Treatment of Coal Mine Drainage with Hybrid Vertical Flow Ponds in the Midwestern U.S.

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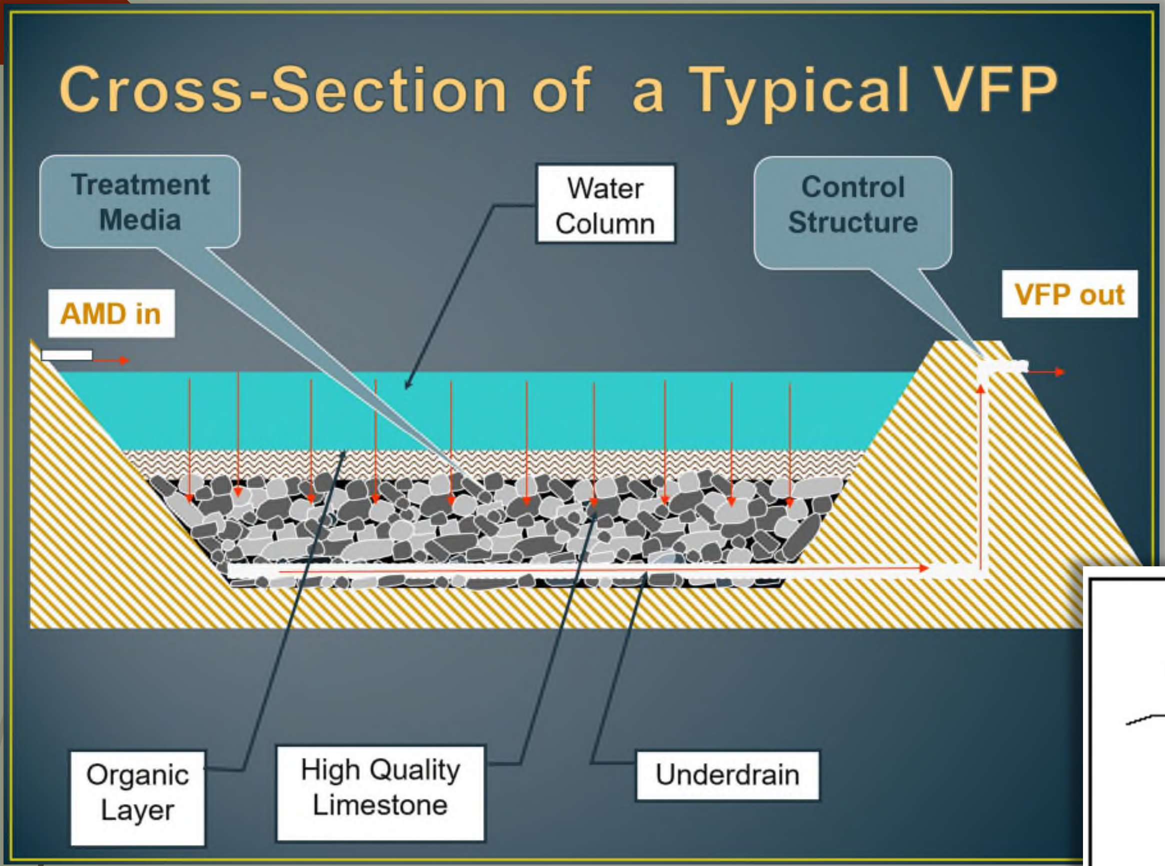
What will we be Covering?

- 1. – What is a "Hybrid Vertical Flow Pond (VFP)?"
- 2. – What reactions occur in the acid mine drainage (AMD) treatment media?
- 3. - What are the design criteria for VFPs?
  - The U.S. Bureau of Mines Method.
  - Empirical Method (Rose and Dietz Method)
- 4. – How does the performance Midwestern Hybrid VFP's compare to Appalachian VFPs?
  - Overview of representative Midwestern Hybrid VFP's?
  - Comparison with empirical data with VFP performance studies (Rose and Dietz, 2002-2006)
- 5. – Alternative design methodology – Consideration of biologic treatment.
- 6. - Thoughts on future research.

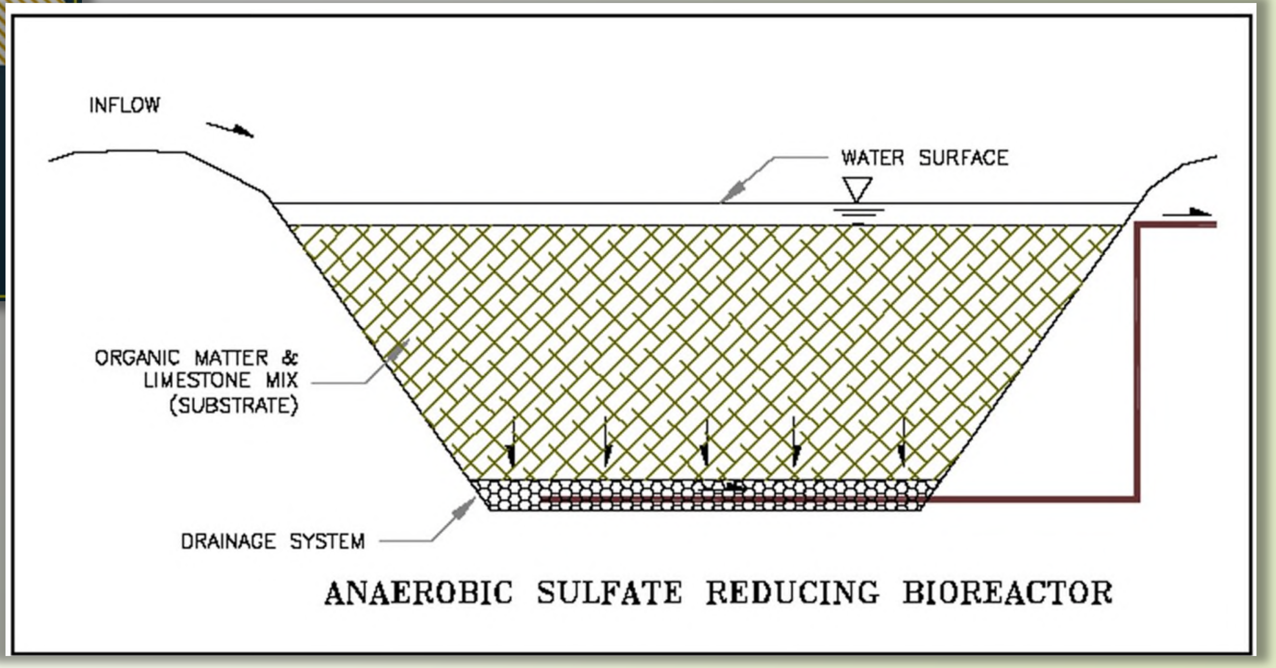
What is a "Hybrid Vertical Flow Pond (VFP).



A Hybrid VFP is a merger of two technologies – a conventional VFP and a Sulfate-Reducing Bioreactor.

Defining attribute is a thicker compost Layer

Source: Gusek and Wildman, 2002



“Hybrid Vertical Flow Pond (VFP) Construction

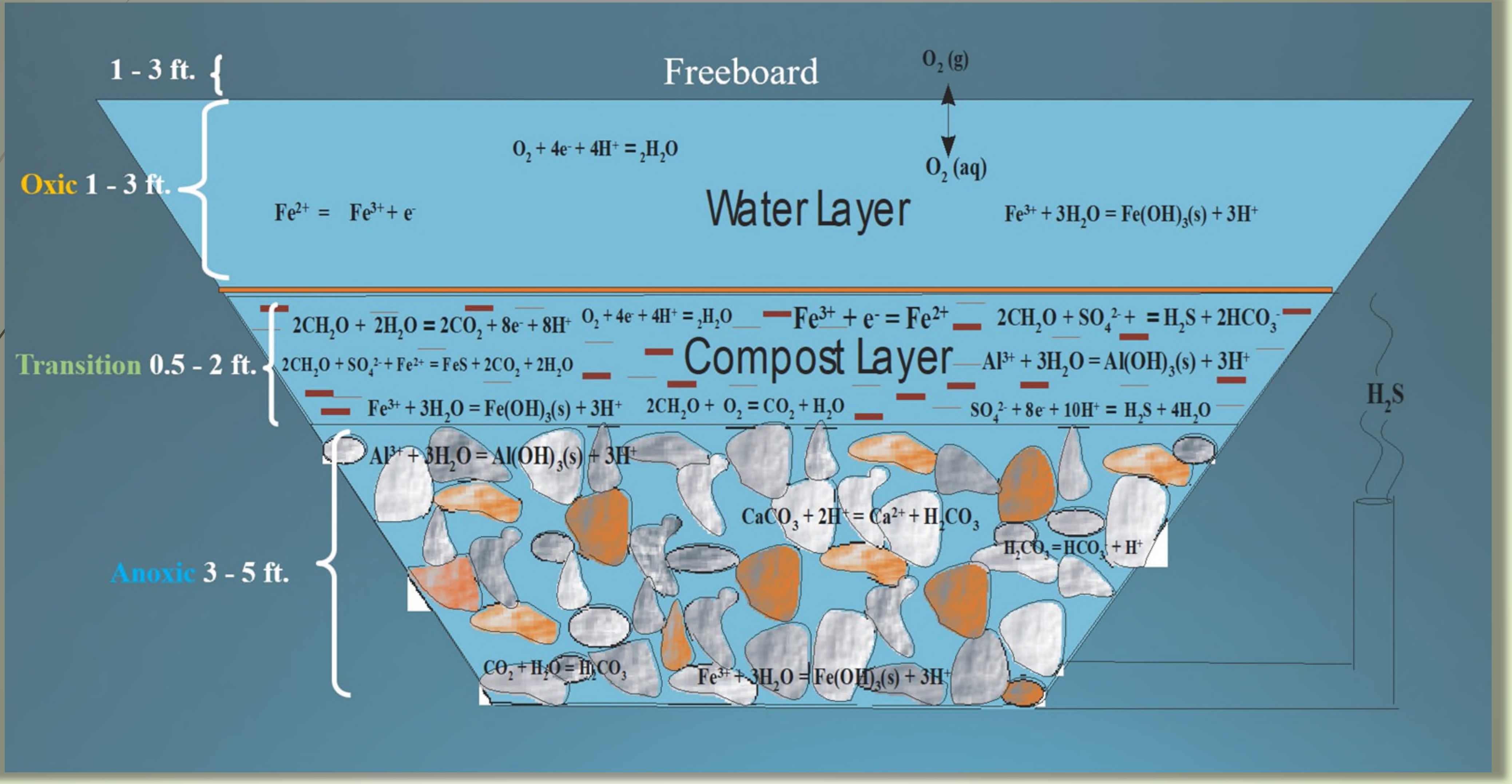
Limestone layer/Under Drain Construction: Rip-rap is shoreline wave erosion protection.

Site IL1: Tab-Simco Vertical Flow Pond/Bioreactor Hybrid

Compost Placement:
5,887 m^3 (7,700 CY)

What reactions occur in the AMD treatment media?

Typical VFP: Alkalinity derived from 3 sources: 1) limestone rock base, 2) aglime in the compost and 3) the sulfate reduction reaction.



Reactions in the AMD Treatment Media

- Generation of Bicarbonate (HCO_3^-)Alkalinity:
  - Limestone + Acidity = Calcium Ion + Bicarbonate Alkalinity
  - **$CaCO_3 + H^+ = Ca^{2+} + HCO_3^-$**
  - 1 mg/L increase in Ca results in ~2.5 mg/l of alkalinity as $CaCO_3$

- Reduction of Sulfate:
  - Organic Carbon + Sulfate = Hydrogen Sulfide + Bicarbonate Alkalinity
  - **$CH_4 + SO_4^{2-} \rightarrow HCO_3^- + HS^- + H_2O$**
  - Where a 1 mg/L decrease in SO_4^{2-} results in ~1.0 mg/l of alkalinity as $CaCO_3$

Reactions in the AMD Treatment Media

- Surface Reactions:
  - Iron hydrolysis:
- $Fe^{3+} + 3\ H_2O \rightarrow Fe(OH)_3 + 3\ H^+$

  (ferric iron) (ferric hydroxide)

  - Formation of Gibbsite*:
- $Al^{3+} + 3\ H_2O \rightarrow Al(OH)_{3(am)} + 3H^+$

  (gibbsite)
- *This reaction may not occur within in VFP/bioreactor substrate due to low oxygen and high sulfate levels!

Reactions in the AMD Treatment Media

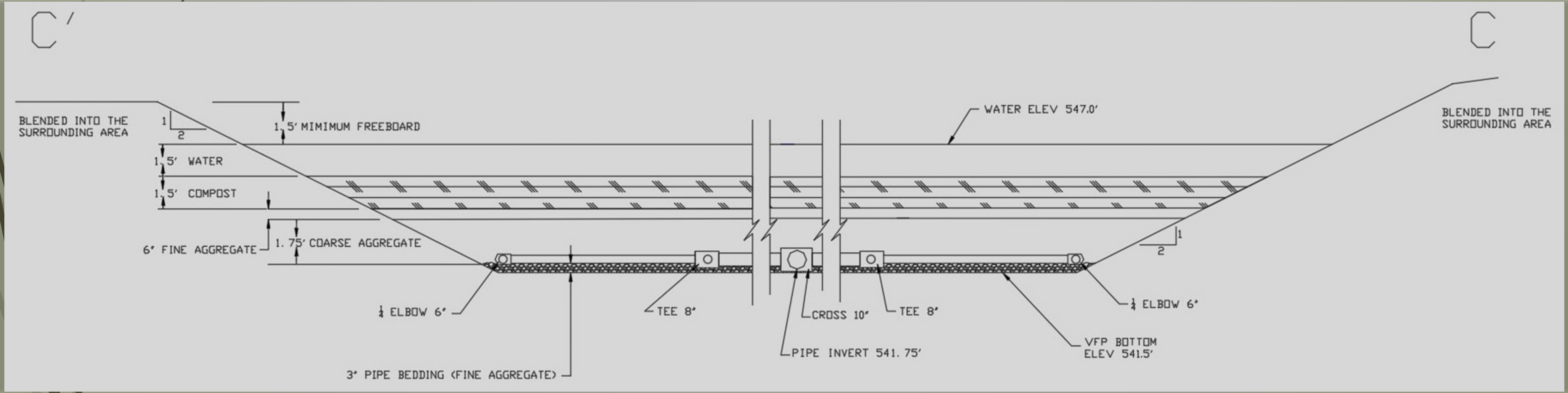
- Precipitation of Metal Sulfides:
  - **$HS^- \rightarrow S^{2-} + H^+$**
  - **$S^{2-} + Me^{2+} \rightarrow MeS_{(s)}$**
  - Where: Me is a divalent metal ion (Co, Ni, Zn, and Fe) and MeS is a metal sulfide mineral.

- Precipitation of Aluminum Oxysulfate Minerals:
  - **$3Al^{3+} + K^+ + 6H_2O + 2SO_4^{2-} \rightarrow KAl_3(OH)_6(SO_4)_2 + 6H^+$** (alunite)

Design Criteria for VFPs

- The U.S. Bureau of Mines Method.
- Empirical Method (Rose and Dietz Method).
- Consideration of preconstruction estimation of alkalinity production from the sulfate reduction in a hybrid VFP.

Old Bevier VFP2 (MO2) Rehab.



No.6 Mine VFP Design Drawing.

Design Criteria for VFPs (Option 1 of 2):

U.S. Bureau of Mines Alkalinity Production Method (USBM -- Hedin and Watzlaf ALD approach)

- VFP Sizing Based on Limestone Layer Mass for:
  - 1) Dissolution.
  - 2) Detention.

$$\text{Mass Limestone} = \frac{(Q)(p_b)(t_d)}{Vv} + \frac{(Q)(C)(T)}{X}$$

- Where: Q = Flow (L/hr.)

  p_b = Limestone Bulk Density (m. ton/L)

  t_d = Detention Time* (hrs.)

  V_v = Decimal limestone void volume

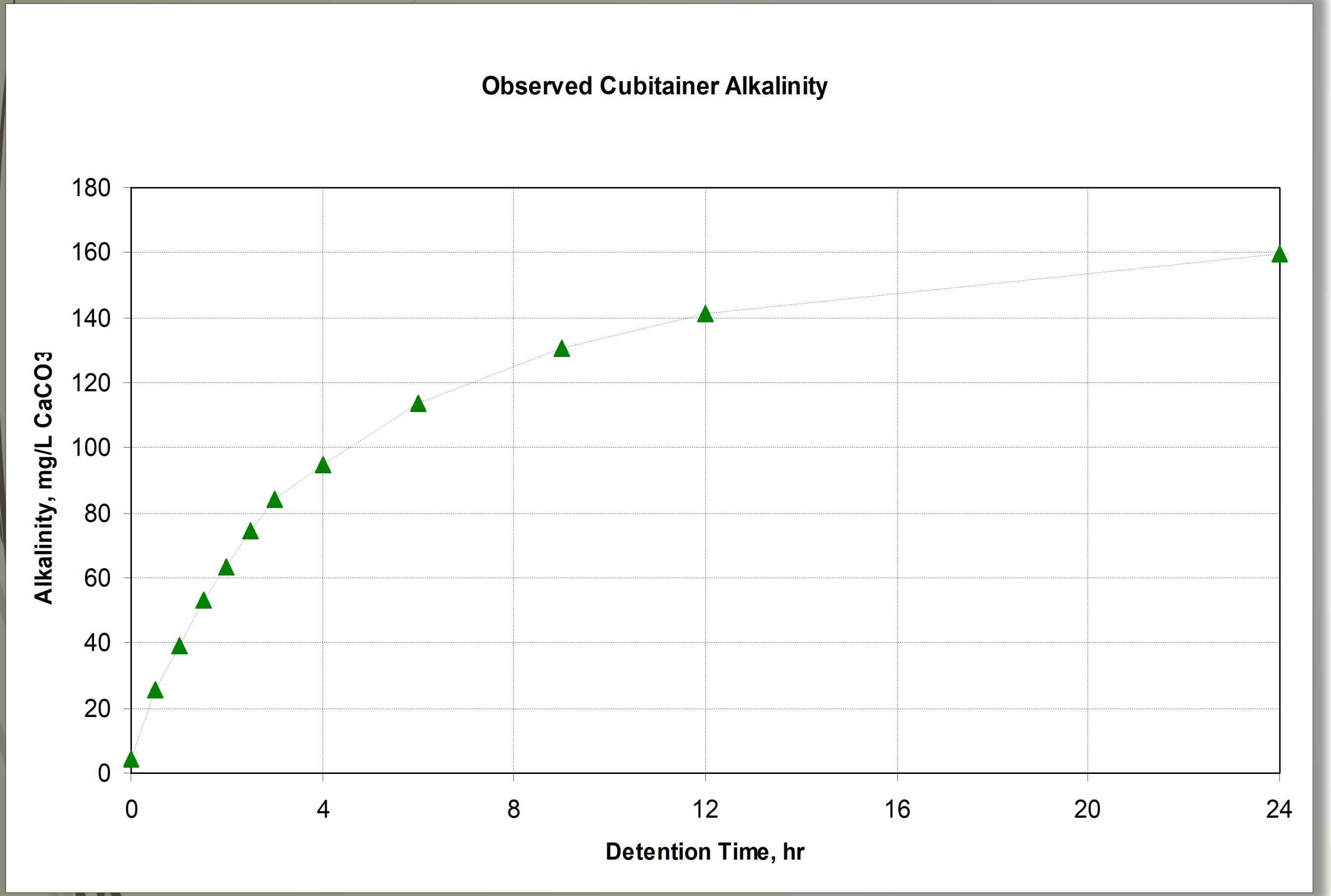
  C = Alkalinity Production* (m. ton/L)

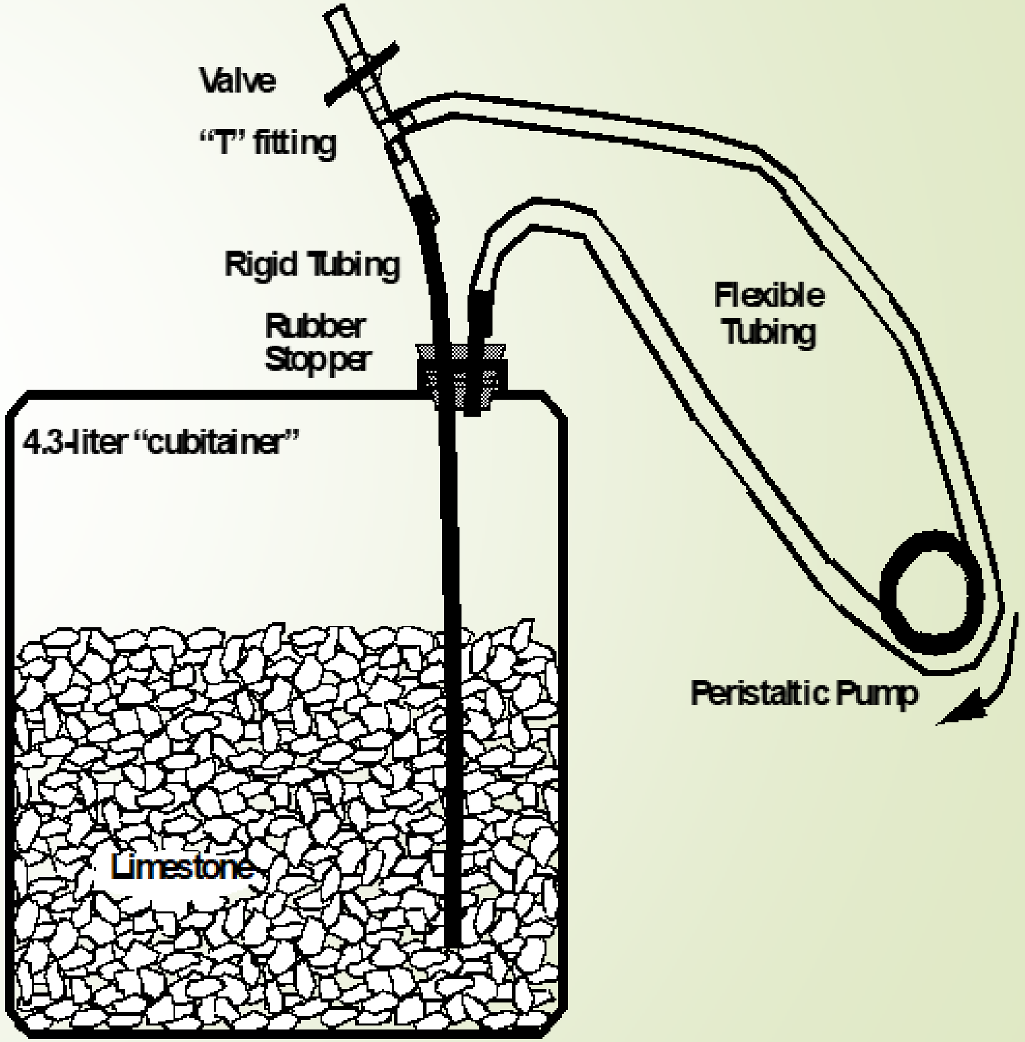
  T = Design Life (hrs.)

  X = Limestone $CaCO_3$ content (fractional)

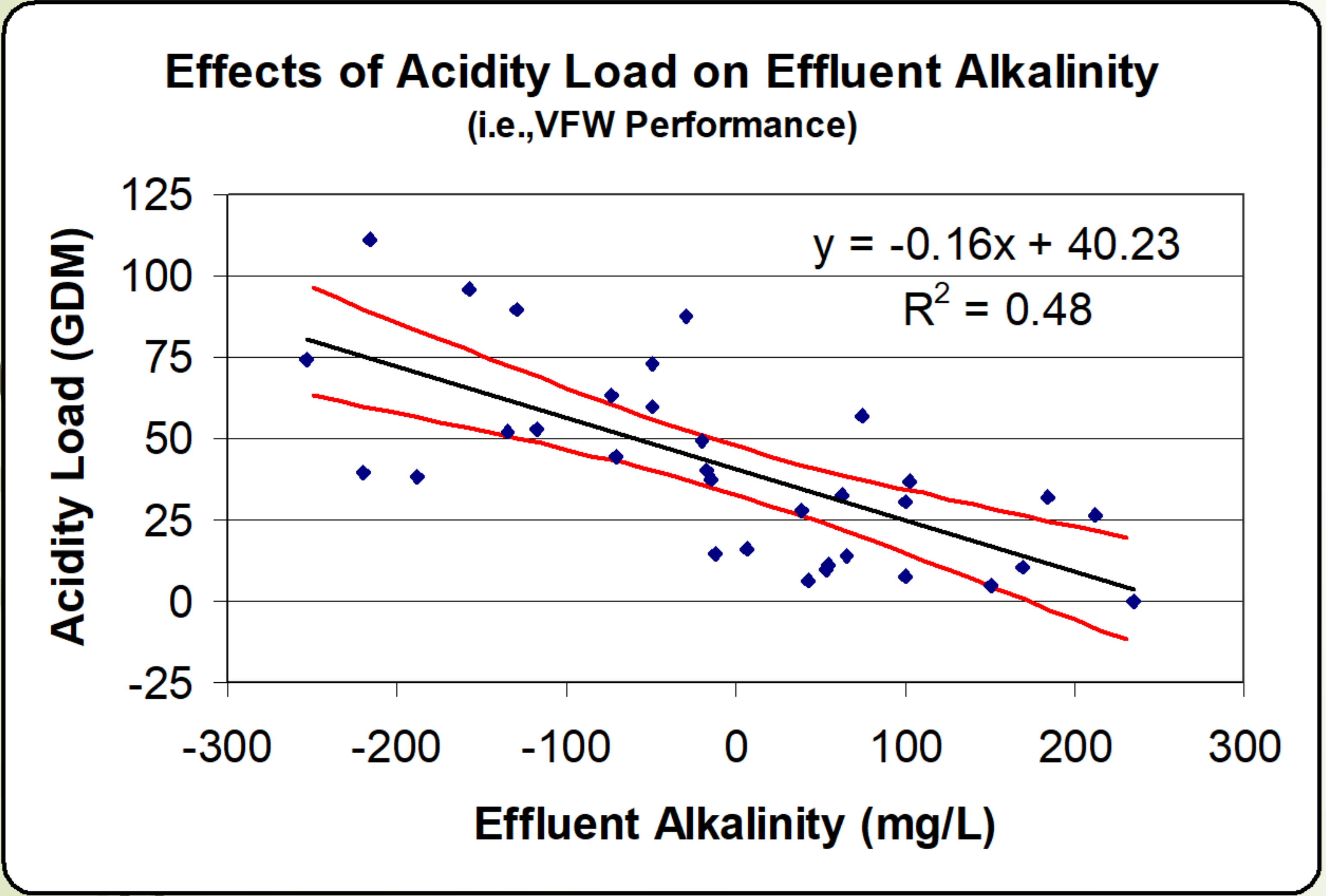
* Determined experimentally with a jar test (Cubitaner)

Cubitainer Test – Used to simulate closed limestone leaching conditions





Design Criteria for VFPs (Option 2 of 2): Empirical Method (Rose and Dietz Method)



VFP Limestone layer is sized to fit a 25* $g/d/m^2$ Acidity Removal Rate.

*Based on removal rates in 30 VFPs with variable construction parameters. Acidity removal rates from 25 to 35 $g/m^2/d$ is accepted practice.

Computes the size of the VFP in m^2 (a design option in *AMDtreat*).

Source: Rose and Dietz, 2002

How does the Performance Midwestern Hybrid VFP's Compare to Appalachian VFPs?

- Due to high acidity and aluminum in typical Illinois Basin AMD passive treatment systems are normally based on sulfate-reducing bioreactors.
- For this study we compiled the construction and performance data for 9 VFPs:
  - Six are Hybrid VFP's with the compost layer > 0.9 M. (3-ft). Parallel installations of Hybrid VFP's are located at two sites treating high flow (> 250 LPM) discharges.
  - Two are conventional VFP's which are arranged in series.
  - One is an experimental bioreactor selected for comparison.
  - Not discussed here are about 20 additional bioreactors constructed in Indiana and five hybrid bioreactors/VFP's built in Missouri.

Performance Midwestern Hybrid VFP's Compare to Appalachian VFPs:

Midwestern VFP Construction Features

- Two midwestern VFPs (IN1 and IN2) were designed as VFPs using the U.S. Bureau of Mines Method and then converted to a hybrid VFP/bioreactor by increasing compost thickness.
- One midwestern VFP (IL1) was constructed as a bioreactor with a limestone layer comparable to conventional VFPs.
- Three Arkansas VFPs (AR1, AR2 and AR3) have compost layers only slightly thicker than a conventional VFPs but are included in the list of hybrid VFPs. AR1 is pretreated by a large vertical anoxic limestone drain (VALD); AR2 and AR3 are pre-treated by low pH iron oxidation.
- An ALD-like highwall drain pretreats the AMD entering MO1 which then discharges into MO2. Oxidation structures separate these alkalinity-producing cells.

Midwestern VFPs Included in this study

Midwestern North PTS Bioreactor

IN3

IN1 IN2

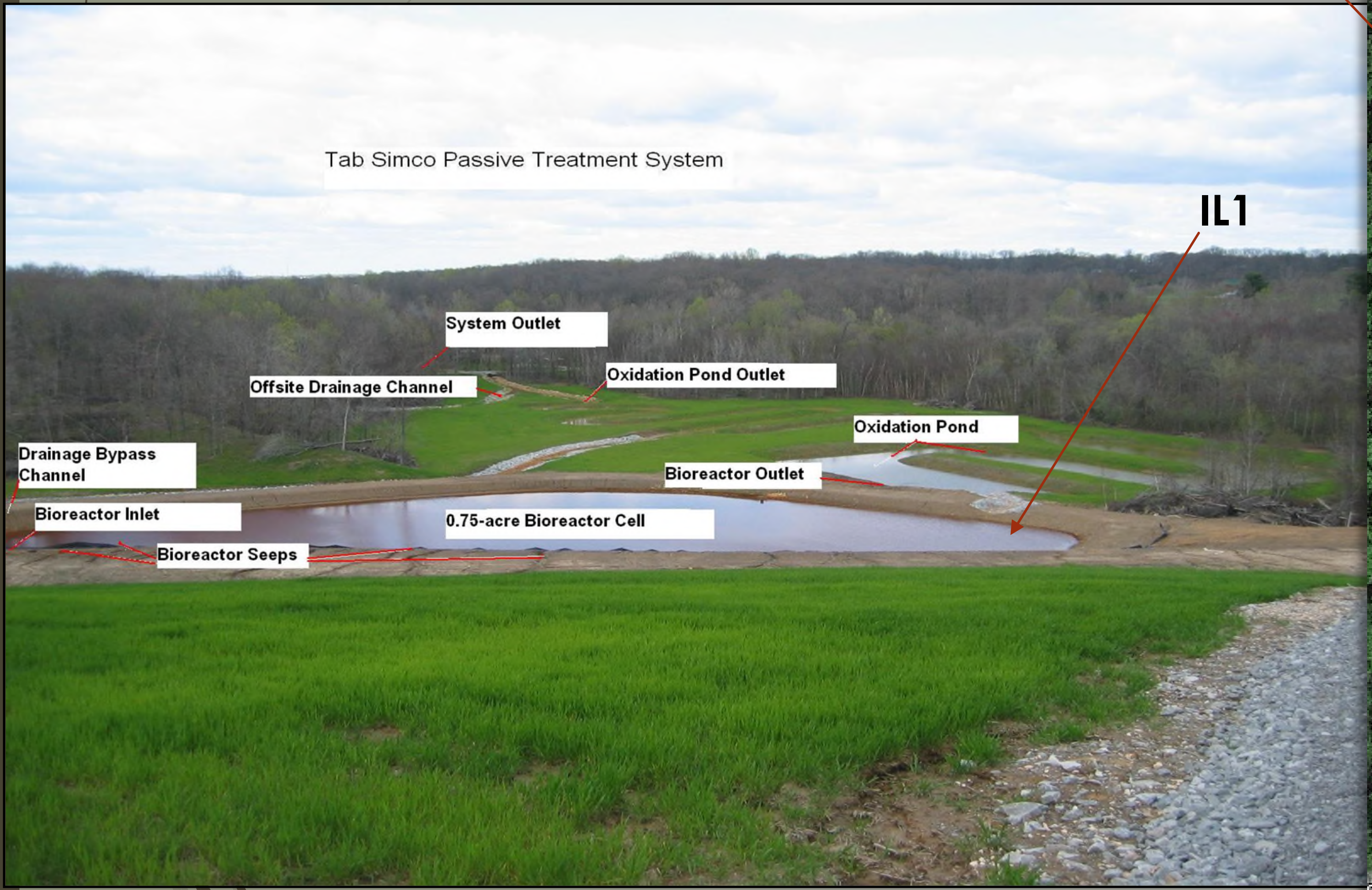
Enos Loop PTS, Indiana

Midwestern VFPs Included in this study

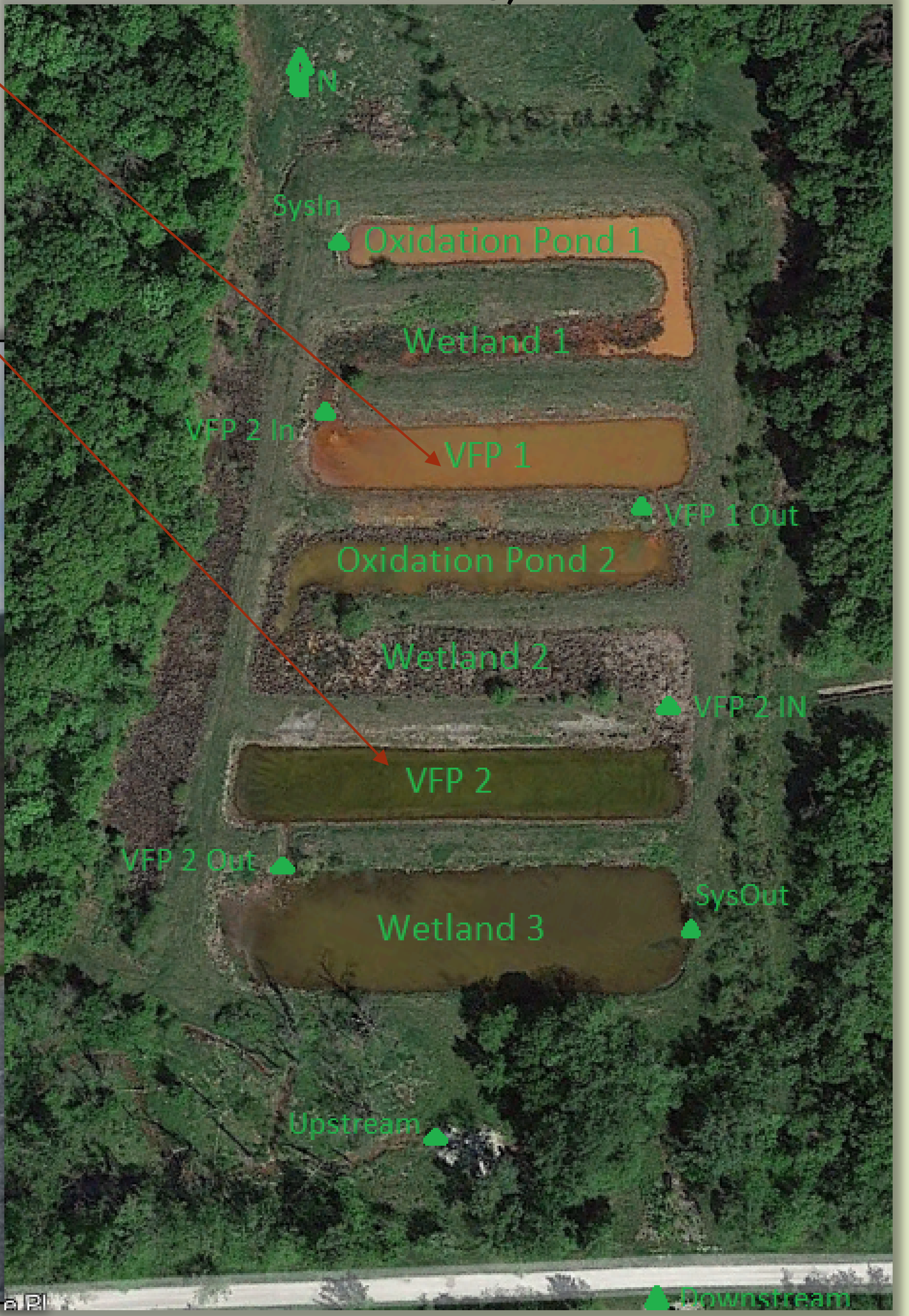
MO1

MO2

IL1

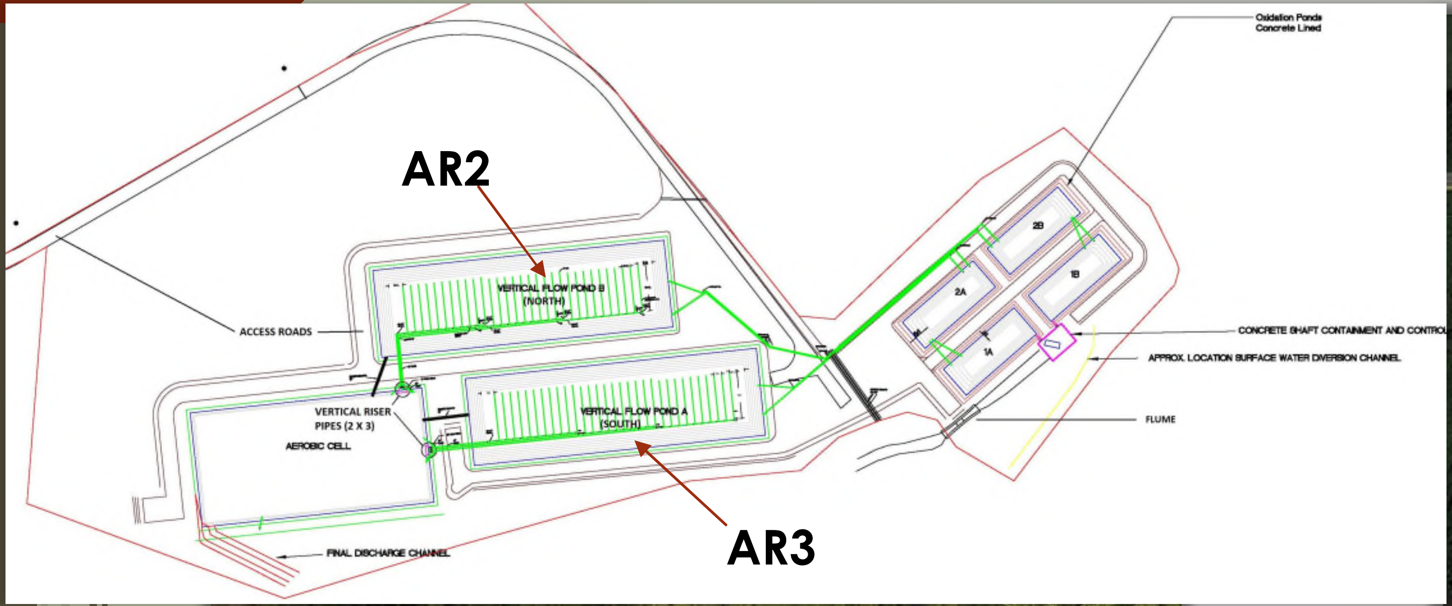


Enos PTS, Missouri

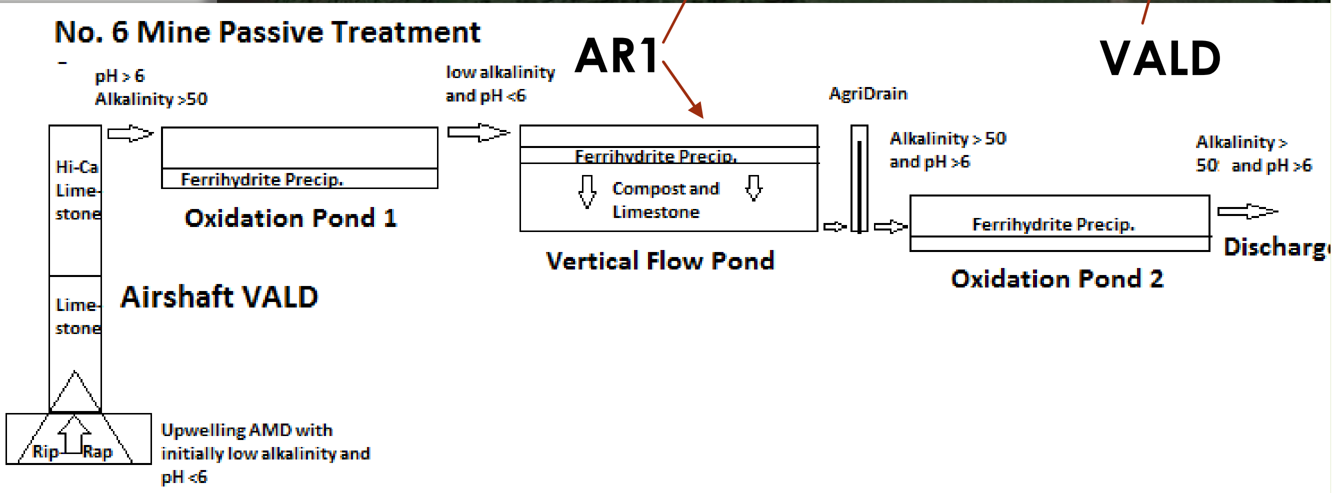


Midwestern VFPs Included in this Study

Hartford PTS, Arkansas



No. 6 Mine PTS, Arkansas



Location, System Type, Design Details, Construction Date, and Operational Data for Midwestern USA Vertical Flow Systems

VFP ID	Location	System Type	Water Layer* (cm)	Compost Layer* (cm)	Limestone Layer* (cm)	Area (m^2)	Construction Date (mo./yr.)	Operation (years)**	Sample Periods (n =)
IL1	Carbondale, Illinois	Hybrid VFP/Bioreactor	30.0	180.0	60.9	3521	12/2007	15.5	70
IN1	Enos Corner, Indiana	Hybrid VFP/Bioreactor	90.0	90.0	60.9	4016	12/2005	18.6	56
IN2	Enos Corner, Indiana	Hybrid VFP/Bioreactor	90.0	90.0	60.9	5487	12/2005	18.6	56
IN3	Augusta, Indiana	Bioreactor	30.0	152.4	0.0	2394	12/2008	14.4	42
MO1	Bevier, Missouri	SAPS1***	76.2	45.7	114.3	918	8/2001	21.8	20
MO2	Bevier, Missouri	SAPS2***	76.2	45.7	114.3	1154	8/2001	21.8	20
AR1	Huntington, Arkansas	Hybrid VFP/Bioreactor	30.0	60.9	68.6	2875	3/2009	11.2	13
AR2	Hartford, Arkansas	North Hybrid VFP/Bioreactor	30.0	60.9	76.2	3776	5/2015	8.0	5
AR3	Hartford, Arkansas	South Hybrid VFP/Bioreactor	30.0	60.9	76.2	3833	5/2015	8.0	5

*All are constructed as downflow systems with a water layer on top, a compost layer in the middle and a limestone layer on the bottom, the water layer thickness = the hydraulic head of the system; porosity of the compost = 30% and porosity of the limestone = 38%; IN3 used woodchips instead of limestone.

**All systems have continuous operations from construction date to a paper preparation date of May 2023.

***SAPS = Successive Alkalinity Producing system and consist of two VFPs in series (MO1 then MO2) with supporting oxidation and wetland cells.

Hydrologic Data for Midwestern USA Vertical Flow Systems*

VFP ID	System Type	Hydraulic Head (cm)	Flow (LPM)	Water (HRT) (Hr.)	Compost HRT (Hr.)	Limestone HRT (Hr.)
IL1	Hybrid VFP/Bioreactor	255.9	85.05	202.8	316.0	110.5
IN1	Hybrid VFP/Bioreactor	226.1	599.4	95.0	25.3	19.7
IN2	Hybrid VFP/Bioreactor	226.1	599.4	130.9	35.4	27.4
IN3	Bioreactor	167.4	70.41	161.8	152.7	0.0
MO1	SAPS1***	221.2	82.44	127.9	19.2	47.4
MO2	SAPS2***	221.2	82.44	162.4	25.0	64.2
AR1	Hybrid VFP/Bioreactor	144.5	27.06	52.6	26.3	37.6
AR2	North Hybrid VFP/Bioreactor	152.1	164.7	114.2	65.5	92.8
AR3	South Hybrid VFP/Bioreactor	152.1	77.17	249.4	139.0	199.1

*All are constructed as downflow systems with a water layer on top, a compost layer in the middle and a limestone layer on the bottom, the water layer thickness = the hydraulic head of the system; porosity of the compost = 30% and porosity of the limestone = 38%; IN3 used woodchips instead of limestone.

Midwestern VFP's: Selected Chemical Data

Cell ID	Type**	Acidity In mg/L*	Fe In mg/L	Mn In mg/L	Al In mg/L	Fe Out mg/L	Mn Out mg/L	Al Out mg/L	Net Acidity* Out mg/L	Net Alkalinity Out mg/L
IL1	Hybrid	1,830.0	495.9	37.34	122.3	127.7	32.78	0.756	92.7	-92.74
IN1	Hybrid	57.2	14.8	2.32	0.96	4.43	2.44	0.143	-87.8	87.81
IN2	Hybrid	57.2	14.8	2.32	0.96	4.27	2.43	0.140	-109.2	109.16
IN3	Bio-reactor	482.5	110.5	10.95	8.05	2.61	6.78	0.250	32.0	-32.00
MO1	SAPS1	385.2	154.5	8.08	1.73	154.0	8.00	0.222	177.3	-177.31
MO2	SAPS2	163.0	15.1	8.62	0.790	36.08	7.67	0.147	-60.9	60.86
AR1	Hybrid	7.45	3.14	2.02	0.033	0.54	1.77	0.027	-82.6	82.55
AR2	Hybrid	56.9	2.16	7.39	0.79	9.60	7.70	0.150	-110.8	110.84
AR3	Hybrid	56.9	2.16	7.39	0.79	0.90	5.70	0.195	-122.3	122.26

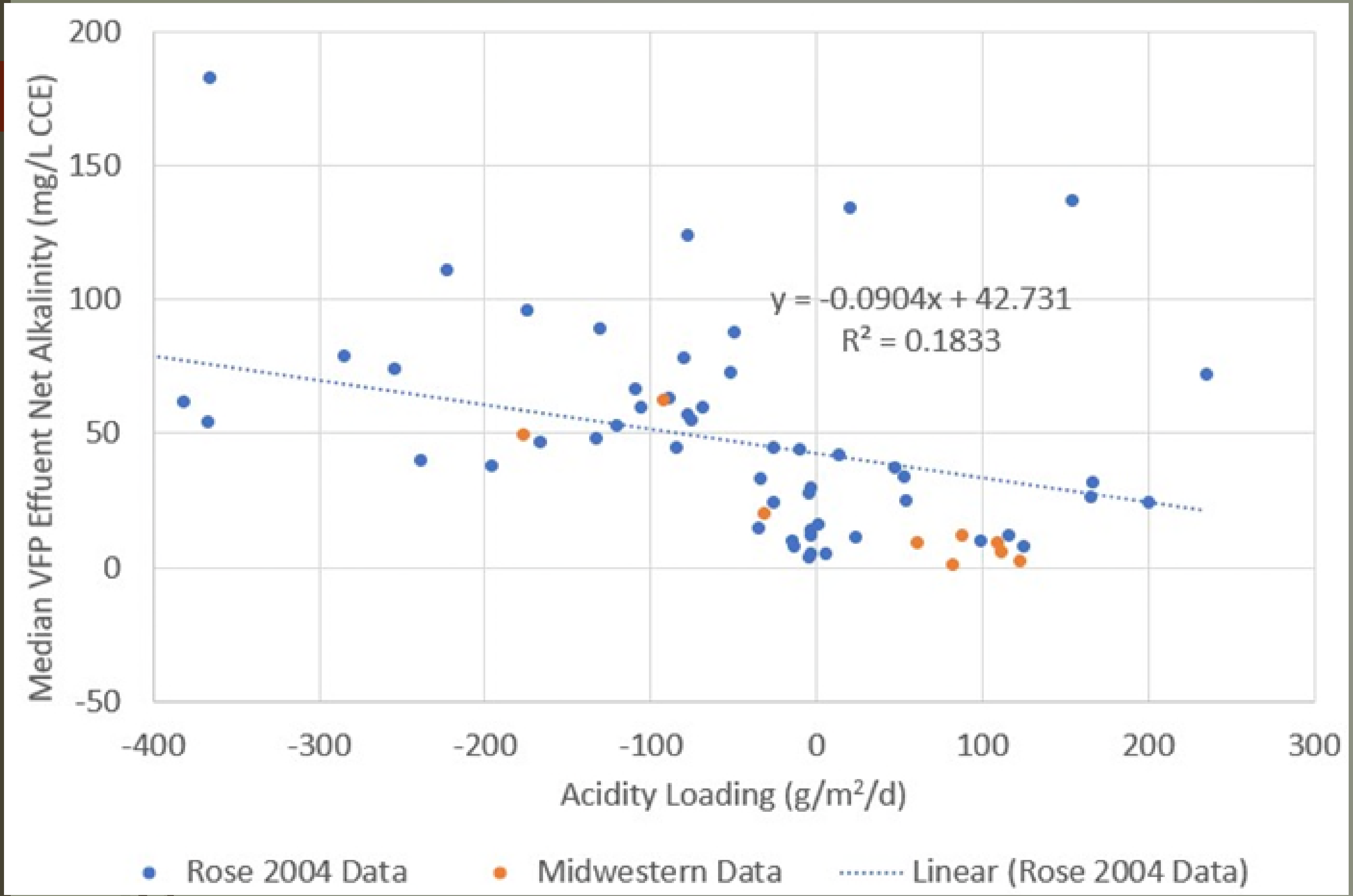
* Alkalinity and acidity values in mg/L calcium carbonate equivalent.

Comparative Performance of Passive Vertical Flow Treatment Cells Treating Net Acidic Coal Mine Drainage

VFP ID	Type**	Acidity Load $g/m^2/d$	Fe Load $g/m^2/d$	Mn Load $g/m^2/d$	Al Load $g/m^2/d$	Cum. Metal Load $g/m^2/d$	Acidity Removal Rate g/m2/d
IL1	Hybrid	62.18	16.85	1.27	4.15	21.60	49.03
IN1	Hybrid	12.29	3.18	0.49	0.21	3.88	85.36
IN2	Hybrid	8.99	2.33	0.36	0.15	2.84	64.64
IN3	Bioreactor	20.43	4.68	0.464	0.341	5.49	19.08
MO1	SAPS1	49.82	20.95	1.07	0.223	22.24	15.44
MO2	SAPS2	8.95	1.55	0.888	0.081	2.519	14.09
AR1	Hybrid	1.01	0.426	0.274	0.004	0.704	13.07
AR2	Hybrid	5.90	0.561	0.422	0.069	1.052	12.93
AR3	Hybrid	2.72	0.259	0.195	0.032	0.486	5.70

1.Based on median values; loading calculations based on discharge and VFP surface area values shown in Tables 1and 2.
*Calcium carbonate equivalent (CCE).
**Hybrid = Hybrid bioreactor/vertical flow pond.

Comparison of Midwestern Hybrid VFP's to Rose and Deitz Performance Data



How does the Performance Midwestern Hybrid VFP's Compare to Appalachian VFPs?

- Midwestern VFP's and Hybrid VFPs are comparable with the data presented by Rose and Dietz (2004) and Rose (2006).
- Midwestern VFP's and Hybrid VFPs are typically required to treat AMD with a higher acidity.
- Plotting an extended dataset of Northern Appalachian data resulted in a similar linear equation but at a much lower R^2 value.
- Performance data from Midwestern sites were derived from median performance over a long operation period of 8.0 - 21.8 years. This is compered with Appalachian data over a much sorter operation term when higher performance is expected.
- Construction of Appalachian VFPs predated most Midwestern VFPs. Midwestern VFP's benefited from lessons learned.

Alternative Design Methodology: Consideration of Biologic Treatment

- **The U.S. Bureau of Mines Method:**
  - Relies on Cubitainer-type jar testing to estimate alkalinity and limestone layer detention time. As conventional VFPs commonly use limestone rock that is larger than the material in the jar test there is a scale error associated with this methodology.
  - There is no consideration of compost layer alkalinity.
- **The Empirical Rose and Dietz Method:**
  - More conservative approach producing larger VFPs.
  - As an area-based method it assumes more-or-less consistent limestone bed thickness.
  - As the population of constructed VFP's and operational life is extended an updated empirical estimate is suggested. Consideration of compost-generated alkalinity is included in this method.

Alternative Design Methodology: Consideration of Biologic Treatment

- Should a VFP's designs consider the impact of sulfate-reduction?
- Due to the thicker compost layer the alkalinity contribution from the compost layer may be considered.
- Aside from alkalinity production sulfide-reducing bioreactors and hybrid VFP's can potentially reduce sulfate to the sulfide ion and sequester a considerable portion iron along with most nickel, zinc and cobalt present in the AMD. This can significantly lower the total dissolved solids content of the discharge.
- Bioreactors are typically designed using a volume of the compost or limestone-buffered organic substrate (LBOS) that to remove ½ of the sulfate in the inlet AMD. A sulfate loading rate of 0.3 moles/m^3/d. has been suggested as the design goal (Gusek, 2004).

Consideration of Biologic Treatment: Comparison of Hybrid VFP/bioreactors to Bioreactor Design Criteria

Compost layer information for select vertical flow ponds the Midwestern U.S.*

VFP ID	System Type	Compost Layer (cm)	Compost Volume (m^3)	Construction Date (mo./yr.)	Compost Replacement Date (mo./yr.)	Operation Before Replacement (years)**	Compost Pore Volume (m^3)
IL1	Hybrid	180.0	5,975.7	12/2007	10/2013	5.83	1792.7
IN1	E. Hybrid	90.0	3,027.4	12/2005	10/2009	3.83	908.2
IN2	W. Hybrid	90.0	4,247.9	12/2005	10/2012	6.83	1274.4
IN3	Bioreactor	152.4	2,150.7	12/2008	N/A	>14.4	645.4
MO1	SAPS1***	45.7	317.3	8/2001	3/2021	19.58	95.2
MO2	SAPS2***	45.7	411.6	8/2001	3/2021	19.58	123.5
AR1	Hybrid	60.9	1,588.8	3/2009	N/A	>11.2	426.6
AR2	North Hybrid	60.9	2,123.0	5/2015	N/A	>8.0	636.9
AR3	South Hybrid	60.9	2,145.6	5/2015	N/A	>8.0	643.7

*All are constructed as downflow systems with a water layer on top, a compost layer in the middle and a limestone layer on the bottom, the water layer thickness = the hydraulic head of the system; porosity of the compost = 30% and porosity of the limestone = 38%; IN3 used woodchips instead of limestone.

**All systems have continuous operations from construction date up to the paper preparation date of May 2023.

***SAPS = Successive Alkalinity Producing system and consist of two VFPs in series (MO1 then MO2) with supporting oxidation and wetland cells.

Consideration of Biologic Treatment: Comparison of Hybrid VFP/bioreactors to Bioreactor Design Criteria

Performance of Vertical Flow Ponds Treating Net Acidic Coal Mine Drainage based on LBOS Volume[1]

VFP ID	Type	Inlet Sulfate mg/L	SO_4 Load g/m³/day	Fe Load g/m³/day	Mn Load g/m³/day	Al Load g/m³/day	Cumulative Metal Load g/m³/day	Sulfate Out mg/L
IL1	Hybrid VFP/ Bioreactor	**3,281**	65.67	9.93	0.747	2.447	13.12	**2,258**
IN1	Hybrid	1,730	493.2	4.219	0.660	0.272	5.151	1,720
IN2	Hybrid	1,730	351.5	3.007	0.470	0.194	3.671	1,528
IN3	Bioreactor	**2,310**	108.9	4.68	0.464	0.341	5.485	**1,945**
MO1	SAPS1	1,867	619.6	60.61	3.096	0.223	63.93	1,858
MO2	SAPS2	1,934	478.8	4.348	2.486	0.081	6.915	1,914
AR1	Hybrid	200	49.13	0.771	0.496	0.008	1.275	146
AR2	Hybrid	782	40.48	0.463	0.348	0.057	0.868	739
AR3	Hybrid	**782**	87.29	0.998	0.560	0.022	1.580	**556**

1.LBOS = limestone-buffered organic substrate; median values; volumetric loading calculations based on discharge and volume values shown

Consideration of Biologic Treatment: Comparison of Hybrid VFP/bioreactors to Bioreactor Design Criteria

Compare ½ sulfate load to design criteria of a loading rate of 0.3 mol SO_4/m^3/day (Gusek, 2005).

Performance of Vertical Flow Ponds Treating Net Acidic Coal Mine Drainage based on LBOS Volume

VFP ID	Type	Inlet Sulfate mg/L	SO_4 Load mol/m³/d	½ SO_4 Load mol/m³/d	Fe Load mol/m³/d	Mn Load mol/m³/d	Al Load mol/m³/	Cumulative Metal Load mol/m3/d
IL1	Hybrid	3,281	0.6836	**0.3418**	0.1777	0.0136	0.0907	0.2820
IN1	Hybrid	1,730	5.134	**2.567**	0.0755	0.0120	0.0101	0.0976
IN2	Hybrid	1,730	3.659	**1.829**	0.0538	0.0086	0.0072	0.0696
IN3	Bioreactor	2,310	1.134	**0.567**	0.0933	0.0094	0.0141	0.1168
MO1	SAPS1	1,656	6.451	**3.226**	1.0853	0.0554	0.0012	1.1419
MO2	SAPS2	1,660	4.984	**2.492**	0.0779	0.0445	0.0004	0.1228
AR1	Hybrid	200	0.5114	**0.2557**	0.0138	0.0090	0.0003	0.0258
AR2	Hybrid	782	0.9087	**0.4544**	0.0179	0.0102	0.0008	0.0289
AR3	Hybrid	782	0.4214	**0.2107**	0.0083	0.0063	0.0021	0.0167

1.LBOS = limestone-buffered organic substrate; median values; volumetric loading calculations based on discharge and volume values shown in above.

Consideration of Biologic Treatment: Discussion

- Most Hybrid VFPs in this study are designed the U.S. Bureau of Mines Method without consideration of sulfate removal.
- Two Hybrid VFPs– AR1and AR3 with a relatively light SO_4 loading have sufficient compost to serve as an effective bioreactor. The AR3 companion parallel cell AR2 is has a SO_4 load 50% higher than ideal. However, the low metal loading of these cells due to pre-treatment is unfavorable for sequestering sulfur as a sulfide.
- Conversely, the metal loading of loading of IL1 and MO1 are higher than the ideal for operation of a bioreactor (URS, 2003).

Consideration of Biologic Treatment: Discussion

- Two vertical flow cells - IL1 and IN3 are designed as bioreactors. Both are undersized due to site limitations. Never-the-less, IL1 is removing 17.45 m. tons/year of sulfur for more than 15 years.
- The principal goal of using thicker compost is to allow VFP application where aluminum is elevated (IL1)or to increase operational life.
- Experience has shown that the LBOS (compost) composition is critical to the effectiveness and operational duration of VFPs and bioreactors. Rehabilitation efforts of failing vertical flow cells has led to an increase in lime amendments and a mix of both short-term and long-term organic molecule sources.

Treatment of Coal Mine Drainage with Hybrid Vertical Flow Ponds in the Midwestern U.S.

Thoughts on future research

- Use of empirical VFP design methods requires periodic updates with performance data from real-work applications. As the population of VFP data grows the impact of design variations diminishes.
- Current design criteria focuses on the creation of net acidic drainage. This promotes a bicarbonate-buffered conditions for metal removal. Because TDS or sulfate is in some cases problematic in receiving streams sulfate removal from AMD discharges by passive treatment systems should be considered.
- When designed, constructed and operated correctly passive AMD treatment technologies such as vertical flow ponds and sulfate-reducing bioreactors and their associated oxidation cells can effectively remove metals and in some cases drastically lower TDS in the AMD source area.

Acknowledgements

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  - The Illinois Department of Mines and Minerals, Land Reclamation Program.
  - The Indiana Department of Natural Resources, Division of Reclamation.
  - Missouri Department of Natural Resources, Land Reclamation Program.
  - Arkansas Department of Energy & Environment, Division of Energy and Mineral Resources.
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Treatment of Coal Mine Drainage with Hybrid Vertical Flow Ponds in the Midwestern U.S.

The End -- Questions?