectiveness for three different concentrations of CCl_4 (Table 2.1). Each plume was analyzed for 100-gpm and 25-gpm flow rates.
- The effluent CCl_4 and chloroform concentrations from each system were 2 ppb or less and 23 ppb or less, respectively. Changes in other ground-water constituent concentrations from the treatment of CCl_4 will be discussed.
- Conceptual designs were based on data from technical literature, laboratory and pilot-scale experiment data, and manufacturer's data.
- The quantity and composition of secondary waste from each system was reported. Costs for secondary waste treatment and/or disposal were not quantified.

TABLE 2.1. Ground-Water Constituents and Concentrations

<u>Constituent</u>	<u>200W-1 Plume</u>	<u>Constituent Concentrations</u> <u>(all Concentrations are in parts per billion except where noted)</u>	
		<u>High</u> <u>Concentration</u> <u>CCl₄ Plume</u>	<u>Low</u> <u>Concentration</u> <u>CCl₄ Plume</u>
Carbon tetra- chloride	1,000	4,200	70
Chloroform	200	200	200
Nitrate	500,000	500,000	500,000
Bicarbonate	150,000	150,000	150,000
Cyanide	50	50	50
Iron	40	40	40
Calcium	70,000	70,000	70,000
Magnesium	22,000	22,000	22,000
Technetium	10,000 pCi/L	10,000 pCi/L	10,000 pCi/L
Uranium	5,000 pCi/L	5,000 pCi/L	5,000 pCi/L
Iodine	10 pCi/L	10 pCi/L	10 pCi/L

- System advantages and disadvantages with respect to influent and operational parameters will be discussed.
- Cost analyses were based on guidelines in the publication Conducting Technical and Economic Evaluations in the Process and Utility Industries (AACE 1990). An economic life of 30 years was used to estimate levelized, life-cycle costs.

3.0 MACRO ASSUMPTIONS

Assumptions were necessary to define the framework for technology comparisons. The following assumptions were applied in completing the conceptual designs and costing of each technology:

- Systems will be operated continuously (24 hours, 7 days) for the duration of remediation. An annual operating fraction of 0.9 was assumed to accommodate planned and unplanned outages.
- System costs will not include ground-water extraction or transport equipment.
- System costs will not include costs associated with the radioactive constituents in the ground water.
- System costs will not include removal of suspended solids from the ground water.
- The ground-water constituents and concentrations listed in Table 2.1 will be used for the study.
- Only the CCl_4 concentration will change for the concentration sensitivity analysis. All other ground-water constituents remain the same and at the same concentration.
- Variation of ground-water flow and constituent concentrations from the design conditions will not be considered in system designs or costing.

4.0 TECHNOLOGY DESCRIPTIONS

The process descriptions, relevant assumptions, and conceptual designs for each technology are presented in this section. For each technology, a process flow chart was developed and major components were designed for the given influent and effluent conditions and macro assumptions. The qualitative performance of each system was assessed with respect to key operational and input parameters. Secondary waste generation was also calculated for each given influent condition.

4.1 BIOLOGICAL SYSTEM

Previous studies have described and demonstrated the ability of certain strains or consortia of bacteria to dechlorinate CCl_4 (Criddle et al. 1990, Egli et al. 1988, and Galli and McCarty 1989). The fluidized-bed, biological reactor (FBR) considered for this study uses a bacterial consortia shown to degrade CCl_4 under denitrification conditions (Brouns 1990). The bacteria grow as a slime layer on the suspended particles in the reactor. Acetate and nitrate are fed as nutrients for the bacteria to support the cometabolic degradation of CCl_4 . To maintain a constant biomass concentration, the rate of biomass wasting from the reactor is equal to the increase in biomass due to acetate utilization. This excess biomass is removed from the effluent stream by filtration and treated as a secondary waste.

4.1.1 Design

The biological system uses an FBR to destroy CCl_4 (Figure 4.1). The reactor consists of a tower packed with 30-mesh anthracite coal particles that provide a surface for bacterial colonization. Influent flow of ground water is combined with liquid recycle to provide sufficient flow to fluidize the biomass-coated coal particles. To maintain an optimal biomass concentration, particles are recycled through a centrifugal pump to shear biomass from the particles and through a hydrocyclone to separate the biomass and coal particles. Coal particles are recycled to the reactor. Biomass is combined with the effluent from the FBR, which is then filtered with a vacuum filter to remove biomass and suspended solids. Ancillary equipment include an influent

FIGURE 4.1. Biological System Flow Chart

heater to maintain the FBR temperature at 30°C, a nutrient feed system to provide the acetate (carbon and energy source) and nitrate (electron acceptor) necessary to support the biomass, and an anaerobic sludge digestion system to stabilize biological secondary waste from the vacuum filter. The following assumptions were used in developing the conceptual design for this system: ground-water constituents are not toxic to the bacteria, influent water hardness will not affect fluidization in the reactor, and influent ground water will contain negligible dissolved oxygen. Data from monitoring wells on the Hanford site supports these assumptions.

4.1.2 Key System Operation Considerations

System advantages

- does not require high temperatures, high pressures, or high energy input
- reduces size of down-stream equipment because of nitrate destruction and chromium, uranium, and possibly other metal removal by biosorption in the same process as CCl_4 destruction

System disadvantages

- produces secondary waste streams
- the process effluent will contain some bacteria that pass through the filter
- requires continuous operation or reinoculation procedure to maintain biomass
- sensitive to rapid changes in influent conditions
- requires addition of nutrients for the bacteria

4.1.3 Impact on Inorganic Contaminants

The biological system will remove a portion of the inorganic contaminants during the process of destroying CCl_4 . Nitrate is used as an electron acceptor and nitrogen source for the biomass. The biomass will convert influent nitrate to N_2 gas (0.8-0.9 moles N_2 -N per mole NO_3^- -N) or incorporate the nitrate into biomass. Thus, nitrate will not be present in the process effluent. The biomass may adsorb chromium and uranium species, thereby removing them from the ground water. Sufficient data do not exist to predict the efficiency of this process in this system. Removal of other multivalent cations by biosorption may also be expected.

4.1.4 Secondary Waste Production

The biological system produces several secondary waste streams. As a result of acetate respiration and denitrification, the FBR produces N_2 and CO_2 gas. In addition, biomass is continuously produced in the FBR and must be removed by the vacuum filter as a secondary waste. Treatment of the biomass secondary waste from the vacuum filter by anaerobic digestion produces an off gas mainly composed of CH_4 (65%) and CO_2 (30%), an aqueous waste with a biochemical oxygen demand (BOD) of 3000 mg/L and an alkalinity of 2000 mg/L, and a solids waste stream (12% solids) composed of inorganic solids and stabilized biological solids. The quantities of each secondary waste stream are listed in Table 4.1 for each influent condition analyzed.

TABLE 4.1. Secondary Waste Production

Waste Stream	Waste Stream Quantities for the Given Influent Stream [CCl ₄ Concentration (ppb)/flow rate (gpm)]					
	1000/100	1000/25	4200/100	4200/25	70/100	70/25
<u>Biological System</u>						
FBR off gas (m ³ /d)	170	45	350	90	150	40
Anaerobic digester Off gas (m ³ /d)	18	4	34	9	13	3.5
Aqueous stream (gpd)	60	18	150	35	55	14
Solids stream (gpd) (12% total solids)	84	21	165	44	62	16.5
<u>Biological/TEES</u>						
FBR off gas (m ³ /d)	170	45	350	90	150	40
TEES process off gas (m ³ /d)			84			8.4
<u>Air Strip/GAC</u>						
Off gas (m ³ /d)	34600	5100	34600	5100	34600	5100
Waste carbon (lb/d)	10	3	35	9	3	1
<u>TEES II</u>						
Off gas (m ³ /d)			0.35			0.002
<u>UV/Oxidation</u>						

See text for explanation of secondary waste for this system.

4.2 BIOLOGICAL SYSTEM WITH TEES PROCESS TO DESTROY SECONDARY WASTE

Secondary waste production is a major disadvantage for the biological system. Because the TEES process is capable of destroying biological solids, an alternative design for the biological system included a TEES process to convert waste biological solids to gas.

4.2.1 Design

The design of the biological system remained the same, except the anaerobic digestion process was replaced with the TEES process (Figure 4.2a). The TEES process for this application is shown in Figure 4.2b. Section 4.3 describes the design of the TEES for treatment of the biological sludge.

4.2.2 Key System Operation Considerations

System advantages

- no aqueous or solid secondary waste streams
- does not require high energy input
- reduces size of down-stream equipment because of nitrate destruction

System disadvantages

- the process effluent will contain some bacteria that pass through the filter
- requires continuous operation or reinoculation procedure to maintain biomass
- sensitive to rapid changes in influent conditions
- requires addition of nutrients for the bacteria

4.2.3 Impact on Inorganic Contaminants

The biological system using the TEES process will remove a portion of the inorganic contaminants during the process of destroying CCl_4 . Nitrate is used as an electron acceptor and nitrogen source for the biomass. The biomass will convert influent nitrate to N_2 gas (0.8-0.9 moles N_2 -N per mole NO_3^- -N) or incorporate the nitrate into biomass. Thus, nitrate will not be present in

FIGURE 4.2a. Biological System with TEES Sludge Destruction Flow Chart

FIGURE 4.2b. TEES System Flow Chart for Treatment of Biological Sludge

the process effluent. Species that were sorbed to the biomass will be released during the destruction of the biological waste by the TEES process. These species will not be removed from the ground water because the effluent

from the TEES process will be combined with the effluent from the biological process.

4.2.4 Secondary Waste Production

Several secondary waste streams are produced by the biological system and TEES process. As a result of acetate respiration and denitrification, the FBR produces N_2 and CO_2 gas. Biomass is continuously produced in the FBR and must be removed by the vacuum filter as a secondary waste. The biomass secondary waste will be converted by the TEES process into an off gas composed of CH_4 (48%), CO_2 (48%), H_2 (2%), ethane (1%), and some higher hydrocarbon gases (1%). Nitrogen-derived products would be a mixture of N_2 and ammonia. Residual chemical oxygen demand (COD) of the sludge treatment effluent stream would be about 300 mg/L, with a pH of 4. Aqueous effluent from this treatment will be combined with the biological process effluent. For each influent condition analyzed, the quantities of the off gas streams are listed in Table 4.1.

4.3 THERMOCHEMICAL ENVIRONMENTAL ENERGY SYSTEM II

The TEES II process destroys organics in a high-temperature, high-pressure, catalyzed reaction. Aqueous organic contaminants are heated and pumped into the reaction chamber where they are completely converted to innocuous gases and dissolved ions. The temperature, pressure, and type of catalyst depend on the specific contaminant.

4.3.1 Design

As described in the introduction, the TEES process is used in two configurations in this study: as a noncatalytic, ground-water treatment system (TEES II) (Figure 4.3), and as a catalytic biological sludge treatment system (TEES) (see Figure 4.2b). In both configurations, vertical high-pressure reactor vessels are used for the processing. The feed is pumped to operating pressure by a reciprocating pump and is preheated by heat exchange with the reactor effluent. A small amount of auxiliary electric heat is added before the feedstock enters the reactors to offset heat losses in the processes. The cooled reactor effluent is depressurized and the gaseous products removed from the product water in a separator vessel.

FIGURE 4.3. TEES II System Flow Chart for Treatment of Ground Water

For the treatment of ground water, a catalyst is not required for the relatively facile thermal hydrolysis of the CCl_4 and chloroform. These reactions also proceed at a lower temperature and pressure than the catalytic conversion of the biological sludge. The assumed reactor sizing is based on the space velocity required for processing the higher concentrations of the chlorinated organics to meet the discharge criteria. This design philosophy sets a conservative estimate of the reactor sizes required in the treatment of the lower concentrations. The conservative design philosophy is reasonable based on the limited experimental data available.

For treatment of the biological sludge, a supported metal catalyst is required as well as a higher temperature and pressure to maintain a balance between the pyrolytic reactions and the catalytic reactions. Maintenance of the catalyst activity is an important consideration, and trace sludge constituents could have significant effects on the catalyst.

4.3.2 Key System Operation Considerations

System advantages

- direct treatment of ground water would not require a catalyst
- flexible to influent conditions
- small space requirements
- no aqueous or solid secondary waste streams

System disadvantages

- requires high temperature, high pressure, and high energy input

- catalyst may be sensitive to trace constituents in the biological sludge

Impact on Inorganic Contaminants

The TEES II process would have minimal impact on the inorganic species. There is evidence of nitrate reduction to nitrogen gas in the presence of organics. However, the reducing potential of the chloroform would be low and the CCl_4 would not have any potential for reducing nitrate. For the treatment of biological sludge, any residual nitrate would likely be reduced, but other cations scavenged in the biotreatment process would be released back to the effluent in the breakdown of the sludge.

Secondary Waste Production

The only secondary waste from the TEES II process is an off gas. For treatment of the ground water, the product gas is essentially carbon dioxide produced by the thermal hydrolysis of the chlorinated organics. The chlorine would be liberated as hydrochloric acid, but at such dilute concentrations, it would be insignificant.

The only secondary waste from the treatment of the biological sludge would also be an off gas. The gas would contain CH_4 (48%), CO_2 (48%), H_2 (2%), ethane (1%), and some higher hydrocarbon gases (1%). Nitrogen-derived products would be a mixture of N_2 and ammonia. Residual COD of the sludge treatment effluent stream would be about 300 mg/L, with a pH of 4.

4.4 UV/OXIDATION SYSTEM

The UV/oxidation process produces hydroxyl radicals that can destroy organics by oxidation. This technology is applicable to destruction of chlorinated organics because the hydroxyl radical is a stronger oxidant than chlorine and can, therefore, dechlorinate carbon atoms. The UV/oxidation system for this study uses hydrogen peroxide that is irradiated with UV light to produce the hydroxyl radicals. The process uses a specific amount of hydrogen peroxide to create enough radicals to fully oxidize the CCl_4 given sufficient contact time.

4.4.1 Design

Figure 4.4 shows a flow chart for the UV/oxidation system. The main component for the UV/oxidation system is a reaction chamber that provides contact between the CCl_4 , hydrogen peroxide, and UV light. The reactor is a channeled tank with rows of UV lights. Enough hydrogen peroxide (from a 50% H_2O_2 feed solution) is added to the influent to oxidize any reduced species and to produce sufficient hydroxyl radicals to destroy the CCl_4 . For the conceptual design, it was assumed that the influent ground-water constituents would not create a significant coating on the UV lights and thus reduce treatment efficiency before scheduled light replacement.

4.4.2 Key System Operation Considerations

System advantages

- does not require high temperatures or high pressures
- flexible to influent conditions

System disadvantages

- requires high energy input
- may have excess oxidant in effluent that must be destroyed prior to down-stream processes
- the 50% hydrogen peroxide feed solution requires special handling

4.4.3 Impact on Inorganic Contaminants

The UV/oxidation system will oxidize all species in the ground water, which may affect their subsequent removal.

4.4.4 Secondary Waste Production

Periodic replacement and disposal of UV lights (after 1500 hours) and other components is necessary. No gaseous, aqueous, or other solid waste stream is produced.

4.5 AIR STRIPPING/GRANULAR ACTIVATED CARBON

Air stripping is a common technique of removing volatile organic compounds from an aqueous stream. Carbon tetrachloride is amenable to this treatment because of its high Henry's law constant. Volatile organics in

FIGURE 4.4. UV/Oxidation System Flow Chart

off-gases from the air stripper are commonly removed by adsorption to granular activated carbon. This technology is also applicable to CCl_4 because it is nonpolar and has a high molecular weight. The combined process uses a packed tower air stripper to provide sufficient contact time between air and the water to allow volatilization of the CCl_4 . The CCl_4 in the off gas stream is then removed by adsorption to granular activated carbon which may be regenerated depending on what other constituents in the off gas also adsorb to the carbon.

4.5.1 Design

The air stripper is a countercurrent, packed tower design (Figure 4.5). Influent ground water enters through a water distributor, flows downward through the packing, and is collected in a wet well for transfer to downstream treatment processes. A blower provides air flow up through the packing. The off gas passes through a demister before exiting the tower. Effluent off gas is heated to reduce its relative humidity to about 50% before entering the granular activated carbon bed. The activated carbon unit is designed to last 90 days before requiring carbon replacement. The following assumptions were used in developing the conceptual design: influent water hardness and other constituents will not affect air stripper performance or maintenance; with the given off-gas conditions, the CCl_4 loading on the carbon is 15% (wt); and the carbon can be regenerated using standard methods.

FIGURE 4.5. Air Stripping/Granular Activated Carbon System Flow Chart

4.5.2 Key System Operation Conditions

System advantages

- does not require high temperatures, high pressures, or high energy input
- simple operation
- flexible to influent conditions

System disadvantages

- CCl_4 is not destroyed, only removed from the ground water
- further off-gas treatment may be necessary to remove any volatilized radioactive species not removed by the activated carbon
- produces secondary waste stream

4.5.3 Impact on Inorganic Contaminants

This system has no significant impact on inorganic species other than moderate oxidation of reduced species.

4.5.4 Secondary Waste Production

The activated carbon used in the system must either be disposed or regenerated. The potential for regeneration depends on the species that are adsorbed to the carbon. Regeneration would also require transportation of the carbon off site. The off gas may also be considered a secondary waste, depending on the species present that did not adsorb to the carbon. For each influent condition analyzed, the quantity of secondary waste is listed in

Table 4.1. Costs for this system were calculated assuming that the carbon was regenerated using standard methods.

5.0 ECONOMIC ANALYSIS

This section of the report describes the approach and presents the results of the comparative cost analysis conducted for the alternative ground-water treatment technologies. The analytical approach is summarized first, followed by more detailed descriptions of the estimating approach and results for the initial capital and annual operating and maintenance (O&M) cost components. The final two subsections present system-level cost results.

5.1 ANALYTICAL APPROACH

In general, the cost analysis was conducted according to guidelines established by the American Association of Cost Engineers (AACE) in their recommended practice, Conducting Technical and Economic Evaluations in the Process and Utility Industries (AACE 1990). Purchased costs were estimated for each piece of major equipment and multiplied by a factor unique to each equipment type to arrive at process capital. In addition to purchased equipment, process capital includes installation materials (foundations, piping, electrical, instrumentation, structures, insulation, painting, and other miscellaneous materials), direct installation labor, and all indirect construction costs (e.g., supervisory labor, field engineering, labor benefits, temporary construction facilities, miscellaneous construction supplies). Plant capital was estimated by multiplying process capital by a factor common to all equipment to allow for general facilities, construction company home office overheads and fees, and contingency. Finally, startup and working capital costs were estimated as fractions of annual O&M and plant capital.

Annual O&M costs include consumables (e.g., electricity, process water, chemicals), direct operating labor, direct maintenance labor and materials, and O&M overheads. Consumable costs were estimated by multiplying the specific quantity required for each consumable item by its unit cost. Direct operating labor was estimated for each process based on the types of equipment involved. Direct maintenance labor and materials costs were estimated by multiplying the plant capital for each piece of equipment by a fraction, which varied depending on the equipment type and operating environment. O&M overhead costs were estimated as a fixed percentage of direct O&M and consumable costs.

5.2 CAPITAL COST ESTIMATES

Purchased equipment cost-estimating equations were developed for each unique piece of equipment to aid in estimating the costs for the various plant design configurations and processing technologies. The equations were developed by applying statistical regression analysis to design point estimates covering the range of component sizes covered in the analysis. Sources for cost data included cost-estimating handbooks and equipment vendors. The principal source of data for purchased equipment cost and process capital cost factors was A Guide to Chemical Engineering Process Design and Economics (Ulrich 1984). All cost data were escalated to mid-1991 price levels using the Chemical Engineering Plant Cost Index published in Chemical Engineering. Other sources of cost data not explicitly cited in the text are listed in Table 5.1.

Rules-of-thumb for estimating plant capital, startup, and working capital, presented in Table 5.2, were based on recommendations presented in AACE (1990) with the following modifications. No "process" contingency covering the uncertainty in technical performance because of limited design data was included--i.e., differences in the current maturity of the alternative technologies were ignored. This approach puts the costs for each technology on equal footing consistent with a long-term perspective. "Project" contingency, covering expected omissions and unforeseen costs caused by lack of complete engineering or incomplete scope, was set at the same AACE-recommended value for all alternatives. In addition, no specific charges for process royalties (if any) or land were included.

TABLE 5.1. Cost Data Sources

Carbon Filter Media Company (vendor contact)
Guthrie (1974)
Corripio, Chrien, and Evans (1982)
Means (1991)
Page (1984)
Indco, Inc. (1991)

TABLE 5.2. Rules for Estimating Plant Capital, Startup, and Working Capital

Plant capital = $1.5875 \times \text{Process capital}$

Startup = 1 month O&M + 1 week fuel + 2% of plant capital

Working capital = 2 months O&M + 0.5% of plant capital

5.3 O&M COST ESTIMATES

Direct operating labor requirements were estimated for each technology based on rules-of-thumb presented in Ulrich (1984) for chemical processing equipment. In general, operating labor depends on the number and type of process equipment and varies little with equipment size. Each of the systems was estimated to require less than or equal to one full-time equivalent (FTE) operator, but one FTE per shift was assumed to be the minimum allowable. Therefore, the direct operating labor requirement was the same for all of the alternatives. Strictly speaking, the number of unit operations included in the bio/TEES combination system would indicate that more than one operator might be required, but the TEES equipment would be so small and compact that one operator was presumed to be adequate for this system as well. Direct operating labor wages were set at \$30,000 per year per FTE based on labor rates reported in the Monthly Labor Review for the chemical industry.

Direct maintenance material and labor (M&L) costs were estimated as a percentage of the initial capital cost. Both AACE (1990) and Peters and Timmerhaus (1980) suggest 6% of initial capital for average processes. M&L percentages of 4%, 6%, and 8% were assigned to each equipment type based on the type of equipment and operating environment. In general, the following rules were applied. Equipment operating at high temperature and pressure, or with abrasive fluids, or with moving parts was assigned a M&L percentage of 6%. If none of these condition applied, the percentage was 4%; if two or three of these conditions applied, the percentage was 8%.

As noted in Section 5.1, consumable costs were estimated by multiplying the quantity required by the appropriate unit cost. Consumable unit cost assumptions and data sources are listed in Table 5.3.

TABLE 5.3. Consumable Unit Costs and Data Sources

<u>Consumable</u>	<u>Unit Cost</u>	<u>Data Source</u>
Electricity	\$0.051/kWh	Energy Information Administration (1992)
Process water	\$1/1000 gal	Peters and Timmerhaus (1980)
Sodium nitrate	\$0.345/lb	Schnell Publishing Company (1992)
Sodium acetate	\$0.62/lb	Schnell Publishing Company (1992)
Hydrogen peroxide	\$0.65/lb	Treatment Equipment Company (vendor quote)
Nickel catalyst	\$10/lb	(vendor quote to D.C. Elliott, PNL)
Carbon regeneration	\$1/lb	Calgon; Cameron Carbon (vendor quotes)

O&M overheads include direct supervisory labor, indirect labor, payroll overhead, and indirect materials. Estimating rules-of-thumb specified by AACE (1990) and listed in Table 5.4 were used for estimating the costs of these components. Rules-of-thumb suggested in AACE (1990) for corporate level overheads and marketing expenses were not included.

5.4 SYSTEM CAPITAL AND O&M COST RESULTS

Capital and O&M cost summaries for each of the five systems are presented in Tables 5.5a through 5.5f for each of the six flow rate and CCl_4 concentrations evaluated in this study. The air stripping/granular activated carbon (AS/GAC) system has the lowest capital and O&M costs at all design points, which can be attributed to its simple design, low temperature and pressure operating conditions, and limited use of electricity and other consumables. The biological system also operates at low temperature and pressure, but has many more unit operations, which increases its capital cost relative to the AS/GAC system. The TEES II and UV/oxidation systems have the highest capital costs. Much of the TEES II system operates at high temperatures and pressures, with equipment requiring stainless steel materials. The UV/oxidation system is constructed of stainless steel as well. Direct operating labor is the same for all systems and direct maintenance labor and materials are proportional to capital. Sodium nitrate and sodium acetate

TABLE 5.4. Labor Overheads

Direct supervisory labor = 15% of direct operating labor

Indirect labor = 75% of direct labor

Payroll overhead = 35% of direct and indirect labor

Indirect materials = 25% of direct labor

TABLE 5.5a. System Cost Summaries, 4200 ppb/100 gpm

	<u>Cost in 1000s of 1991 dollars</u>				
	<u>Biological</u>	<u>TEES II</u>	<u>Bio/TEES</u>	<u>UV/Oxide</u>	<u>Air Strip/GAC</u>
<u>Capital</u>					
Plant	1064	3051	1067	5106	283
Startup	66	131	67	193	38
Working	86	134	87	178	65
Total Capital	1216	3316	1221	5477	386
<u>Annual O&M</u>					
O&M M&L	487	715	488	914	383
Consumables	1542	0	1543	134	11
Electricity	216	485	217	673	9
Total O&M	2245	1200	2248	1721	403

TABLE 5.5b. System Cost Summaries, 1000 ppb/100 gpm

	<u>Cost in 1000s of 1991 dollars</u>				
	<u>Biological</u>	<u>TEES II</u>	<u>Bio/TEES</u>	<u>UV/Oxide</u>	<u>Air Strip/GAC</u>
<u>Capital</u>					
Plant	823	3051	-	4297	227
Startup	59	131	-	166	36
Working	81	134	-	159	64
Total Capital	963	3316	-	4622	327
<u>Annual O&M</u>					
O&M M&L	460	715	-	826	378
Consumables	697	0	-	108	3
Electricity	210	485	-	541	8
Total O&M	1367	1200	-	1475	389

TABLE 5.5c. System Cost Summaries, 70 ppb/100 gpm

	<u>Cost in 1000s of 1991 dollars</u>				
	<u>Biological</u>	<u>TEES II</u>	<u>Bio/Tees</u>	<u>UV/Oxide</u>	<u>Air Strip/GAC</u>
<u>Capital</u>					
Plant	801	3051	-	2118	171
Startup	59	131	-	97	35
Working	80	134	-	109	63
Total Capital	940	3316	-	2324	269
<u>Annual O&M</u>					
O&M M&L	458	715	-	590	374
Consumables	625	0	-	55	1
Electricity	210	485	-	266	7
Total O&M	1293	1200	-	911	382

TABLE 5.5d. System Cost Summaries, 4200 ppb/25 gpm

Cost in 1000s of 1991 dollars					
	<u>Biological</u>	<u>TEES II</u>	<u>Bio/TEES</u>	<u>UV/Oxide</u>	<u>Air Strip/GAC</u>
<u>Capital</u>					
Plant	541	953	-	1449	132
Startup	48	61	-	76	34
Working	74	83	-	94	62
Total Capital	663	1097	-	1619	228
<u>Annual O&M</u>					
O&M M&L	417	470	-	518	370
Consumables	388	0	-	33	3
Electricity	64	122	-	164	3
Total O&M	879	592	-	715	376

TABLE 5.5e. System Cost Summaries, 1000 ppb/25 gpm

Cost in 1000s of 1991 dollars					
	<u>Biological</u>	<u>TEES II</u>	<u>Bio/TEES</u>	<u>UV/Oxide</u>	<u>Air Strip/GAC</u>
<u>Capital</u>					
Plant	439	953	-	1232	97
Startup	45	61	-	69	33
Working	71	83	-	88	62
Total Capital	555	1097	-	1389	192
<u>Annual O&M</u>					
O&M M&L	415	470	-	494	368
Consumables	180	0	-	27	1
Electricity	63	122	-	134	2
Total O&M	658	592	-	655	369

TABLE 5.5f. System Cost Summaries, 70 ppb/25 gpm

	<u>Cost in 1000s of 1991 dollars</u>				
	<u>Biological</u>	<u>TEES II</u>	<u>Bio/TEES</u>	<u>UV/Oxide</u>	<u>Air Strip/GAC</u>
<u>Capital</u>					
Plant	434	953	430	714	71
Startup	45	61	45	52	32
Working	71	83	71	77	61
Total Capital	550	1097	546	843	164
<u>Annual O&M</u>					
O&M M&L	415	470	415	438	366
Consumables	156	0	156	14	0
Electricity	63	122	63	67	2
Total O&M	634	592	634	519	368

consumption combine to give the biological system the highest annual consumable charge. Electricity consumption is greatest for the TEES II and UV/oxidation systems. The former consumes significant electricity in preheating and pressurizing the feed stream, while electricity is consumed in the UV lamps of the latter system. Note that the TEES II system design developed for a CCl_4 concentration of 4200 ppb was also employed for the lower concentrations, which means this system is conservatively sized at 1000 and 70 ppb.

5.5 SYSTEM-LEVELIZED COST RESULTS

The economic evaluation was conducted by calculating and comparing the levelized production cost (LPC) in terms of \$/1000 gallons of contaminated water treated or \$/lb of CCl_4 destroyed. Levelized cost analysis combines initial capital costs, annual O&M costs, and the annual processing rate with financial parameters to produce a single figure-of-merit (the LPC) that is economically correct and can be used to compare the projected treatment costs of alternative technologies. The specific economic methodology employed was that defined in Brown et al. (1987). The economic assumptions listed in Table 5.6 were used to calculate that the LPC are consistent with Federal ownership (Brown et al. 1992, EPA 1988).

LPC results are presented in Tables 5.7 and 5.8. The AS/GAC system was estimated to have significantly lower levelized costs than any of the other system, with costs about 1/3 to 1/2 the cost of the next least costly alternative at each design point. Differences in initial capital and annual O&M tend to offset each other for the remaining systems. Given the uncertainty in the design and cost analysis, the levelized costs for biological, TEES II, biological/TEES and UV/oxidation should be considered approximately equal. However, the TEES II system may offer a significant cost advantage at the highest CCl_4 concentration.

Other general trends in the levelized cost results are consistent with expectations. All systems show declining levelized costs when comparing the 100-gpm flow rate with the 25-gpm flow rate at the same CCl_4 concentration. Levelized costs in \$/lb CCl_4 increase with decreasing CCl_4 concentration, while levelized costs in \$/gallon of water treated increase with increasing CCl_4 concentration.

TABLE 5.6. Economic Assumptions

<u>Economic Factor</u>	<u>Value</u>
Economic life	30 years
Property tax rate	0.0%
Insurance rate	0.0%
Income tax rate	0.0%
Discount rate	10.25% (nominal) 5.0% (real)
General inflation rate	5.0%
Electricity inflation rate	5.6%
Annual capacity factor	0.90
Depreciation	N/A
Price year	1991
Net salvage value	\$0

TABLE 5.7. Levelized Production Costs for CCl₄ Destruction

<u>Treatment</u>	<u>Cost in dollars per pound of CCl₄ destroyed</u>				
	<u>Biological</u>	<u>TEES II</u>	<u>Bio/TEES</u>	<u>UV/Oxide</u>	<u>Air Strip/GAC</u>
4200 ppb/100 gpm	1451	854	1451	1280	256
1000 ppb/100 gpm	3670	3670	-	4609	1024
70 ppb/100 gpm	49500	52920	-	39260	14510
4200 ppb/25 gpm	2218	1621	-	2048	938
1000 ppb/25 gpm	7080	6824	-	7677	3839
70 ppm/25 gpm	97243	97243	97243	83595	54593

TABLE 5.8. Levelized Production Costs for Treatment of Ground Water

<u>Treatment</u>	<u>Cost in dollars per 1000 gallons</u>				
	<u>Biological</u>	<u>TEES II</u>	<u>Bio/TEES</u>	<u>UV/Oxide</u>	<u>Air Strip/GAC</u>
4200 ppb/100 gpm	49	31	49	45	9.1
1000 ppb/100 gpm	31	31	-	38	8.7
70 ppb/100 gpm	29	31	-	23	8.5
4200 ppb/25 gpm	78	57	-	70	33
1000 ppb/25 gpm	59	57	-	65	32
70 ppm/25 gpm	57	57	57	49	32

6.0 RESULTS OF ANALYSIS

6.1 MACRO SCALE ANALYSIS

When compared on a macro scale using costs in dollars per pound of CCl_4 destroyed, or dollars per 1000 gallons treated, the AS/GAC system is significantly more cost effective than the CCl_4 destruction technologies. The AS/GAC system does not require large energy or chemical inputs and has a low capital cost because CCl_4 is amenable to both air stripping and granular activated carbon. These features give AS/GAC a cost advantage over the other technologies for the given assumptions of this study and without considering secondary waste production.

The secondary waste produced by the AS/GAC system may be a significant cost and/or regulatory problem with this technology. The waste carbon must be either transported off site for regeneration or disposed at the Hanford site. The biological/TEES, UV/oxidation, and TEES II CCl_4 destruction technologies do not produce any aqueous or solid secondary waste streams and would, therefore, not have the problems associated with secondary waste disposal. All of the systems except UV/oxidation produce off gas, and costs associated with air discharge regulations may increase costs for a given treatment depending on the composition of the off gas.

6.1.1 Macro Scale Analysis for Destruction Technologies

The life cycle costs for the CCl_4 destruction technologies were all comparable within the uncertainty of this cost estimate. The destruction technology costs were all dominated by operation and maintenance costs. Each technology required a large input of either energy or chemicals that caused operations costs to be high. The life cycle assumptions of this study also contributed to the large impact of operational costs.

Capital costs did not significantly affect life cycle costs, but may become a significant factor for different operation scenarios (Figure 6.1). The biological and biological/TEES systems had the lowest capital costs for all treatments and were relatively insensitive to CCl_4 concentration or flow rate. The capital costs for the UV/oxidation system were the highest for the

FIGURE 6.1. Capital Costs of Technologies at each Treatment

two highest concentrations at both flow rates and were most sensitive to both CCl_4 concentration and flow rate. The capital cost for the TEES II system was sensitive only to flow rate and was the highest at the low concentration for both flow rates, although these costs were affected by the design assumptions for the TEES II system.

The biological and biological/TEES systems had the highest annual O&M costs for most of the treatments (Figure 6.2). The annual O&M costs for these systems were very sensitive to both concentration and flow rate because of large changes in the nutrient demand caused by the different influent conditions. The annual O&M cost for the UV/oxidation system was also sensitive to concentration and flow rate, and those costs ranged from the highest to the lowest. The annual O&M cost for the TEES II system was not sensitive to concentration (a result of design assumptions) and was the least sensitive to flow rate.

FIGURE 6.2. Annual O&M Costs for Technologies at each Treatment

6.2 SYSTEM COST ANALYSIS FOR DESTRUCTION TECHNOLOGIES

6.2.1 Biological and Biological/TEES Systems

The nutrient requirement had the greatest impact on cost for both of the biological systems. The size of the FBR and the acetate and nitrate degradation rates determine the amount of nutrients required. The size of the FBR is determined by the reaction rate of CCl_4 destruction. Thus, the greatest impact on cost effectiveness for the biological system can be achieved by changing the relevant reaction rates. Important improvements would include increasing the CCl_4 destruction rate by optimizing microbial parameters, increasing the CCl_4 destruction rate by optimizing reactor parameters, and decreasing the nutrient degradation rates. Each of these improvements increase the ratio of CCl_4 destruction rate to nutrient degradation rate. Significant opportunity exists to achieve these improvements over the rates used for the conceptual design in this study. For the reactor design, rate data from laboratory and pilot-scale experiments were used. These experiments were not designed to optimize the ratio of CCl_4 destruction to nutrient degradation. The cost effectiveness of biological treatment may become very competitive if

the system is optimized for the maximum ratio of CCl_4 destruction to nutrient degradation. Improvement of this ratio is important to both ex situ and in situ bioremediation efforts because it directly impacts associated costs for CCl_4 treatment.

The biological/TEES system was clearly the best biological system because essentially the same treatment was achieved for the same cost as the system using anaerobic digestion, and no secondary waste other than off gases was produced.

6.2.2 TEES II System

A potentially important omission from this study was the inclusion of a pre-concentration step for the treatment of the ground water. Size reduction of the TEES II process by an order of magnitude or more may be possible with the addition of a steam-stripping pretreatment. Further research would be required to verify that the discharge criteria could still be met when treating higher concentration feed stock. Electricity requirements and the type of unit operations were significant factors in the cost of the TEES II process. The electricity is required to heat the influent to the appropriate temperature for the reactions to occur. Optimization of the system may decrease the electricity requirement, especially for the treatment of the lower concentrations, because of the conservative design used for these applications. Because the unit operations in the TEES II process are high temperature and high pressure, the associated O&M materials and labor costs were high for this system. It is unlikely that these costs could be decreased. Capital costs were also high for the TEES II process because of the high-temperature, high-pressure operating conditions. Optimization of unit operations may decrease these costs.

6.2.3 UV/Oxidation

Electricity requirements had the greatest impact on cost for the UV/oxidation system. The UV energy necessary to create enough hydroxyl radicals to destroy the CCl_4 in the residence time of the reactor determines the electricity required. Optimization of the system may decrease the electricity requirement. The only significant secondary waste produced by the UV/oxidation system is the disposal of UV lights every 1500 hours (2 months). Because the

system does not produce off gases, it may have an advantage over the other CCl_4 destruction systems depending on air discharge regulations. However, disposal of the UV lights may also present regulatory or cost problems. Capital costs were high for the UV/oxidation system, especially at the higher CCl_4 concentrations. Optimization of the system may decrease these costs, although decreasing system efficiency at higher CCl_4 concentrations may limit possible capital cost improvements.

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