

The Optimization of a Three-Phase Surfactant Washing System

Tylisha Baber
Melinda Baker
La Keya Belcher
Rebekah Stephenson

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Abstract: In this analysis, the economics of MBI International's three-phase surfactant washing system for the removal of polychlorinated biphenyls (PCBs) from sediment was optimized. The system, which consists of a screw washer, an oil/water separator, and a vacuum filter, transfers PCBs to a sacrificial oil layer through two individual two-phase partitioning steps. At the completion of the washing process, the sacrificial oil layer is incinerated. Cleaned soil is disposed of in a municipal solid waste facility, and the spent surfactant layer is recycled. The washing system was modeled using the MATLAB mathematical program and an economical analysis was conducted using the results from the program. When connecting-equipment between operating units, product maintenance, and capital depreciation are considered, the economic results were reported with a 35% confidence level. According to the cost analysis, the manufacturing cost to treat 20 tons of sediment per hour was determined to be approximately 15 million dollars. This cost includes the usage of 6% (by volume) surfactant in the aqueous phase and 375 kilograms of sacrificial oil. The net profit was calculated to be approximately 56 thousand dollars. The three-phase surfactant washing system is technically feasible and sound. It is recommended that a pilot plant investigation be initiated for the patent-pending process.

Work done under the direction of Blaine Severin, PhD., of MBI International in partial fulfillment of the requirements of Michigan State University MTH 844, advised by Professor J. A. Courtney.

Table of Contents

Introduction.....	3
Relevant Assumptions	5
Experimental Procedure.....	6
Results and Discussion	9
Discussion of the Spreadsheet and Data Analysis	11
Conclusions and Recommendations	11
References.....	12
Appendix A.....	14
Appendix B.....	14
Appendix C.....	17
Appendix D.....	22

Introduction

Polychlorinated biphenyls (PCBs) are ubiquitous anthropogenic environmental contaminants (Nakata et al., 1998). The United States Environmental Protection Agency (US EPA) guidelines allow removal of PCBs from soils via solvent extraction (Nam et al., 2001), which is economically unfavorable and raises health and environmental concerns. However, MBI International has developed a surfactant system that is non-toxic and biodegradable. The surfactant system has high detergency, yet low emulsion carrying capacity. Within the three-phase surfactant washing system, a screw-washer is used to contact contaminated soil with an aqueous surfactant layer into which PCBs partition as a function of the surfactant concentration (Figure 1). Micelle encapsulated PCBs are then concentrated to a smaller volume by partitioning into a sacrificial oil layer, due to their enhanced solubility in hydrocarbon oils relative to their solubility in waterborne surfactants (Severin, 2002).

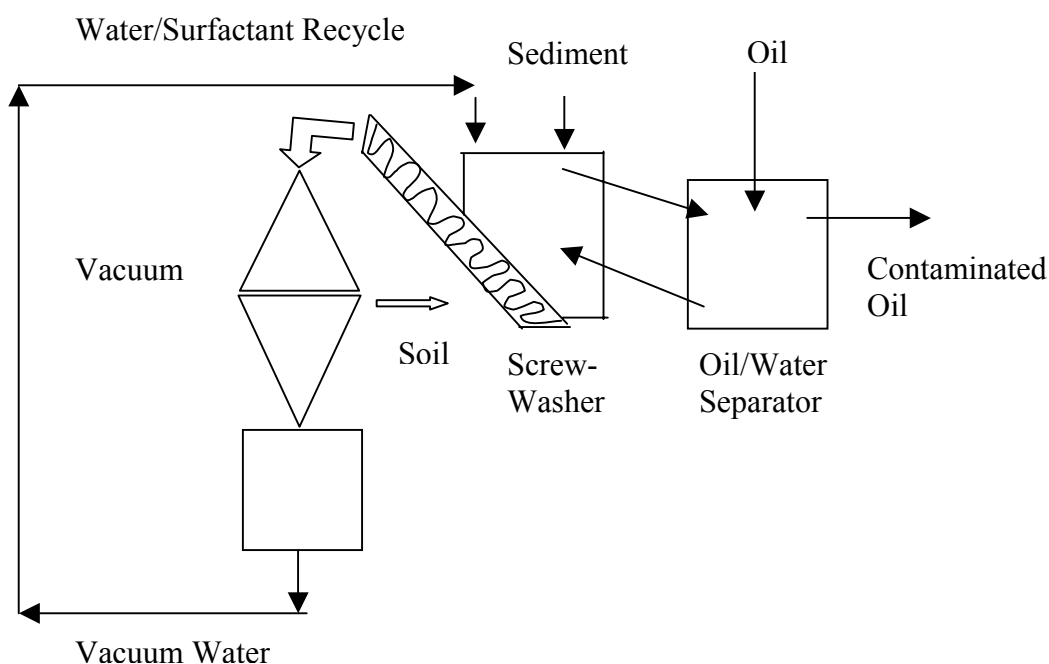


Figure 1. Conceptual Three-Phase Washing System.

Existing technologies significantly differ from the second two-phase extraction of the system. Current technologies are restricted to the disposal of large volumes of contaminated water or to the extraction of PCBs into highly flammable, organic solvents that must be distilled in order to concentrate recovered PCBs (Borah, 1998; Darian et al., 1994; Everett et al., 1994; Heins and Nowack, 1997; Jaffe and Park, 1993 and 1995; Plunket, 1999). MBI International's laboratory experiments report 90(+)% removal of PCBs from 500mg/kg of contaminated soils (Severin, 2002). Thus, this process has a high potential to generate positive economical impact within the pollution remediation industry.

MBI International has fostered partnerships with surfactant and equipment manufacturers, a soil washing company, and a federal agency. These ventures will use the generated models to commercialize this process for pollution remediation and to address common clean-up problems in the safest, productive and most cost-effective manner by sharing knowledge, experience, equipment, and facilities. In order to commercialize this novel three-phase pollutant extraction process, which is based on the

unique properties of a proprietary surfactant system, it is essential to predict the field-scale performance of soil washing equipment based on MBI International's laboratory equilibrium phase distribution data for PCBs and site-specific soils. It is therefore necessary to obtain an equipment-specific treatment model coupled with a cost optimization model.

Significant influences on this system are the federally mandated PCBS concentrations in soils disposed of in municipal solid waste (MSW) facilities, carrying capacity of the hopper and oil/water separator units, and the initial and final water content of the soil. The EPA currently limits the bulk soil concentration to be ≤ 50 mg/kg for disposal in an MSW. This requires the proposed process to remove 95% of PCBS contained in contaminated soils and deposited-cleaned soils so it is not leach PCBs into surrounding groundwater (EPA, 2001). MBI International suggests a successful operation that will process 20 tons soil/hr. All treated soil will have moisture content of 32% water by weight. The surfactant molecules introduced within the aqueous layer will be associated with this water; likewise, the total surfactant concentration within the system is diluted upon sediment-aqueous layer contact. This dilution must be accounted for in the calculation of the overall efficiency of partitioning PCBS into the surfactant layer, and water associated soil will leave the system with PCBS encapsulated surfactant micelles.

In the present analysis, equilibrium data are incorporated into a pseudo non-steady state analysis. The motivation for the analysis was the removal of a small aliquot of surfactant from the soil/surfactant contactor to the surfactant/oil contactor and the return of an equal volume of refreshed surfactant to the soil contactor. A turnover is defined as the movement of a known volume (i.e., one total volume of surfactant held within the soil contactor) of surfactant solution from the screw washer to the oil/water separator and back to the screw-washer. The above influences will alter both the number of turnovers and associated clean-up costs. The ideal model will optimize the operation of the 3-unit system and minimize the cost.

MBI's Environmental Technologies Development Program uses the *Stage Gate Management Process* to monitor the research and development activities, its achievement of milestones, and costs (Figure 2). In this process, a research idea is channeled through *Preliminary Investigation, Detailed Investigation, Development, and Validation*. At each step of the process, a critical review occurs to assure that resources are spent wisely. The evaluation criteria for each step are:

- *Strategic fit*: project fits the needs of a stake-holder with the qualifications of the research team
- *Utility Screening*: project appears to be applicable to solving a recognized problem,
- *Technical Feasibility and Risk*: project is technically feasible with the available resources
- *Advantageous*: project reduces costs using, less material or a new approach or provides, better results
- *Legal and Regulatory Compliance*: Methods comply with laws and regulations
- *Critical success factors and show-stoppers*: Success and failure are clearly defined
- *Plan to Proceed*: Projects must meet a reasonable set of goals

At each of the stages, the project must pass the stated criteria. The project may be “passed” to the next step, “held” pending new research and research items identified, or “abandoned” to conserve resources and minimize financial risk. In general, projects at Stage 1 (Preliminary Investigation) are at the “proof-of-concept” level bringing ideas to the first laboratory testing. Projects at Stage 2 (Detailed Investigation) are based on showing reproducibility and optimization at the laboratory scale. Projects at the Stage 3 (Development) are designed to demonstrate process range and scale-up potential at the pilot scale. Stage 4 (Validation) projects are usually at the field-pilot stage, and Stage 5 (Demonstration) are large pilot or small production scales.

The soil-washing program is presently in Stage 2 (Detailed Investigation) of the Stage Gate Process. Previously conducted laboratory experiments, in combination with modeling studies, will create a detailed business plan to guide the proposed project toward commercialization. The present report is critical to the overall management plan as an indicator of “Technical Feasibility and Risk,” and the results will impact the “Plan to Proceed” from Stage 2 to Stage 3. The project will continue onto the next stage in

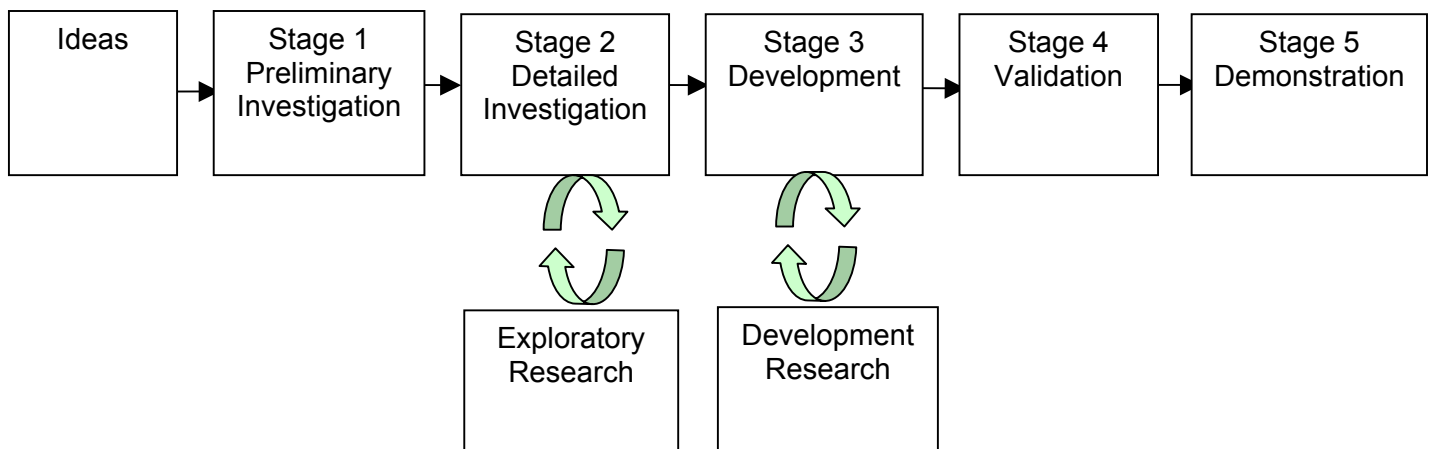


Figure 2. Stage Gate Process: Projects from Preliminary Investigation to Demonstration

commercialization only if the remediation process is shown to be technically and economically feasible at the 20-ton soil/hr scale. In the third stage (Development), monetary contributions and industrial involvement significantly increase as a prototype is designed to operate at real processing conditions (DOE citation). If modeling of field-scale performance does not effectively control the influences mentioned above such that turnovers are minimized, production of a pilot plant would not be warranted. The following analysis will continue a detailed operation and economic investigation of the proposed three-phase surfactant soil washing system.

2. Relevant Assumptions for the Project

1. $A \pm 35\%$ confidence level
2. The screw washer and attached units are skid mounted and equipment required to connect units account for 30 % of equipment costs.
3. The large McLanahan unit will treat 20 tons of soil/hr.
4. Non-operating costs such as transportation of soil to and from site, personal safety equipment for workers, and special operating insurances and licenses can be neglected from costs analysis.
5. Equipment will depreciate with a 7% interest rate over 10 years.

6. The process possesses no significant salvage value.
7. The cost of surfactant and oil will not change over the lifetime of the process.
8. Density of surfactant is 1.0 g/ml
9. Equilibrium occurred instantaneously within the system
10. Sediment retained it's 32% moisture content

3. Experimental Procedure

Physical Model of the Three-Phase Washing System for the MATLAB Model. The purpose of the mathematical model of the extraction system was to determine optimal operating and cost ranges of the following parameters: surfactant, sacrificial oil, and surfactant in water solution. The washing system was modeled as two distinctive extraction processes in the program simulation. For extraction I, sediment with 32% moisture content and 500 ppm of PCBs was contacted with the aqueous surfactant phase in the screw-washer. Upon physical contact, the PCBs partitioned between the two phases (sediment and surfactant solution) until equilibrium was approached. The concentration ratio (fraction of PCBs in sediment/fraction of PCBs in aqueous surfactant solution) of PCBs was derived from the following equation:

$$\frac{C_1 m_1}{C_1 m_1 + C_2 m_2} = \frac{C_2 m_w + C_1^* m_s}{C_2 m_w + C_1^* m_s + C_2 m_2} = [0.1198x^{-0.4972} = b], \quad (1)$$

where C_1 , C_1^* and C_2 are the concentrations of PCBS in wet sediment, dry sediment and surfactant solution respectively, m_1 , m_s , m_w and m_2 are the masses of the wet sediment, dry sediment, water associated with the wet sediment and surfactant solution respectively, x (also defined as k_0 in the program) is the volume fraction of surfactant in water, and b is the weight fraction of PCBS remaining in the sediment after extraction I has been completed (Severin, 2002). The bracketed portion of equation (1) was developed by fitting the experimental data conducted at MBI (Figure 3).

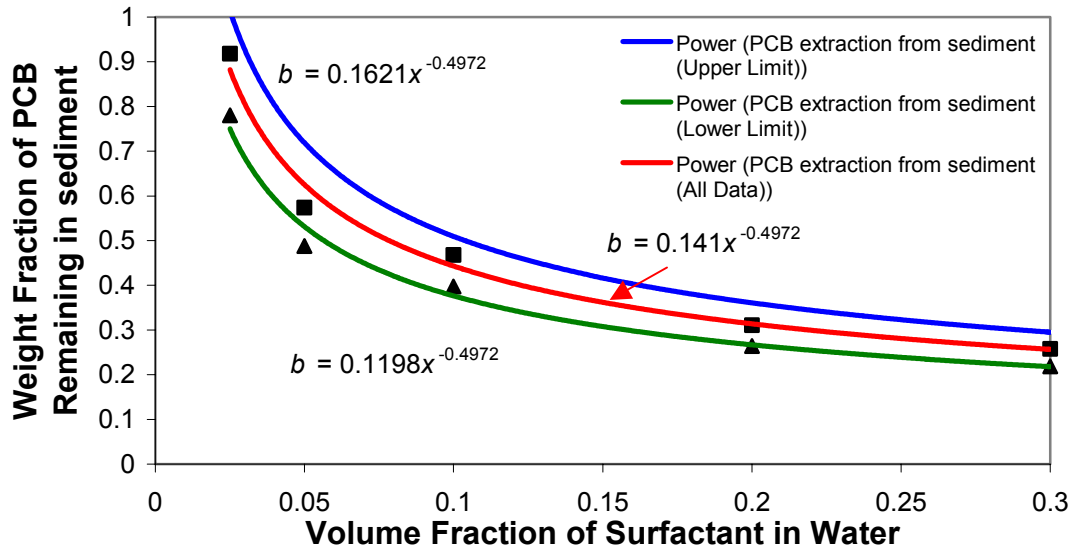


Figure 3. Fraction of PCBS remaining in spiked sediment samples after Extraction I.

Once the first extraction equilibrated, a volume percentage of the aqueous surfactant layer was transferred to an oil/water separator tank, where it came into physical contact with the sacrificial oil phase for extraction II. Again, the PCBs partitioned between the two phases (surfactant solution and oil layer) until equilibrium was reached. Analogous to extraction I, the concentration ratio (fraction of PCBs in the aqueous surfactant solution/fraction of PCBs in oil layer) of PCBs was derived from the following equation:

$$\frac{C_2 m_2}{C_2 m_2 + C_3 m_3} = [0.0008x^{-0.8438} = a] \quad (2)$$

where C_3 is the concentration of PCBs in oil, m_3 is the mass of oil and a is the weight fraction of PCBs remaining in the aqueous surfactant layer after extraction II has been completed (Severin, 2002). The bracketed portion of equation (2) was developed by fitting the experimental data (Figure 4). Once equilibrium was reached, the surfactant solution was recycled to the screw-washer. The extraction processes were then repeated.

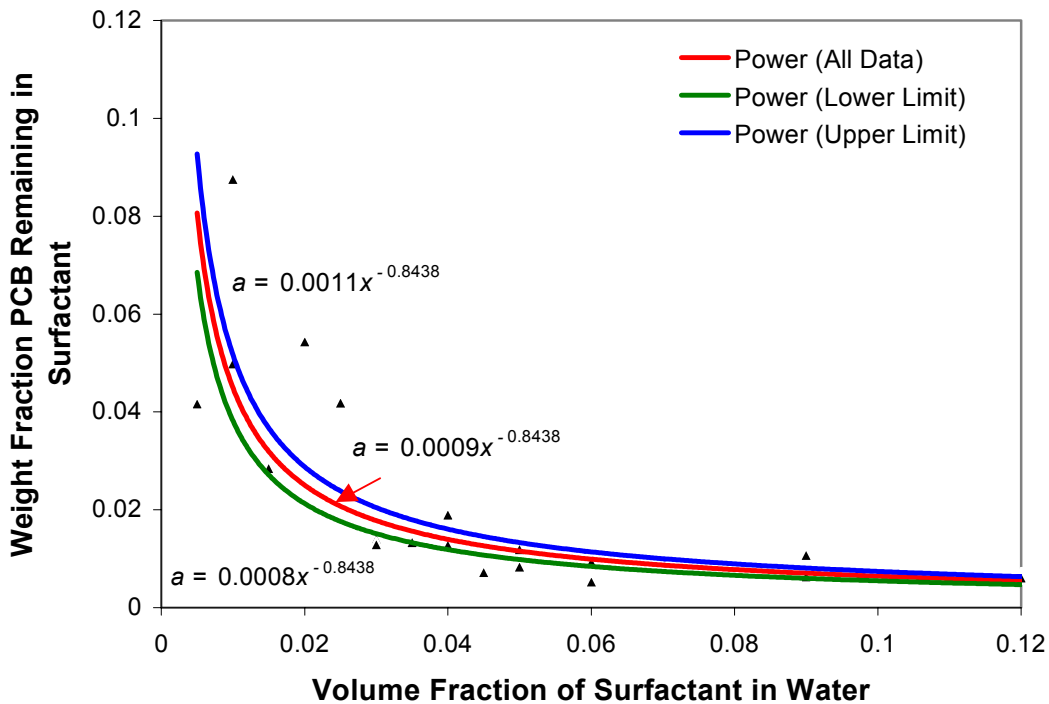


Figure 4. Fraction of PCBS remaining in the surfactant layer after extraction II.

Optimization of the Mathematical Model Parameters by Economical Analysis. The following parameters were fixed and used as inputs for a single simulation: volume fraction of surfactant in water (k_0), mass ratio of surfactant solution to sediment (k_1) and the mass ratio of surfactant solution to oil (k_2). The k_0 , k_1 and k_2 parameters ranged from 0.04 to 0.1, 1.5:1 to 2.0:1 and 0.025 to 0.25, respectively (Appendix A, Table I). These different ranges were chosen arbitrarily to mimic a realistic extraction process. In order to pick the optimal value of each parameter, a series of cases were programmed in MATLAB, in which two parameters were held constant and the third parameter was varied. Then, the output results from the program were used to conduct the economical analysis.

Procedure of Mathematical Model. Equations (1) and (2) can be rearranged, respectively, to the following equations:

$$\frac{C_2}{C_1^*} = \frac{m_s(b-1)}{m_w - bm_2}, \text{ and} \quad (3)$$

$$\frac{C_3}{C_2} = \frac{m_2}{m_3} \left(\frac{1-a}{a} \right). \quad (4)$$

Equations (3) and (4) were used to compare the concentrations of PCBs at various times in the program. First, a value for k_0 , k_1 and k_2 , within in their operating ranges, were inserted into the program as initial conditions. Next, based on these initial conditions, m_s , m_w , m_2 and m_3 were calculated. After Extraction I, a new k_0 value was calculated because pure surfactant in the aqueous layer was diluted by the water in the sediment (m_w). Then, b was calculated. Next, C_2/C_1^* was calculated using equation (3). After extraction I, a volume fraction of the surfactant layer was transferred to the oil/water separator, where it contacted the sacrificial oil. After extraction II, a was calculated. Then, C_3/C_2 was calculated using equation (4).

The aqueous surfactant layer was transferred back to the screw-washer tank. However, since pure surfactant from the aqueous layer was diluted with the sediment-associated water during extraction I, the amount of pure surfactant returning to the screw-washer was less than the original amount in the screw-washer. To compensate for this loss, the same amount of surfactant that was lost to the wet sediment was replaced. Then extractions I and II were repeated, and the concentrations ratios C_2/C_1^* and C_3/C_2 were recalculated. This process continued until the concentrations of the surfactant solution going and returning between the tanks were equal, which is represented by a loop in the program. The second loop terminated when the constraint of 95% removal of PCBs from the sediment was met. The output results were used for the economical analysis. The completion of the loops represented a simulation of a single batch. In one batch, 5 tons of sediment, which constitutes $\frac{1}{4}$ of a truckload, was treated for 15 minutes. At the end of a batch being cleaned, the oil remained in the oil/water separator and the sediment was removed with its original 32% moisture. Then, a new batch of sediment was added, and the initial conditions were set to the final conditions of the previous batch. The program was conducted for four batches in series. Due to previous research, the oil was changed halfway in a simulation of a single batch in order to optimize the oil usage and the rate at which the PCBs are transferred (Severin, 2002). Figure 5 shows a schematic of one iteration (in other words one time through each “exit” loop).

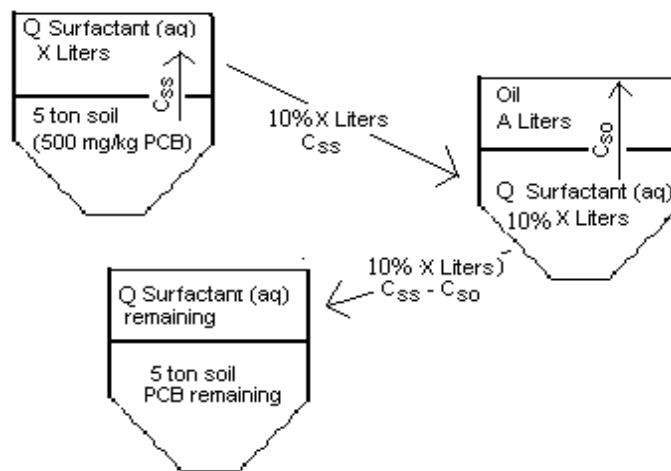


Figure 5. Schematic of one iteration (X is the volume of the surfactant used to treat 5 tons (1/4 truck load) of soil and F is the fraction of aqueous surfactant transferred to the oil water separator in one turnover, and A is the volume of the oil used to remove half of the PCBS dissolved in the aqueous surfactant layer).

Cost Analysis. A pilot plant capable of producing 20 tons/hr of soil has been projected, and the capital investment and costs of profitability have been determined. The mathematical model was used first to determine the optimal fraction of surfactant in water by volume with respect to the cost of feed materials and the amount of oil used, and then that fraction was used to complete the economic evaluation (Appendix C). A $\pm 35\%$ confidence level was assumed for the evaluation. There was no salvage value, and a straight-line depreciation and 10 year-life assumed. The plant was expected to operate approximately 94% of each year. There was expected to be no cost for land, and the plant would be built on an existing site. A sensitivity analysis was done by varying the amounts of raw materials, utilities, labor, and capital investment used, and observing how these values changed the manufacturing cost and selling prices. The values were increased by 20-100%, and plotted (Appendix C).

4. Results and Discussion

Discussion of the Experimental Data Analysis. When considering the proper interpolating function for the data, the power fit generated in Excel was chosen. The exponential fit was considered, but then discarded because it did not account for the weight of data clusters, in other words many data points together, and outliers. In addition, it was suggested that in order to use the exponential fit the data should be fit with the sum of two exponentials. One of the exponentials would account for the slope or steepness of the function, while the other would account for the different data points. The use of the proper function was limited by the number of data points. Working with such few data points (in other words less than 20), allowed for substantial error in the actual interpolating function.

Results and Discussion of Mathematical Model and Economical Analysis. From experimental data, an upper limit, middle, and lower limit for error analysis of the data was generated. So, the upper limit and lower limit represented the possible error of $\pm 15\%$ in the data points. A wide band of error was chosen in order to observe the stability of the system. For the system to be considered unstable, the upper limit would have to greatly diverge from the middle curve. By comparison in Figure 6, the upper

limit does not diverge in the trial region from 0.04 to 0.10 volume fraction of surfactant. Thus, the system was considered to be stable for an error up to 15% in the data. The results of the mathematical model were determined by graphing the mass of oil required to obtain a 95% removal of PCBs from the sediment while varying the fraction of surfactant. Also, the minimum amount of the aqueous layer was estimated to be $15,000 \pm 1000$ kg. This was established by observing the different surfactant fractions and varying the amount of oil required, from one fraction to the next.

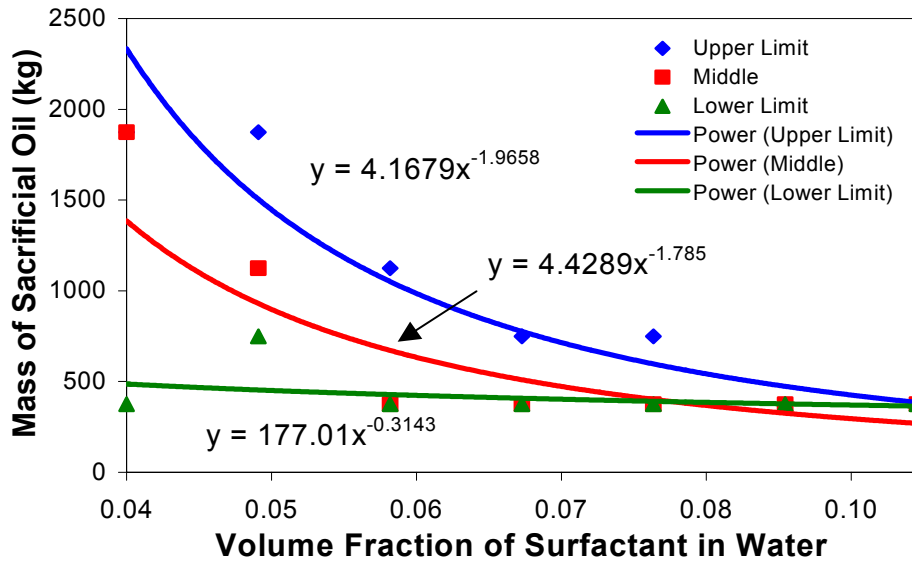


Figure 6. Amount of oil vs. fraction of surfactant for a 95% removal of PCBs.

The cost was determined for the respective amount of oil and fraction of surfactant used. For a large-scale process, the optimum percent of aqueous surfactant and the amount of oil was determined to be 6% and 375 kg, respectively, and the minimum cost of the feed materials associated with these values was 15 million dollars/year (Figure 7).

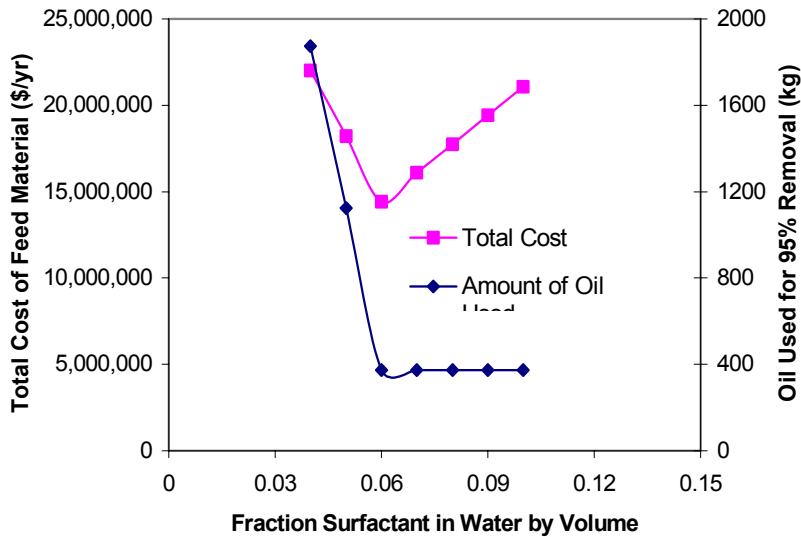


Figure 7. Cost versus volume of surfactant used for complete separation for each surfactant mixture and volume of oil used for complete separation for each surfactant mixture.

The manufacturing costs and selling prices were affected the greatest when performing a sensitivity analysis with respect to raw materials. Nevertheless, when performing a sensitivity analysis with respect to labor, the manufacturing costs and selling prices were affected the least. At positive 40-100% sensitivity, the graphs became linear for all variations of the sensitivity analyses performed (Appendix C). The net profit of \$156,000 per year was calculated using critical results obtained from the economic evaluation (Table 1).

Table 1. Critical Results of the Economic Evaluation.

Cost of Equipment (\$)	130,000
Manufacturing Cost (\$/yr)	15,000,000
Selling Price (\$/ton)	87
Return on Investment (%/yr)	4.26
Cash Flow (\$/yr)	522,000
Cash Flow Payout Period (\$/yr)	7
Net Profit (\$/yr)	156,000
Break-even Selling Price (\$/ton)	86.37
Break-even Production Rate (ton/hr)	19.77

6. Conclusions & Recommendations

The technical feasibility and risks of Stage 2 (Detailed Investigation) in the Stage Gate Process has been analyzed. The three-phase surfactant system is advantageous to other separation methods. It is estimated that one ton of contaminated sediment cost \$115-170 to landfill. Given the selling price of \$87 per ton, the proposed process is economically competitive. It is therefore concluded that a pilot plant investigation be initiated for the patent-pending process.

It is recommended that “leaching” of PCBs from the treated sediment should be addressed. All water in the system originates from either the aqueous surfactant solution or contaminated sediment (32 % by mass). Upon termination of the washing process, sediments will leave with a 32 % moisture content and surfactant will be associated with this water. The PCBs remaining in the sediment after cleaning will continue to be encapsulated within the surfactant micelles for the lifetime of the sediment and surfactant. These PCBs are now mobilized much like PCBs distributed between two phases during the extraction process. Since EPA federal regulations require landfilled PCBs bulk waste to not leach into the surrounding ground water, further investigation is needed to ensure remaining PCBs will not move through sediment due to rainfall. Development of an experiment to simulate average rainfall and monitor PCBs movement would be the best way to continue to address legal and regulatory concerns, in compliance with the Stage Gate Process.

In addition, as more money is invested in research, a more accurate model of the three-phase surfactant washing system should be developed. The insufficient amount of experimental data points in the soil remediation process limits the quality of the current program. In order to make a better and more accurate model, more experimental data points would be needed. This will allow for a more tightly fit interpolating function of all the data points and will result in less error.

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Appendix A

Table A-1. Variation of Input Parameters for MATLAB Program

Case	Concentration PCBS in soil (g/kg)	Ratio Surfactant/Sediment (X:1)	Fraction Oil(A) of Surfactant	Quality of Surfactant
1	.500	1.5:1	[.025 .050 .075 .100 .125 .150 .175 .200 .225 .250]	[.04 .05 .06 .07 .08 .09 .10]
2	.500	1.6:1		
3	.500	1.7:1		
4	.500	1.8:1		
5	.500	1.9:1		
6	.500	2.0:1		

Description: We vary only one column at a time. For instance, say we fix the ratio of surfactant to sediment as 2.0:1 and the quality of surfactant to be 7%. We will then take the fraction of oil (A) and vary it from .025 to .250 and record the results.

Appendix B

The mass of PCBS initially was compared to the mass of PCBS at the end. This is done within the code and is the comparison between M1 and M2 in the following program.

```
% Mathematical Model
```

```
% k0,k1,k2,k4 are user defined parameters. In other words, these are put in manually by the user.
```

```
% k4 is fixed in this context, because it follows from Severin's research.
```

```
% k2 varies from .025 to .25 see Appendix A
```

```
% k1 varies from 1.5 to 2 (this is in ratio to the sediment which is 1)
```

```
% Remark: vary only one of the variables at a time
```

```
k0=.07; %the quality of surfactant used
```

```
k1=1.5; %the surfactant vs. sediment
```

```
k2=.025; %the oil vs. surfactant
```

```
k4=.5; %the portion(halfway) of the "experimental cycle," after which oil is changed
```

```
% Defining the masses in terms of the sediment and surfactant
```

```
m1=1; %the total mass of the sediment
```

```
m2=m1*k1; %the total mass of the surfactant
```

```
m3=m2*k2; %the total mass of the oil
```

```
% Recalculation of the surfactant because it gets diluted with the wetness of the soil added.
```

```
k0=k0*m2/(m2+.32*m1); %the new quality of surfactant, resulting from the added water from the sediment
```

```
m2=m2+.32*m1; %the new mass of surfactant, resulting from the added water from the sediment
```

```

% Using the equations from the graphs in Appendix E to generat the concentration ratios
b=.1453*k0^(-.5062);
kss=.64*m1*(b-1)/(.32*m1-b*m2);           %the sediment-surfactantcoefficient,
                                           C2/C1=kss, or p2/p1=kss
m1=.64*m1;                                %the new mass of sediment after all water has been
                                           removed, i.e. the mass of dry sediment
a=.1027*k0^(-1.217);
kso=m2/m3*(1-a)/a;                         %the surfactant-oil coefficient, C3/C2=kso, or p4/p3=kso

% Step size of the amount of surfactant going and returning between tanks
% This could also be varied, again this was chosen by talking with Severin and his
research
t=.1;                                       %fraction of surfactant going for cleaning

% Initial concentration of the PCBS in the sediment
p0=.5;

% Since p1 the concentration of PCBS will be changing, we use p0 as a dummy variable
to retain
% the original concentration as a comparison
p1=p0;                                     %initial concentration of PCBS in sediment (in g per kg)
p20=0.0;                                   %concentration of PCBS in surfactant at the beginning of
                                           current batch of sediment
                                           %it is 0 for the 1st batch and then it is the value of the
                                           output p2
% Initial Mass used for the Mass Balance; this is compared to M2 at the end of the code
M1=p1*m1

% assigning p1 to its new value after taking account of the dry sediment/wet sediment
p1=(p20*m2+p1*m1)/(m1+kss*m2); %concentration of PCBS in sediment (in g per kg)
p2=kss*p1;                                 %concentration of PCBS in surfactant
pt=p2;                                     %the test concentration
p3=0;                                      %concentration of PCBS in the return batch of surfactant
p4=0;                                      %concentration of PCBS in oil
j=0;

% This loop determines the amount of equilibriums encountered without changing the oil
for 95% removal of PCBS from
% the sediment
while p3<.99*pt                            % this compares the conc. of the PCBS in the outgoing surfactant
                                           with the conc. of the
                                           % PCBS in the returning surfactant. Note the computer cannot
                                           compare exactly. So,.99 was used instead of equality

pt=p2;
p3=(p4*m3+p2*t*m2)/(t*m2+kso*m3);         %the concentration of PCBS in the return
                                           batch after the redistribution
p4=kso*p3;                                 %the concentration of PCBS in the oil after the batch
departs
p2=p2*(1-t)+p3*t;                          %the concentration of PCBS in surfactant in the 1st tank
                                           right after the batch returned

```

```

p1=(p2*m2+p1*m1)/(m1+kss*m2); %the concentration of PCBS in sediment
                                after redistribution
p2=kss*p1; %the concentration of PCBS in surfactant after the
                                redistribution
j=j+1;
end;

% this value "l" is the value that will force the next loop to stop when it reaches the
"halfway" point
l=round(k4*j); %this is how long every cycle between oil changes is going
to be

%reset all the parameters; the experimental cycle is over.
p1=(p20*m2+p0*m1)/(m1+kss*m2); %concentration of PCBS in sediment (in g per kg)
p2=kss*p1; %concentration of PCBS in surfactant
pt=p2; %the test concentration
p3=0; %concentration of PCBS in the return batch of
surfactant

% Note from one batch to the next, the value at the end of the previous batch must be
inserted as p4's value. We use pf at the end of the program to store the value that gets
placed into p4 the next iteration

p4=0;

% initializing counter of oil changes
n=-1;

% after each oil change calculate the percent of PCBS left in the sediment. When less
than 5% is left or 95% is removed, then exit the loop

while p1/p0>.05 % p1/p0 is the ratio of the final amount of PCBS in sediment to the
original one
n=n+1; %the number of oil changes
i=0;
while i<=l
p3=(p4*m3+p2*t*m2)/(t*m2+kso*m3); %the concentration of PCBS in the
return batch after the redistribution
p4=kso*p3; %the concentration of PCBS in the
oil after the batch departs
p2=p2*(1-t)+p3*t; %the concentration of PCBS in surfactant in the 1st
tank right after the batch returned
p1=(p2*m2+p1*m1)/(m1+kss*m2); %the concentration of PCBS in sediment
after redistribution
p2=kss*p1; %the concentration of PCBS in surfactant after the
redistribution
i=i+1;
end
pf=p4;
p4=0; %new oil (with no PCBS) is put in -- oil change

```

end;

% output the number of oil changes, the percent of PCBS remaining, and the concentration of the oil at the end of one batch. Remember that pf needs to replace p4 for the next batches

n, p1/p0, pf

% Mass balance check with M1 from above

$$M2 = m1 * p1 + m2 * p2 + m3 * pf$$

% Retention value for the fraction of surfactant used initially in the next batch

$$k0 = 1.5 * (k0) / 1.82$$

Appendix C

Economic Analysis of MBI International Pollution Remediation Project

	Cost (\$/yr)
Oil Incineration (\$1000/ton)	3,412,201
Total Process & Utilities Investment	3,412,201
Interest on Capital loan at 7% per year, construction period of 6 months with interest on total fixed capital for one half of this period	238,854
Analytical costs	10,000
Total Depreciable Capital	3,661,055
Working Capital (10% Equip. Cost)	13,000
Total Capital Investment	3,674,055
<u>Variable Costs</u>	
<u>Feed Materials</u>	
Surfactant (\$7.00/gal)	10,002,868
Sacrificial Oil (\$0.40/lb)	2,729,744
Water (\$1.00/1000gal)	30,747
Soil (\$10/ton)	1,650,923
Total Feed	14,414,281
<u>Utilities</u>	
Electricity (\$0.08/kWh)	2,462
Total Utilities	2,462
Total Variable Costs	14,416,743
<u>Fixed Costs</u>	
<u>Labor</u>	
Operating (2 men/shift @ \$20/hr & 35% fringe)	341,583
Total Labor	341,583
<u>Miscellaneous Costs</u>	
Maintenance materials (5% Equip. Cost)	6,500
Operating materials	not applicable
General Overhead	not applicable
Local Taxes and Insurance	not applicable
Total Miscellaneous Costs	6,500
Total Fixed Costs	348,083

Calculations (Manufacturing excluding interest on Working Capital)

$$Manuf.Cost(1) = total\ variable\ cost + total\ fixed\ cost + \frac{total\ depreciable\ capital}{10}$$

Manufacturing Cost (\$/yr.) 15,130,932

Calculations (Manufacturing including interest on Working Capital)

$$Manuf.Cost(2) = Manuf.Cost(1) + 0.07 * Working\ Capital$$

Manufacturing Cost (\$/yr.) 15,131,842

Calculations

Let Selling Price = X (\$/ton)

MC=Manufacturing Cost

GP=Gross Profit

IT=Income Tax

Rev.=Revenue

NP=Net Profit

T_R=Tax Rate

CF=Cash Flow

Dep.=Depreciation

i=interest

TCI=Total Capital Investment not including land

WC=Working Capital

TDC=Total Depreciable Capital

C=Capacity

Revenue=X*C (3)

GP=Rev.-MC (4)

NP=GP-IT (5)

IT=GP*T_R (6)

Put (6) into (5)

NP=GP(1-T_R) (7)

Put (3) into (4)

GP=X-MC (8)

Put (8) into (7)

NP=[X-MC](1-T_R) (9)

where T_R=0.07

CF=NP+Dep. (10)

Put (9) into (10)

CF=[X-MC]*0.93+Dep.

Depreciation	10yr., straight line
Interest on Working Capital	0.07
Taxation Rate	0.07
Cash flow (\$/yr.)	522,162
Cash flow payout period (CFPP) (yrs.)	7.01
Return on Investment (ROI) (%/yr.)	4.26
Interest (i)	0.07
Selling Price (\$/ton)	87.33
Break-even selling price (\$/yr.)	86.37
Solver Reference Cell	0
Solver Reference Cell	0
Break-even production rate (\$/yr.)	19.77
Net Profit (\$/yr.)	156,056
Gross Profit (\$/yr.)	167,803
Equipment cost (\$)	130,000

$$ROI = \frac{NP}{TDC}$$

$$CFPP = \frac{TDC}{\frac{TDC}{10} + NP}$$

Selling Price (X)

87.32673673

Calculating selling price
(Including WC)

$$TCI * (1 + i)^{10} = CF \left[\frac{(1 + i)^9 + (1 + i)^8 + (1 + i)^7 + (1 + i)^6 + (1 + i)^5}{+ (1 + i)^4 + (1 + i)^3 + (1 + i)^2 + (1 + i) + 1} \right] + WC$$

Left Side

7227423.035

Right Side

7227423.035

Left - Right

0

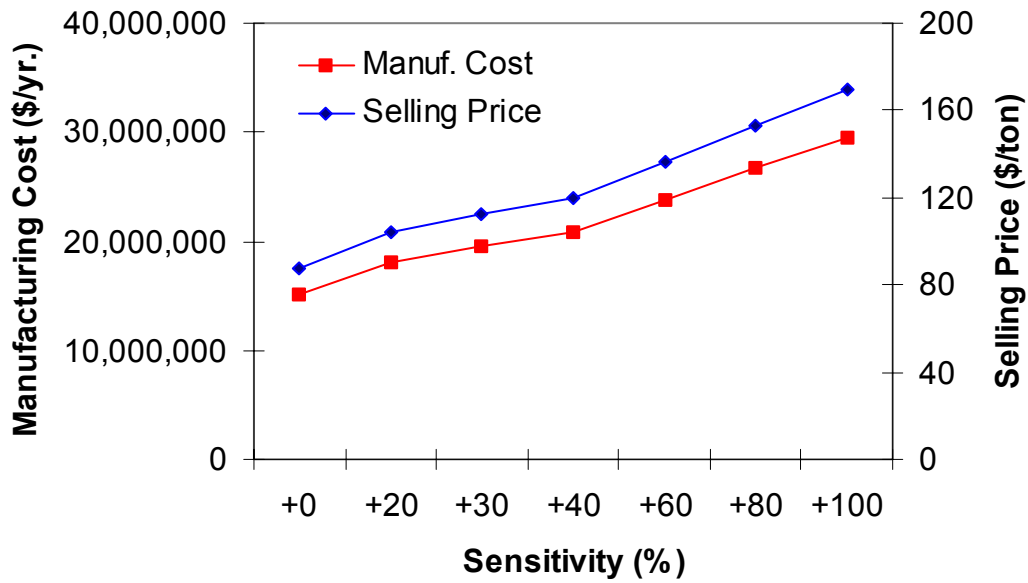


Figure C-1. Sensitivity analysis via Feed Materials.

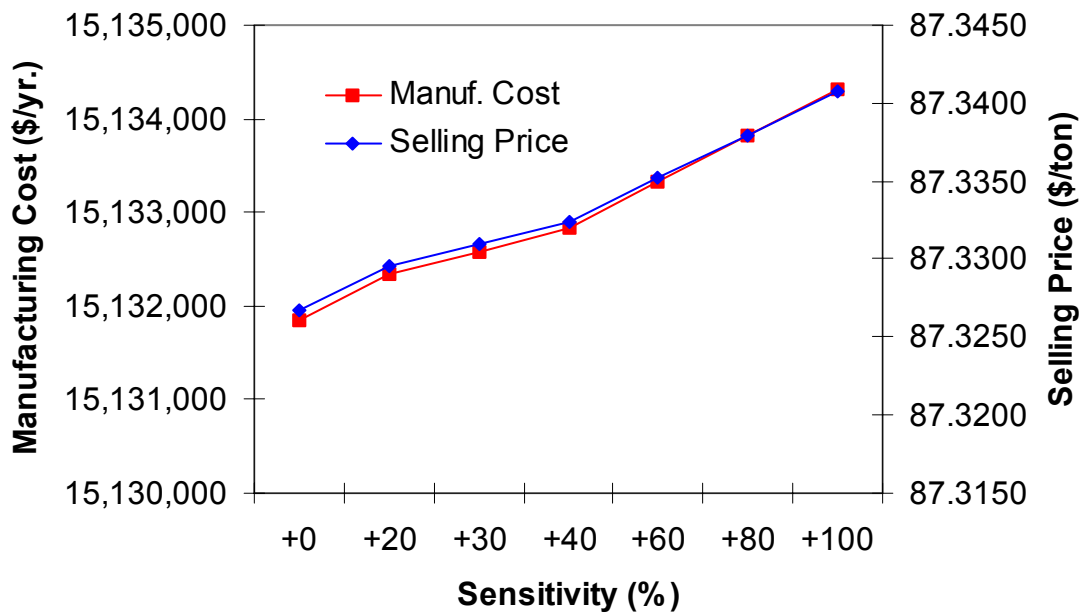


Figure C-2. Sensitivity analysis via utilities.

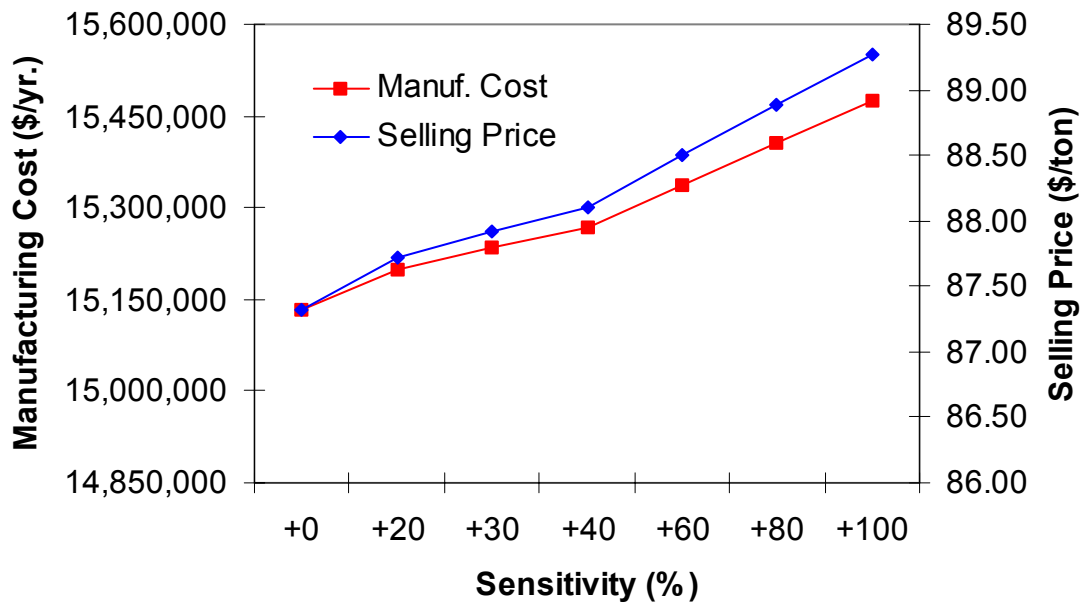


Figure C-3. Sensitivity analysis via utilities.

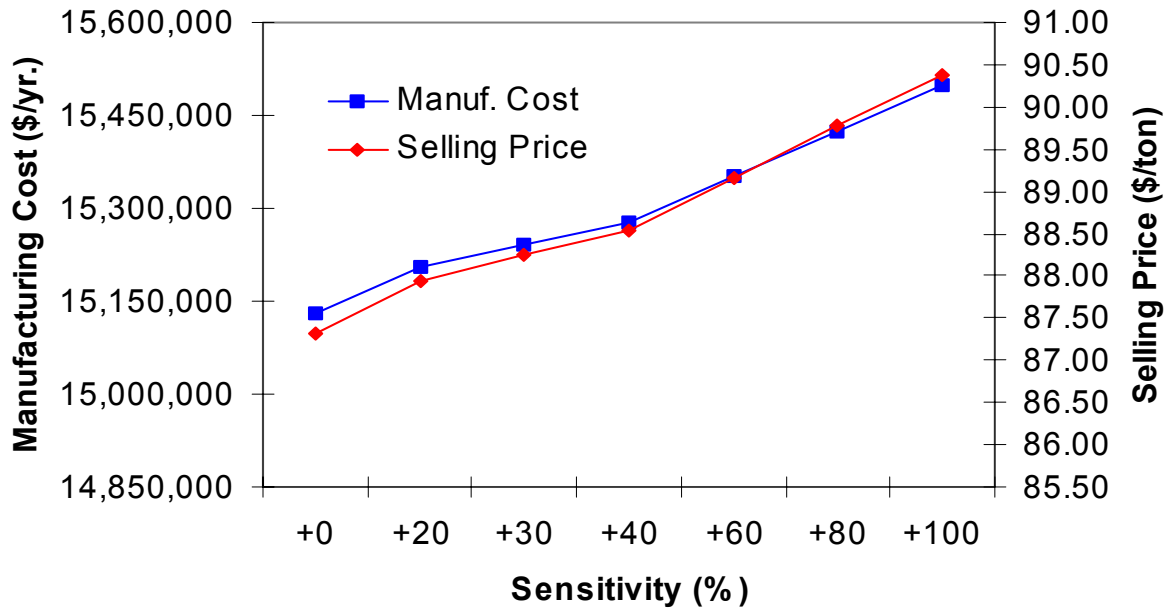


Figure C-4. Sensitivity analysis via capital investment.

Appendix D

Sample Calculations for Economic Analysis:

Calculating cost of feed materials:

$$\begin{aligned}
 \text{- Cost of Surf.} &= (\% \text{ of surf. from aqueous}) + \\
 & \quad (\text{gal/hr of surf.}) (\text{cost of surf./gal}) \left(\frac{24 \text{ hrs}}{\text{day}}\right) \left(\frac{365 \text{ days}}{\text{yr}}\right) \left(\frac{49}{52}\right) \\
 &= 237.753 \% \text{ yr} + (173.08 \text{ gal/hr}) \left(\frac{24 \text{ hrs}}{\text{day}}\right) \left(\frac{365 \text{ days}}{\text{yr}}\right) \left(\frac{57}{94}\right) \left(\frac{49}{52}\right) \\
 &= \$10,002,868 / \text{yr}
 \end{aligned}$$

$$\begin{aligned}
 \text{- Cost of Oil} &= (\text{kg/hr of oil used}) (2.20462 \text{ lb/kg}) (\text{cost of oil/lb}) \left(\frac{24 \text{ hrs}}{\text{day}}\right) \left(\frac{365 \text{ days}}{\text{yr}}\right) \left(\frac{49}{52}\right) \\
 &= \left(\frac{375 \text{ kg}}{\text{hr}}\right) (2.20462 \text{ lb/kg}) (\$8.40 / \text{lb}) \left(\frac{24 \text{ hrs}}{\text{day}}\right) \left(\frac{365 \text{ days}}{\text{yr}}\right) \left(\frac{49}{52}\right) \\
 &= \$2,729,744 / \text{yr}
 \end{aligned}$$

$$\begin{aligned}
 \text{- Cost of Water} &= (\text{gal/hr of water}) (\text{cost of water/gal}) \left(\frac{24 \text{ hrs}}{\text{day}}\right) \left(\frac{365 \text{ days}}{\text{yr}}\right) \left(\frac{49}{52}\right) \\
 &= (3724.80 \text{ gal/hr}) (\$1000 / \text{gal}) \left(\frac{24 \text{ hrs}}{\text{day}}\right) \left(\frac{365 \text{ days}}{\text{yr}}\right) \left(\frac{49}{52}\right) \\
 &= \$30,747 / \text{yr}
 \end{aligned}$$

$$\begin{aligned}
 \text{- Cost of Sediment} &= (\text{ton/hr of sed.}) (\text{cost of sed./ton}) \left(\frac{24 \text{ hrs}}{\text{day}}\right) \left(\frac{365 \text{ days}}{\text{yr}}\right) \left(\frac{49}{52}\right) \\
 &= \left(\frac{20 \text{ tons}}{\text{hr}}\right) (\$10 / \text{ton}) \left(\frac{24 \text{ hrs}}{\text{day}}\right) \left(\frac{365 \text{ days}}{\text{yr}}\right) \left(\frac{49}{52}\right) \\
 &= \$1,650,923 / \text{yr}
 \end{aligned}$$

- Calculating volume of aqueous layer assuming the density of surfactant is equal to 1 g/cm^3 .

$$\text{density conversion: } \left(\frac{1 \text{ g}}{\text{cm}^3}\right) \left(\frac{1 \text{ kg}}{1000 \text{ g}}\right) \left(\frac{1 \times 10^6 \text{ cm}^3}{264.17 \text{ gal}}\right) = d$$

$d = m/V$ where m and V are mass and volume

$$\begin{aligned}
 V &= m/d \\
 V &= 15000 (\text{kg/hr}) / d = 3960.55 \text{ kg/gal}
 \end{aligned}$$

Sample calculations for economic analysis (cont.):

- Calculating operating cost at \$20/hr + 35% surge

$$\text{operating cost} = \underbrace{(\text{men/shift})(\text{cost/hr})(24\text{hr/day})}_{A} \left(\frac{365\text{days}}{\text{yr}} \right) (49\%) + 0.35A$$

$$= (2\text{ men/shift})(20\text{ \$/hr}) \left(\frac{24\text{hr}}{\text{day}} \right) \left(\frac{365\text{days}}{\text{yr}} \right) (49\%) + 0.35A$$

$$= 341,583\text{ \$/yr. for 6 men}$$

(Since there is 3 shifts in a day this would be the salary for 6 men per year.)

- To calculate selling price the following 2 eqns were used (also see excel spreadsheet for acronym)

(1) Cash Flow - (Selling Price - Manuf. Cost) * 0.93 + Depreciation

(2) $TCI * (1+i)^n = CF \left[\frac{(1+i)^n - 1}{i} \right] + WC$

Eqn (1) was placed into eqn (2), and excel's "solver" was used to find the only unknown, which is the selling price by telling solver to set the left-hand side of eqn (2) minus the right-hand side of eqn (2) equal to zero.

- Calculating Break-even selling Price (let X = selling price)

$$\text{Gross Profit} = \text{Revenue} - \text{Manufacturing Cost} = 0$$

$$= (X)(20)(24)(365)(49\%) - 15,131,942$$

$$X = 86.37\text{ \$/ton}$$

Sample Calculations for Economic Analysis (cont)

Calculating Break-even Production Rate:
(Let Z be the production rate)

$$\text{Gross Profit} = \text{Revenues} - \text{Manufacturing cost} = 0$$
$$= (\text{Selling Price})(Z)(24)(365) - \left[\text{Fixed Costs} + \text{Variable Cost} \left(\frac{Z}{20 \frac{\text{tons}}{\text{hr}}} \right) \right] + \frac{\text{TDC}}{16} + 0.7 \text{WC}$$

Using Solver

$$Z = 19.77 \text{ ton/hr.}$$

New mass of surf. solution resulting from the added water from the sediment

$$\tilde{m}_2 = m_2 + \underbrace{.32 \text{ ml}}_{\substack{\text{mass of} \\ \text{original} \\ \text{surf. solution}}} \underbrace{\quad}_{\substack{\text{mass of water in soil}}}$$

New mass of sediment or dry sediment

$$\tilde{m}_1 = \underbrace{.64 \text{ ml}}_{\substack{\text{original} \\ \text{sediment}}}$$

Solving for C_2/C_1^*

$$\frac{C_2 m_w + C_1^* m_s}{C_2 m_w + C_1^* m_s + C_2 m_2} = b$$

$$C_2 m_w + C_1^* m_s = b (C_2 m_w + C_1^* m_s + C_2 m_2)$$

↓
from data graphs

$$C_2 m_w - b C_2 m_w - b C_2 m_2 = b C_1^* m_s - C_1^* m_s$$

$$C_2 (m_w - b m_w - b m_2) = C_1^* (b m_s - m_s)$$

$$C_2 (m_w (1-b) - b m_2) = C_1^* m_s (b-1)$$

$$m_2 = \tilde{m}_2 - m_w \quad \frac{C_2}{C_1^*} = \frac{m_s (b-1)}{m_w (1-b) - b m_2} = \frac{m_s (b-1)}{m_w (1-b) - b (\tilde{m}_2 - m_w)}$$

$$= \frac{m_s (b-1)}{m_w - b m_w - b \tilde{m}_2 + b m_w}$$

$$= \frac{m_s (b-1)}{m_w - b \tilde{m}_2}$$

↳ In Matlab $m_2 = m_2 + .32 \text{ ml}$ assigns the new value to m_2 .

Solving for C_3/C_2

$$\frac{C_2 m_2}{C_2 m_2 + C_3 m_3} = a$$

$$C_2 m_2 = a(C_2 m_2 + C_3 m_3)$$

$$C_2 m_2 - a C_2 m_2 = a C_3 m_3$$

$$C_2 m_2 (1 - a) = a C_3 m_3$$

$$\frac{m_2 (1 - a)}{m_3 a} = \frac{C_3}{C_2}$$

The following equation is for the amount of surfactant to add at the end of each batch. It is done for 0.04 fraction of surfactant volume in water and accounts for dilution.

$$\frac{18200 (.033 - .027)}{.04} = A$$

We obtained .027 from recalculating the concentration of PCB in the screw washer tank when the new batch is added, but no new surfactant.

$$\frac{15000 (.033)}{18200} = .027$$