Design and Evaluation of Engineering Systems to Remove VOCs From Groundwater

IPRO 296/496-304B
Spring 2003
Problem Statement

- Desired clean up of trichloroethylene (TCE) from groundwater at Wurtsmith AFB located in Oscoda, Michigan
- Investigate the most cost-effective and reliable treatment technology at full-scale performance
  - minimizes energy requirements
  - costs associated with the construction and operation of various control systems
Trichloroethylene

- $C_2HCl_3$ (131.30 g/mole.)
- Removes grease from metal parts
- Found in adhesives, spot removers, and typewriter correction fluid

Drinking or breathing high levels of trichloroethylene may cause nervous system effects, liver and lung damage, abnormal heartbeat, coma, and possibly death.

Reason for proper disposal and remediation
Requirements

- 95% removal of TCE
- Other removal efficiencies based on the drinking water regulations
- Drinking water standards for TCE vary from $1.5 \mu g/l$ to $5 \mu g/l$ in individual states
  - Michigan’s discharge limit: $1.5 \mu g/l$
Methodology

- Ion exchange
- Membrane separation
- Biological treatment
- Carbon Sorption and Air Stripping
- Oxidation
- Distillation
- Phytotremediation
Carbon Sorption Design

- Carbon sorption operates on equilibrium equations between liquid and solid phases
- The governing mole balance equation is an empirical equation known as the Freundlich isotherm
Physical Process

- Water passes through granular activated carbon (GAC)
- TCE binds to GAC surface up to saturation
- Carbon is then thermally regenerated or replaced

GAC is a processed material with a very high surface to volume ratio
Design Method

- System with large flow rate (4500 L/min)
- Achieved by empirical equations
  - Summers
  - Snoyienk
  - Eckenfelder

- MTZ: mass transfer zone
- EBCT: empty bed contact time
Design

- MTZ and EBCT are a function of the approach velocity
- Approach velocity is a function of the volume of flow, a constant in our case, and of the total cross-sectional area of the carbon sorption units
- Pressure drop constraint 18 inches H$_2$O per bed due to potential GAC crushing
Estimates of MTZ and EBCT

EBCT and MTZ vs V approach

y = 1.9753x  
$R^2 = 1$  
12.83

y = 0.2989x - 0.6726  
$R^2 = 0.9897$  
EBCT (minutes)  
MTZ Length (meters)  
Linear (EBCT (minutes))  
Linear (MTZ Length (meters))
Physical Parameters

- Approach velocity and total cross-sectional area as controlling variables for the system physical parameters:
  - bed volume
  - bed length
  - total overall length
  - pressure drop
Costing of Carbon Sorption

- Costing models provided by EPA
- Costing variables: volume and flow rate
- Volume and flow rate are directly related to design variables
Trends

- Lower approach velocity leads to lower capital costs and electricity costs

- Operating costs are a function of two opposite variables: frequency of carbon changes and bed volume

- End result: Costing curves highly sensitive to changes in approach velocity
Overall Costing Curves

Annual Costs

Approach Velocity (m/hr)

Annual Cost (dollars)

22 ft
16 ft
14 ft
12 ft
10 ft
Poly. (10 ft)
Poly. (12 ft)
Poly. (16 ft)
Poly. (14 ft)
Poly. (22 ft)
Electrical Cost

Electrical Cost Sensitivity to Velocity

\[ y = 1156x^2 - 5345.5x + 7948.3 \]

\[ R^2 = 0.9998 \]
Cost Sensitivity to Concentration

Effect of Concentration on Carbon Costs

Sorption is not very sensitive to concentrations changes!
Two Design Options

Aggressive
- $42,000/year
- 2 cylindrical units in series
- 22 ft diameter
- MTZ 0.45 m
- EBCT 7.8 minutes
- Velocity 3.25 m/hr

vs.

Conservative
- $50,000/year
- 2X2 (2 units parallel/ 2 units in series)
- 14 ft diameter
- MTZ 0.85 m
- EBCT 9.88 minutes
- Velocity 5 m/hr
Advantages and Limitations

- Robust, well studied concept
- Few operating parts
- Easy adaptation to concentration levels
- Has already met Michigan regulations at this very site

- Isothermal operation
- Interfering organic compounds
- Low or high pH
- Offsite carbon regeneration
Mass Transfer Coefficient
\((K_L a)\)

\[
\frac{1}{K_L a} = \frac{1}{H' k_g a} + \frac{1}{k_L a}
\]

- \(H', k_g, k_L,\) and \(a\) are determined with fluid properties (density, viscosity, etc.) and dimensionless quantities (Reynolds Number, etc.)

- This quantity is critical to find the correct packed bed volume
Packed Bed Volume

\[ V = Z \times A = L \left( \ln \left[ \frac{c_1}{c_2} - \frac{LRTa}{GH} \left( \frac{c_1}{c_2} - 1 \right) \right] \right) \]

- G/L is the gas to liquid ratio, critical for optimization
- Note the mass transfer coefficient in the denominator
- \(c_1\) and \(c_2\) denote inlet and outlet concentrations of TCE in the water
Pressure Drop

Parameter of curves is pressure drop in inches of water/foot of packed height

\[
\frac{G^2 F}{A (\frac{w}{g})} 
\]

\[
(L/G) (\frac{A}{w})^{1/2} 
\]
Packing

- State of the art Tri-Pak Packing to be used
- Bigger packing needed due to large inlet flow
- 12:1 optimum diameter ratio (tank - packing)
- Mass Transfer coefficient and pressure drop dependent on packing choice
Air Stripper Cost Estimate

- Capital costs estimated using Ulrich’s costing charts (1984)
- Amortized at 10% over 15 years
- Operating costs based on power requirements calculated using HYSYS
- Electricity rate for Oscoda, MI: $0.08235/kWh
- Costs compared as function of G/L ratio
Functional Cost Comparison

Cost Comparison for various G/L ratios

- Annual Cost ($)
- Amortized Cost
- Operating Cost

G/L vs. Annual Cost ($)
Cost Comparison

Cost Comparison for various G/L ratios

Annual Cost ($)

G/L
Functional Cost Comparison

<table>
<thead>
<tr>
<th>Capital cost for vessel</th>
<th>G/L</th>
<th>30</th>
<th>33</th>
<th>35</th>
<th>37</th>
<th>40</th>
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<td>35</td>
<td>37</td>
<td>40</td>
<td>45</td>
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</tbody>
</table>
Final Stripper Design

Tower diameter: 1.067 m
Bed height: 5.98 m
Tower height: 7.18 m

WATER IN
4540 Liters/minute
[TCE]=5.0 \times 10^{-4} g/L

AIR OUT
158900 Liters/minute

WATER OUT
4540 Liters/minute
[TCE]=1.5 \times 10^{-6} g/L

AIR IN
158900 Liters/minute
[TCE]=0.0 g/L
Conclusion

- Carbon Sorption vs. Air Stripping
  - Tough competition
- Most cost-effective design is the Air Stripping Column
- Do Not Pollute, saves $$$!!!
Accomplishments of Senior Team Members

- Research of unit operations
- Design of unit operations
- Costing of chosen designs
- Working together with sophomore team members
- Utilizing everyone’s knowledge to accomplish a common goal
Accomplishments of Sophomore Team Members

- Working with a team that involves delegation of tasks
- Apply classroom material to real-life situations
- Learning more about different unit operations and design process
- Cost estimation
- IPRO process as a whole
Acknowledgements

Dr. Kenneth E. Noll

Professor J. Abbasian
The End

Any Questions???