Passive Treatment of Coal-mine Drainage by a Sulfate-reducing Bioreactor in the Illinois Coal Basin

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Tab-Simco is an abandoned coal mine located in the Illinois Basin 3.2 km southeast of Carbondale, Illinois, USA.

Source: U.S. Geological Survey
Geology of the Project Area

- **Geologic Setting**: Located on a dissected, low plateau underlain by coal-bearing Pennsylvanian System.

- **Surficial Geology**: Plateau areas are capped by 1 to 21 meter thick mantle of unconsolidated glacial till of the Illinoian Glasford Formation.

- **Shallow Bedrock**: A series of sandstone, shale, siltstone, claystone and coal of the Spoon Formation and underlying Abbot Formation.
Coal Mining History

**Underground Mining:** Between the 1890’s and early 1955 mined - the 2.5 m (8.2 ft) thick Murphysboro Coal and the overlying discontinuous 0-1.5 m (4.9 ft) thick Mt. Rorah Coal.

**Surface Mining:** Contour-type surface mining by the Tab and SIMCO coal companies during the 1960-s and 1970’s in a horseshoe-shaped pattern removed coal in the outcrop barrier and “daylighted” some of the old underground workings.
Tab-Simco Underground Mine Workings

Tab-Simco Problem Identification:

- **Mine Pool**: The old underground workings are partially flooded with seasonal fluctuations and contains 40,000-77,000 m³ (10.6-20.3 million gallons) of acidic, metal-laden water (Smith, 2004).

- **Acid Seeps**: North Seep at 1.2 LPS (19 GPM) (pH= 2.4; total acidity = 1,816 mg/L CCE, median values).

- **Kill Zone**: 3.7-ha (9-acre) area was devoid of vegetation and covered with acid salts.

- **Sycamore Creek**: 3.2 km (2 miles) were impacted with acidic water and metal precipitates.
Mine Pool and Main Acid Seep

### Baseline Data:

**North Seep**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value* (median)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>2.40</td>
<td></td>
</tr>
<tr>
<td>SpCon</td>
<td>3,645</td>
<td>$\mu$S/cm</td>
</tr>
<tr>
<td>D. Fe.</td>
<td>389.3</td>
<td>mg/L</td>
</tr>
<tr>
<td>D. Al</td>
<td>123.2</td>
<td>mg/L</td>
</tr>
<tr>
<td>Tot. Mn</td>
<td>27.9</td>
<td>mg/L</td>
</tr>
<tr>
<td>Tot. Acidity</td>
<td>1,631</td>
<td>mg/L</td>
</tr>
<tr>
<td>Sulfate</td>
<td>2,188</td>
<td>mg/L</td>
</tr>
</tbody>
</table>

* Number of samples (n) = 8.

Flow = 1.2 liters per second (19 gpm)
Problem ID: 3.7-ha (9-acre) “Kill Zone”
## Sycamore Creek Impacts

### Downstream Sample Site

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value* (low flow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>2.92</td>
</tr>
<tr>
<td>SpCon</td>
<td>2,350</td>
</tr>
<tr>
<td>Tot. Fe.</td>
<td>109.0</td>
</tr>
<tr>
<td>Tot. Al</td>
<td>56.6</td>
</tr>
<tr>
<td>Tot. Mn</td>
<td>28.9</td>
</tr>
<tr>
<td>Tot. Acidity</td>
<td>705.97</td>
</tr>
</tbody>
</table>

* October 26, 2005

Sycamore Creek prior to passive treatment system construction.
Timeline: AMD remediation at the Tab-Simco Mine Site

- **2005-2007:** Site investigation and design Illinois DNR/Office of Mines and Minerals/OSM/SIUC.
- **Fall 2007:** Passive treatment system designed and constructed.
- **Winter 2007-Present:** Post-construction evaluation.
- **2012:** OSM awarded a cooperative agreement with SIUC.
Passive Treatment System Construction

- A major shortfall of the passive remediation technologies is the inability of providing long-term (> 10 year) treatment of drainage with high metal and Al (>20 mg/L) contents.
- Operational problems arise from plugging by precipitates, dissolution or coating of available carbonate minerals, and exhaustion of the organic carbon source.
Selected Solution: AMD Passive Treatment System

- **Stage 1:** The principle technology employed was a 0.3-ha (0.75-acre) Sulfate Reducing Bioreactor: Reduce sulfate, iron, and aluminum, add alkalinity and increase pH.

- **Stage 2:** Deep Oxidation Pond
  Oxidize remaining ferrous iron and store iron precipitates.

- **Stage 3:** Surface Flow Wetlands –
  Complete iron oxidation and precipitation.

- **Stage 4:** Open Limestone Drain –
  Aerate discharge and lower manganese levels.
Tab-Simco Bioreactor Cell Construction

ORGANIC MIXTURE COMPOSED
OF:
(1) 53% wood chips
(2) 9% agricultural ground limestone
(3) 27% straw mulch
(4) 11% seasoned compost

TYPICAL SECTION THROUGH ANEROBIC BIOREACTOR CELL
2007 Bioreactor Construction

Under Drain Construction

Compost Placement - 5,887 m³ (7,700 cubic yards)
Overview of the Passive Treatment System looking North from the edge of the Plateau.
Stage 1: Sulfate Reducing Bioreactor

- Reduce sulfate and iron; add bicarbonate (HCO$_3^-$) alkalinity – The principle processes are:
  - Anaerobic microbial sulfate reduction CH$_2$O representing biodegradable organic compounds).
    \[ 2 \text{CH}_2\text{O} + \text{SO}_4^{2-} \rightarrow \text{H}_2\text{S} + 2 \text{HCO}_3^- \]
  - Limestone dissolution.
    \[ \text{CaCO}_3 + \text{H}^+ \rightarrow \text{Ca}^{2+} + \text{HCO}_3^- \]
- Bicarbonate neutralizes the acidity--raising pH and increasing the precipitation of metals such as Fe and Al.
  \[ \text{HCO}_3^- + \text{H}^+ \rightarrow \text{H}_2\text{O} + \text{CO}_2 \text{ (aq)} \]
Stage 1: Sulfate Reducing Bioreactor - Metal removal processes.

- Hydrogen sulfide readily dissolves in water and combines with divalent metals (Me), such as Fe, Ni, and Zn, to form sulfide mineral precipitates MeS according to the following reaction:
  \[ \text{H}_2\text{S}_{(aq)} + \text{Me}^{2+} \rightarrow \text{MeS}_{(s)} + 2 \text{H}^+ \]
- Adsorption of metals on clay minerals, metal hydroxides and organic matter within the bioreactor.
- Cation exchange reactions.
Sequestration of Metals: Iron

Discharge of suspected FeS from the bioreactor; possible reaction within pond sediments:

\[ \text{FeS} + \text{S} \leftrightarrow \text{FeS}_2 \]

(iron monosulfide*) (pyrite)

*Intermediate precursors such as Mackinawite \([(\text{FeNi})_{1+x}\text{S}]\) (where \(x = 0 - 0.11\)) and Greigite \([\text{Fe(II)Fe(III)}_2\text{S}_4]\) are expected.
Stage 2: Deep Oxidation Pond
Stage 3: Surface Flow Wetlands

**Goal:**
Oxidize remaining ferrous iron and store iron precipitates;

Possible reactions:
\[ Fe^{+2} + 3 \text{H}_2\text{O} \leftrightarrow Fe(\text{OH})_3 + 3\text{H}^+ \]

\[ 4 \text{Fe}^{+2} + \text{O}_2 \text{(aq)} + 10 \text{H}_2\text{O} \leftrightarrow 4 \text{Fe(OH)}_3 + 8\text{H}^+ \]
Sample locations: Tab-Simco Passive Treatment System

Legend
- Waterway
- Sample Point
- Bioreactor
- Surface Mine
- AMD Kill Zone
- Underground Mine

Map showing sample locations and features of the Tab-Simco Passive Treatment System.
# Performance Data: Tab-Simco Passive Treatment System, Illinois*

<table>
<thead>
<tr>
<th>Site ID</th>
<th>pH</th>
<th>D. Fe</th>
<th>D. Mn</th>
<th>D. Al</th>
<th>D. Ni</th>
<th>D. Zn</th>
<th>Acidity</th>
<th>Alk.</th>
<th>SO₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Seep</td>
<td>2.83</td>
<td>654.2</td>
<td>38.4</td>
<td>173.5</td>
<td>2.25</td>
<td>2.87</td>
<td>2,551</td>
<td>0</td>
<td>3,563</td>
</tr>
<tr>
<td>Bioreactor In</td>
<td>2.93</td>
<td>606.5</td>
<td>39.3</td>
<td>147.1</td>
<td>2.48</td>
<td>2.64</td>
<td>2,313</td>
<td>0</td>
<td>3,913</td>
</tr>
<tr>
<td>Well B2</td>
<td>2.85</td>
<td>287.3</td>
<td>34.6</td>
<td>98.2</td>
<td>1.33</td>
<td>1.92</td>
<td>1,306</td>
<td>0</td>
<td>2,373</td>
</tr>
<tr>
<td>Bioreactor In/B2 Mix</td>
<td>2.89</td>
<td>446.9</td>
<td>37.0</td>
<td>122.7</td>
<td>1.91</td>
<td>2.28</td>
<td>1,760</td>
<td>0</td>
<td>3,143</td>
</tr>
<tr>
<td>Bioreactor Out</td>
<td>6.34</td>
<td>113.0</td>
<td>32.5</td>
<td>0.85</td>
<td>0.07</td>
<td>0.12</td>
<td>275.8</td>
<td>289</td>
<td>2,099</td>
</tr>
<tr>
<td>System Out</td>
<td>5.79</td>
<td>6.80</td>
<td>24.6</td>
<td>0.96</td>
<td>0.16</td>
<td>0.25</td>
<td>71.0</td>
<td>27.3</td>
<td>1,691</td>
</tr>
</tbody>
</table>

*2007 through 2011; All values except pH are in mg/L; acidity and alkalinity (Alk.) are calcium carbonate equivalent values or CCE; acidity = calculated acidity.
Changes in Acidity and Alkalinity

Acidity has dropped from a median 1,647 to 64.6 mg/L CCE, a 96.1% improvement.

Median Alkalinity at the bioreactor discharge is used to offset the remaining metal acidity.
Changes in Sulfate and Bicarbonate values within the Treatment System

The discharge remains a median of 1,750 mg/L. Alkalinity generated by the bioreactor is used up in the oxidation structures.
Median Loading and Removal Rates

<table>
<thead>
<tr>
<th>Site ID</th>
<th>D. Fe (moles/m³/day)</th>
<th>D. Al (moles/m³/day)</th>
<th>D. Mn (moles/m³/day)</th>
<th>D. Ni (moles/m³/day)</th>
<th>D. Zn (moles/m³/day)</th>
<th>Cumulative Metals</th>
<th>SO₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioreactor Loading* Rate</td>
<td>0.168</td>
<td>0.092</td>
<td>0.014</td>
<td>0.0007</td>
<td>0.0007</td>
<td>0.261</td>
<td>0.670</td>
</tr>
<tr>
<td>Bioreactor Removal Rate</td>
<td>0.120</td>
<td>0.091</td>
<td>0.0020</td>
<td>0.0006</td>
<td>0.0007</td>
<td>0.212</td>
<td>0.215</td>
</tr>
<tr>
<td>Removal (%)</td>
<td>71.2</td>
<td>99.3</td>
<td>14.0</td>
<td>96.3</td>
<td>94.7</td>
<td>81.2</td>
<td>32.1</td>
</tr>
<tr>
<td>Oxidation Cell Load Rate</td>
<td>0.148</td>
<td>0.083</td>
<td>0.0127</td>
<td>0.0005</td>
<td>0.0006</td>
<td>0.2321</td>
<td>0.6139</td>
</tr>
<tr>
<td>Oxy. Cell Removal Rate</td>
<td>0.160</td>
<td>0.090</td>
<td>0.0014</td>
<td>0.0005</td>
<td>0.0007</td>
<td>0.251</td>
<td>0.663</td>
</tr>
<tr>
<td>Cum. Removal (%)</td>
<td>99.9</td>
<td>99.2</td>
<td>36.2</td>
<td>89.8</td>
<td>89.5</td>
<td>99.6</td>
<td>42.8</td>
</tr>
</tbody>
</table>

*Bioreactor inlet channel and B2 mix.
Sulfate Removal (SIU, 2010 Study)

- 32.1% of the $\text{SO}_4^{2-}$ is removed by the bioreactor cell (2008-2011).

- $\delta^{34}\text{S}$ value of $\text{SO}_4^{2-}$ increased in the bioreactor from an average value of 6.9‰ (inlet) to 9.2‰ (outlet), suggesting the presence of bacterial sulfate reduction processes (Segid, 2010).
Sulfate Removal Rates - Summary

- McCauley et al. (2009) reported an average sulfate removal rate of 0.308 moles/m$^3$/day in bench tests.

- Gusek (2002, 2005) suggested a removal rate of 0.30 moles/m$^3$/day as a design criterion.

- Tab-Simco system is 0.215 moles/m$^3$/day, a value lower than the optimal rates. Detrimental factors include:
  - Undersized system due to site constraints.
  - Lower than optimum inlet pH (2.9).
  - High metal loading (Fe = 447 mg/L, Al = 123 mg/L).
  - Variable inlet chemistry (seasonal metal and sulfate changes).
Metal Removal Rates

- Reaction: \( \text{H}_2\text{S}_{(aq)} + \text{Me}^{2+} \Rightarrow \text{MeS}_{(s)} + 2 \text{H}^+ \)
- Suggests that for every mole of sulfate removed one mole of metals are also removed.
- The cumulative metal load of 0.26 moles/m³/day is higher than sulfate a removal rate of 0.202 moles/m³/day.
- A 2003 study by URS of a metal mine site recommended a lower cumulative heavy metal flux value of only 0.15 moles/m³/day.
Percent iron, manganese and sulfate removal declined in late 2009 but rebounded some in late 2010.
Future SIUC Studies (OSM-funded):

- **Bench Scale Studies:** Investigate organic substrate options using six microcosms.
  - Evaluate seasonal variability of the above processes.
  - Evaluate aluminum removal mechanisms and geochemistry.
  - Conduct additional microbial community analysis.

- **Tab-Simco Bioreactor Evaluation:** Investigate the bioreactor failure by geochemical and biochemical studies of substrate.
Acknowledgements

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- Nick Grant and Joy Schieferstein, Office of Surface Mining, Mid-Continent Region assisted in the evaluation of the biologic impact of the system on Sycamore Creek.

- Landowners Mike Page and Carla and Treg Brown provided access to the property and allowed facility construction.
The End: Questions?