Comparison of Midwestern U.S. Conventional and Hybrid Vertical Flow Ponds to Previous Performance Data

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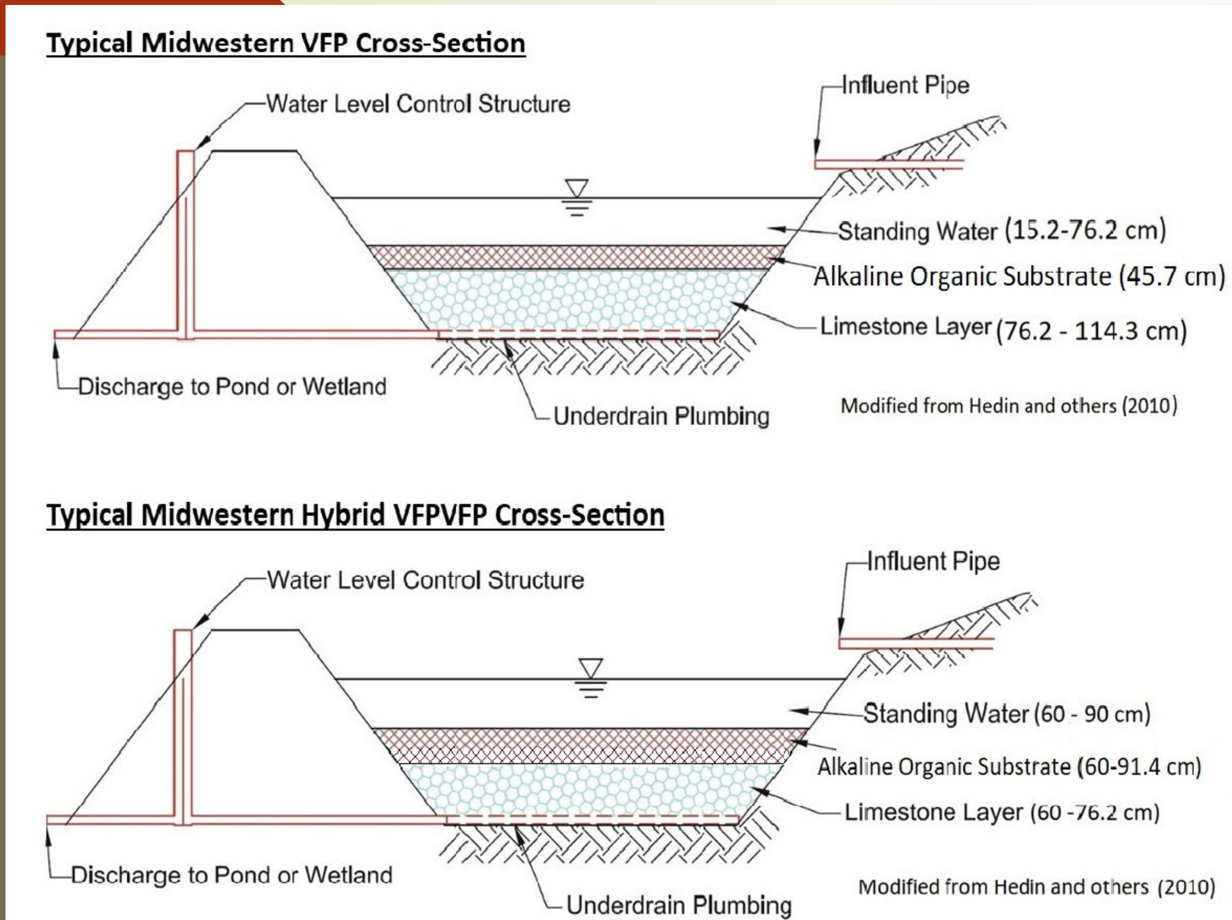
Treatment of Coal Mine Drainage with Hybrid Vertical Flow Ponds in the Midwestern U.S.

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; Rose 2004, 2006).

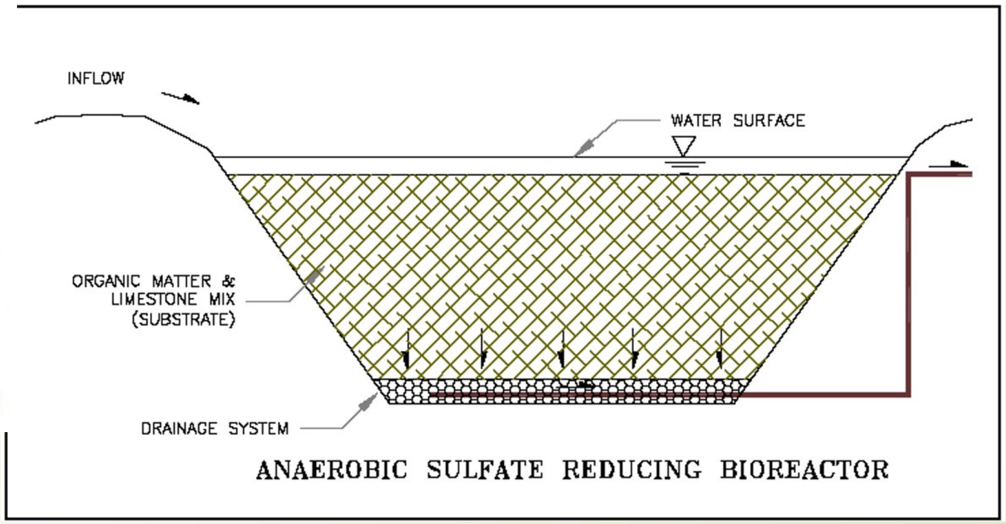
What is a “Hybrid Vertical Flow Pond (VFP)



Comparison of a VFP and a Hybrid VFP (this study)

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

Defining attribute is a thicker compost Layer



Bioreactor cross-section (source: Gusek and Wildman, 2002)

“Hybrid” Vertical Flow Pond (VFP) Construction

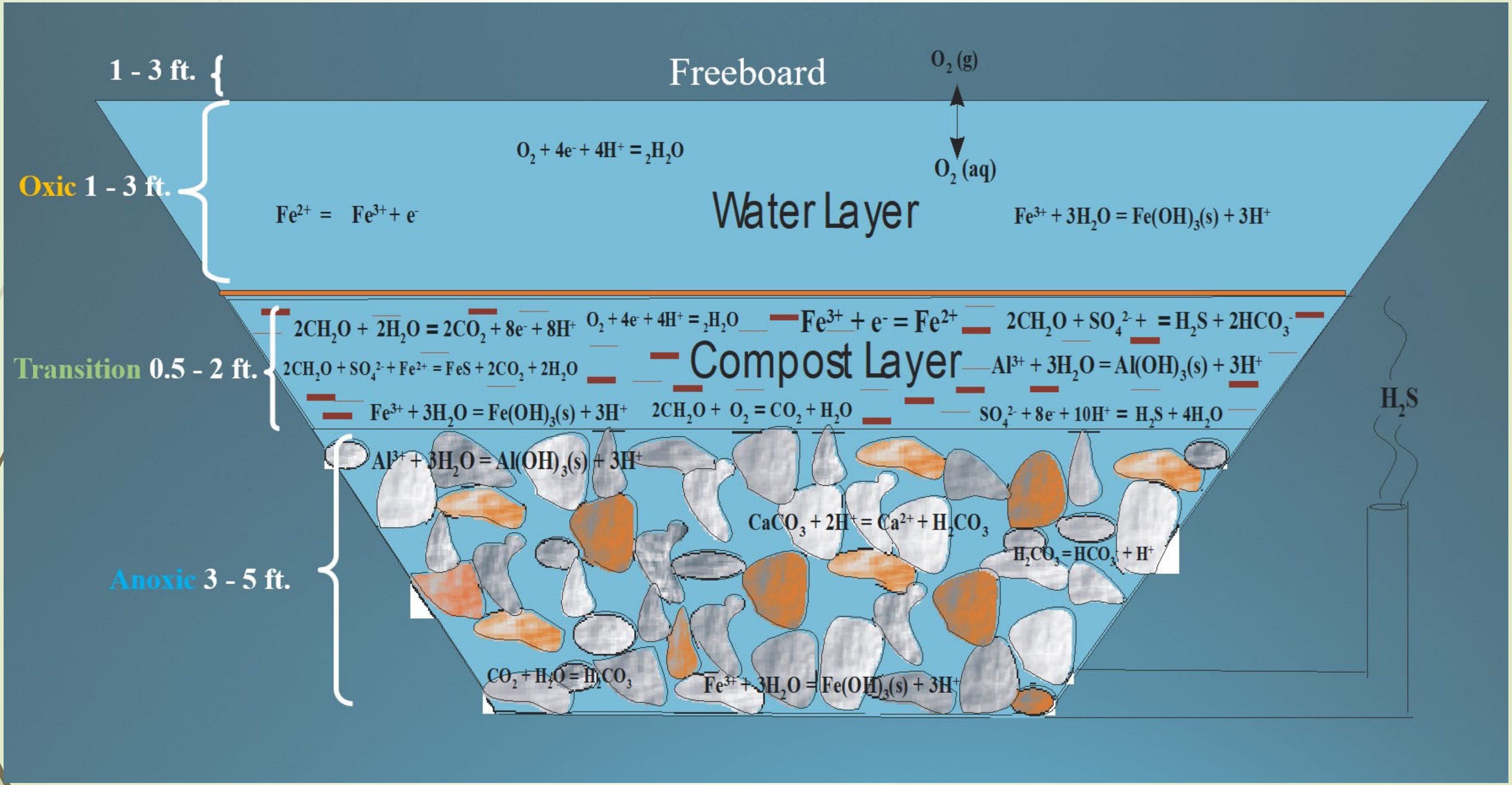
Site IL1: Tab-Simco Vertical Flow Pond/Bioreactor Hybrid

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

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

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)

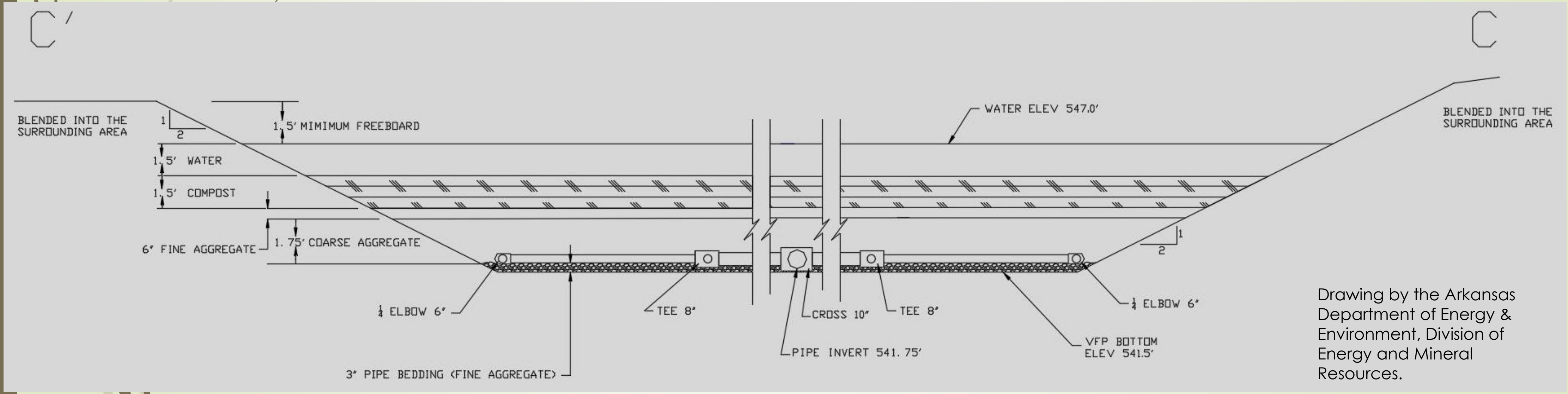
VFP and Hybrid VFP Design Considerations

- VFPs, hybrid VFPs and bioreactors all require follow-up oxidation ponds and aerobic wetlands to allow precipitation of metals.
- Because alkalinity production from aerobic oxidation ponds and wetlands is limited VFPs hybrid VFPs and bioreactors must produce sufficient alkalinity to yield net alkaline drainage.
- Alternatively, some VFPs have included a second VFP to increase alkaline addition and produce net alkaline drainage.
- Conversely, many of the vertical flow systems discussed here were proceeded by alkaline addition from either an anoxic limestone drain (ALD), limestone-based highwall drain, or dilution water.
- Midwestern VFPs typically contain at >15% fine ground limestone (aglime) to bolster alkalinity in the media.
- Rose (2004) recommended VFPs with limestone-amended compost compost have 2X remediation performance and an increased compost thickness aided high aluminum AMD treatment.

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.



Drawing by the Arkansas Department of Energy & Environment, Division of Energy and Mineral Resources.

No.6 Mine, Arkansas (AR1) - 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.

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

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

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

  t_d = Detention Time* (hrs.)

  V_v = Decimal limestone void volume

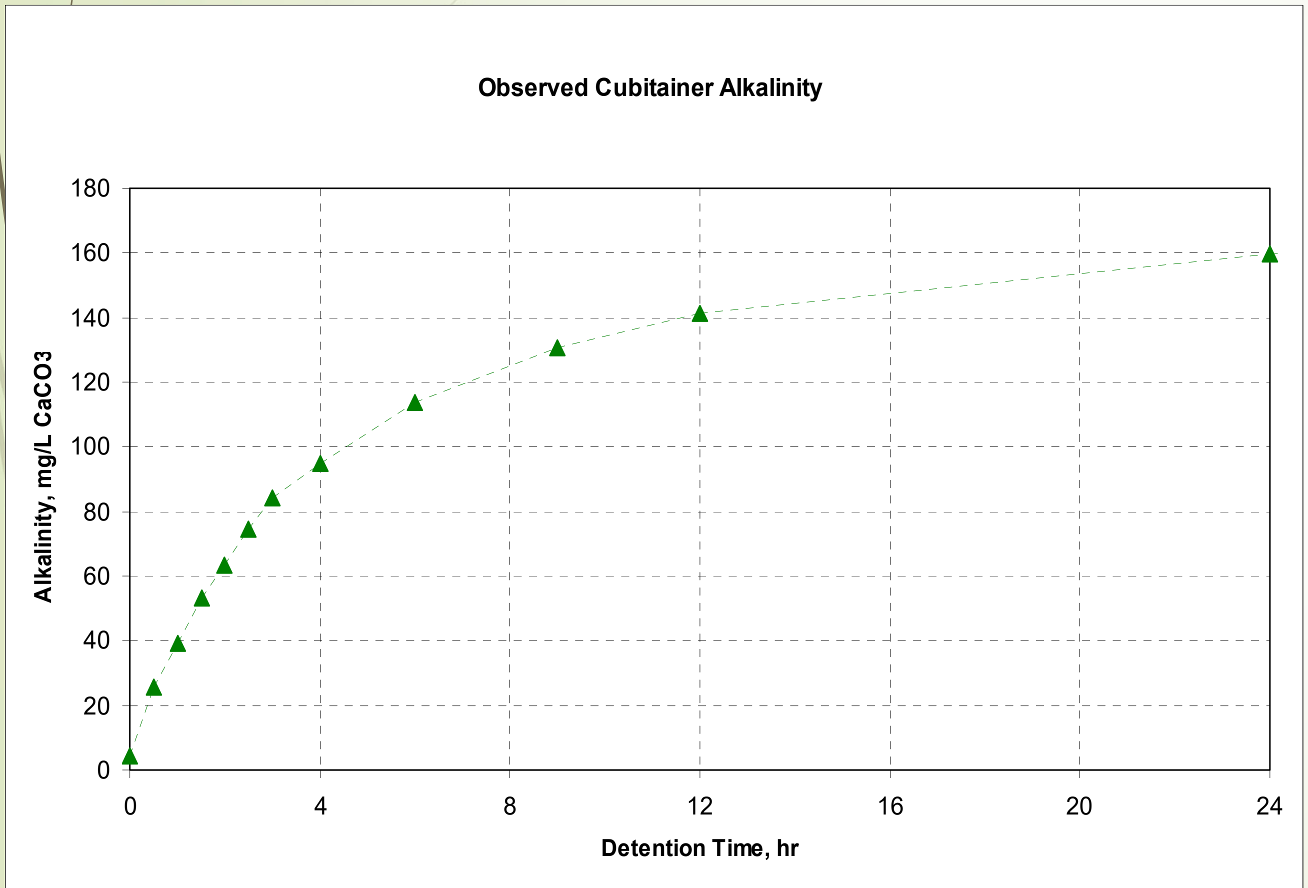
  C = Alkalinity Production* (m. ton/L)

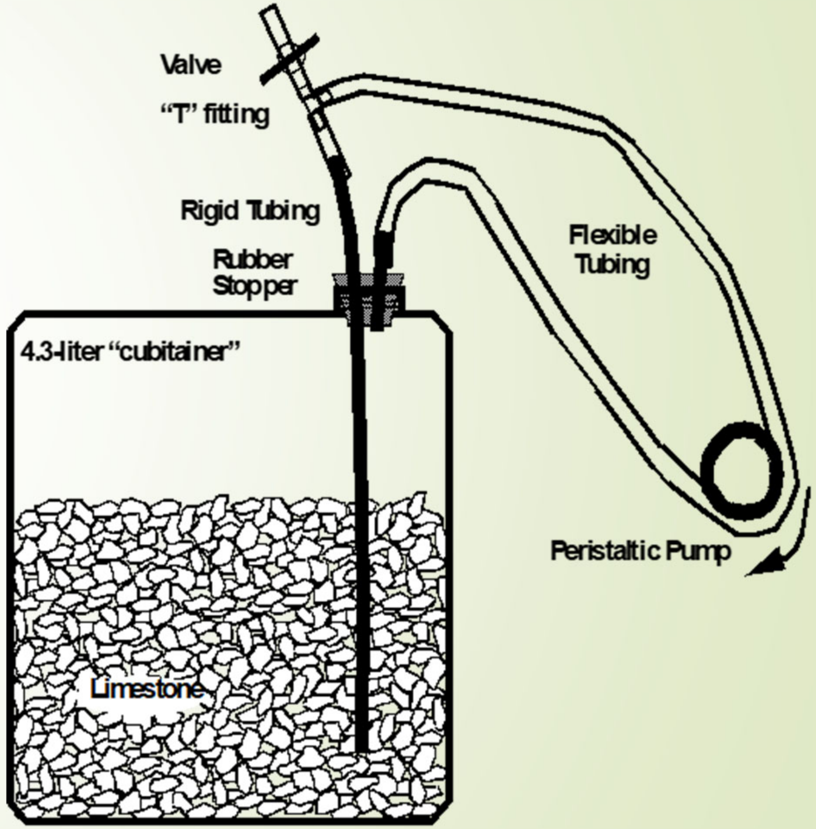
  T = Design Life (hrs.)

  X = Limestone $CaCO_3$ content (fractional)

* Determined experimentally with a jar test (Cubitaner)

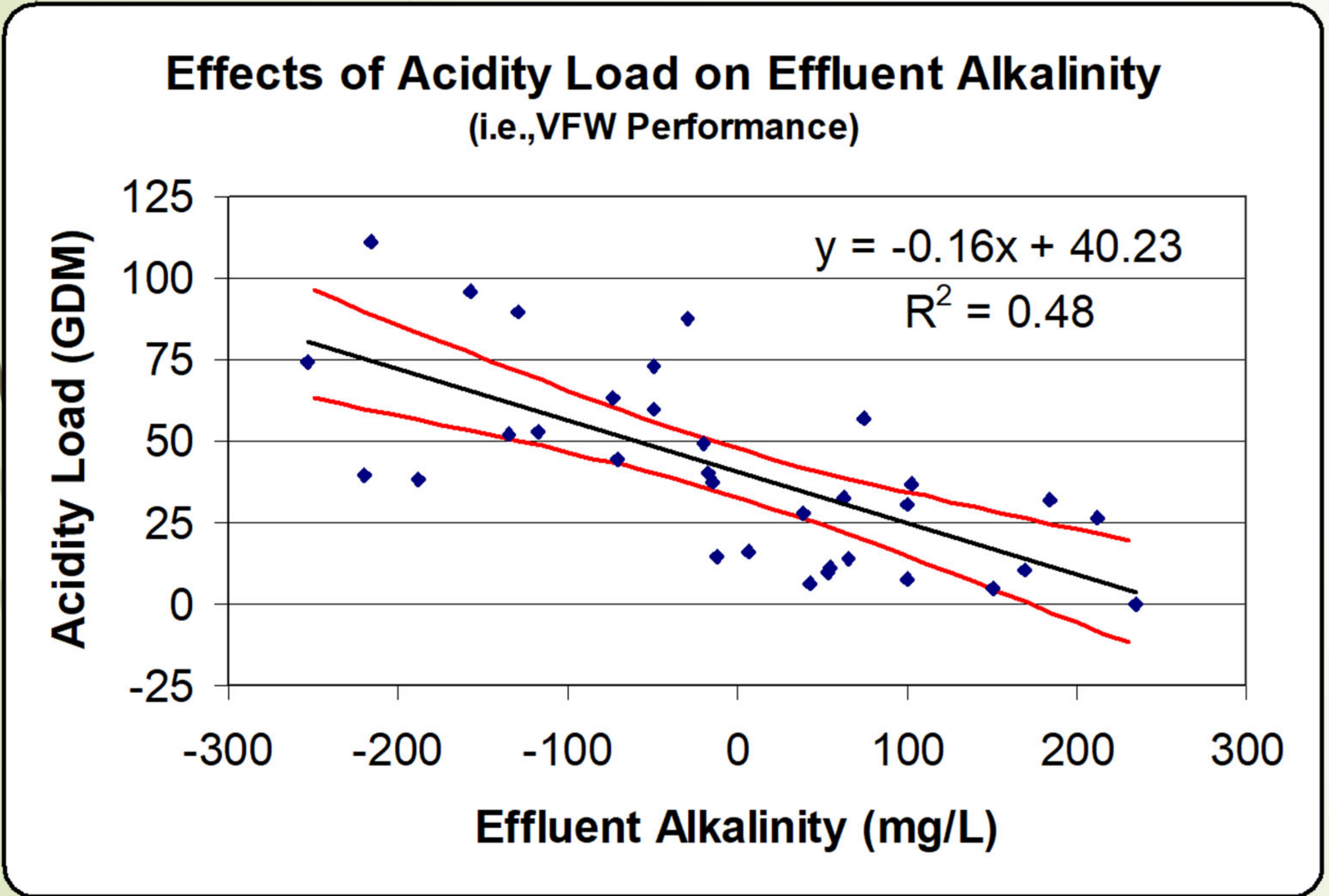
Cubitainer Test – Used to simulate closed limestone leaching conditions





Source: Cravotta (2003)

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/m²* Acidity Removal Rate.

*Based on removal rates in 30 VFPs with variable construction parameters. Acidity removal rates from 25 to 35 g/m²/d is accepted practice.

Computes the size of the VFP in m² (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 VFPs or sulfate-reducing bioreactors.
- For this study we compiled the construction and performance data for 9 VFPs:
  - Seven 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.
  - Four are conventional VFP's; two of these are arranged in series (SAPS).
  - One is a bioreactor selected for comparison.
  - Not discussed here are about 20 additional bioreactors constructed in Indiana and three additional hybrid bioreactors/VFP's built in Missouri.

Performance Midwestern Hybrid VFP's Compared to Appalachian VFPs: Midwest 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.
- Two additional midwestern VFPs (IL1 and MO3) were 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 the three alkalinity-producing cells.
- Two VFPs constructed in MO have convectional VFP configurations (MO4 and MO5).

Midwestern VFPs Included in this study

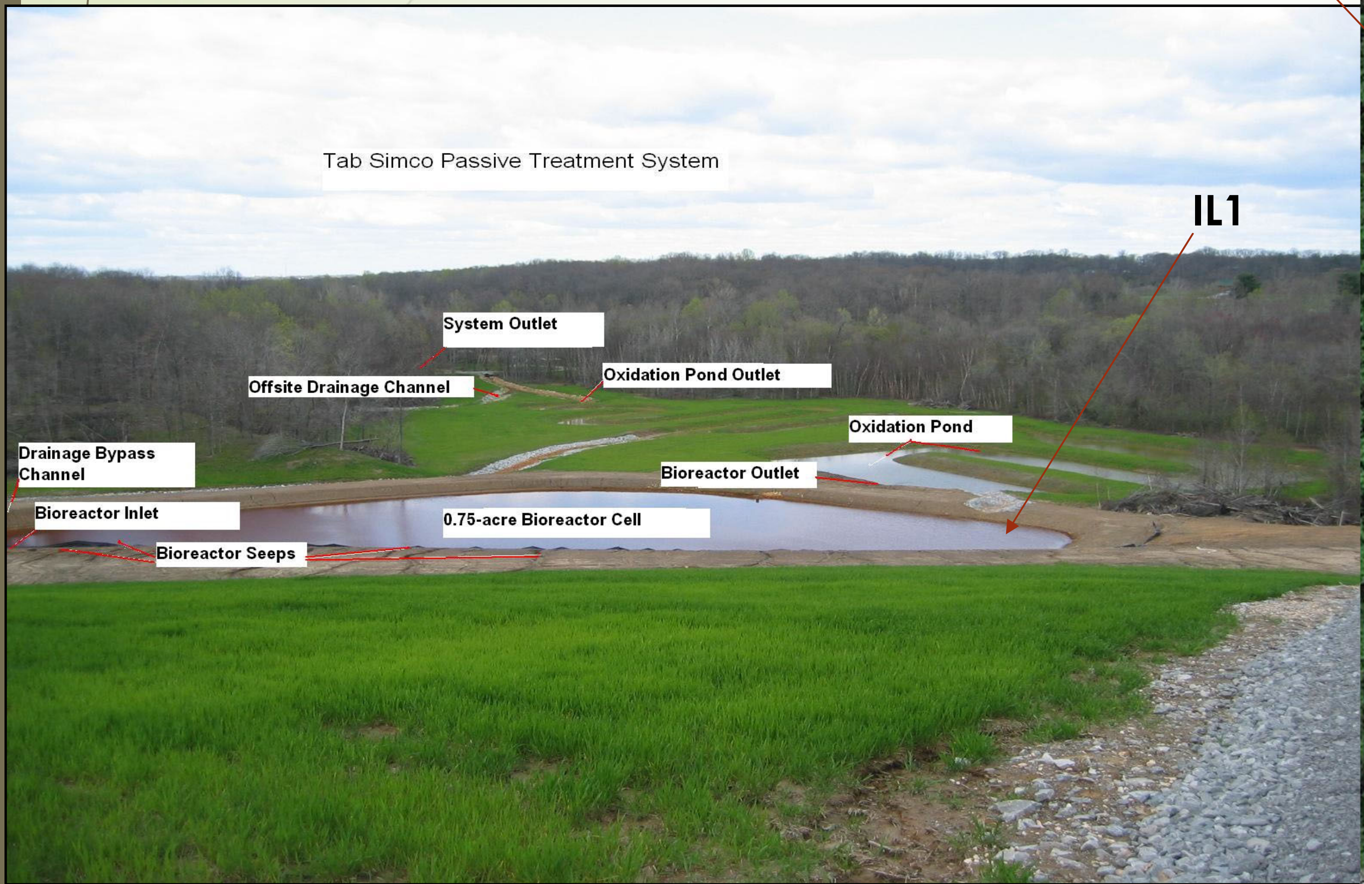
Midwestern
North PTS
Bioreactor

IN3

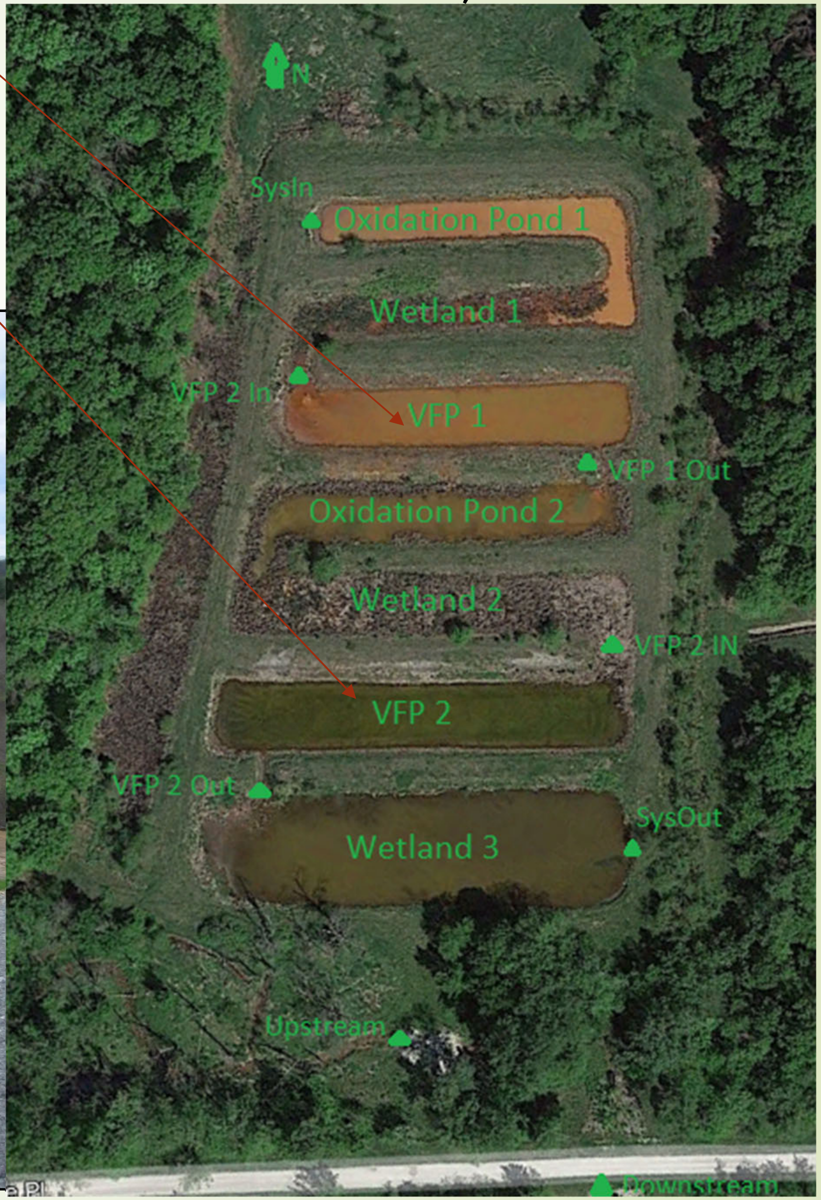
IN1 IN2

Enos Loop PTS, Indiana

Midwestern VFPs Included in this study

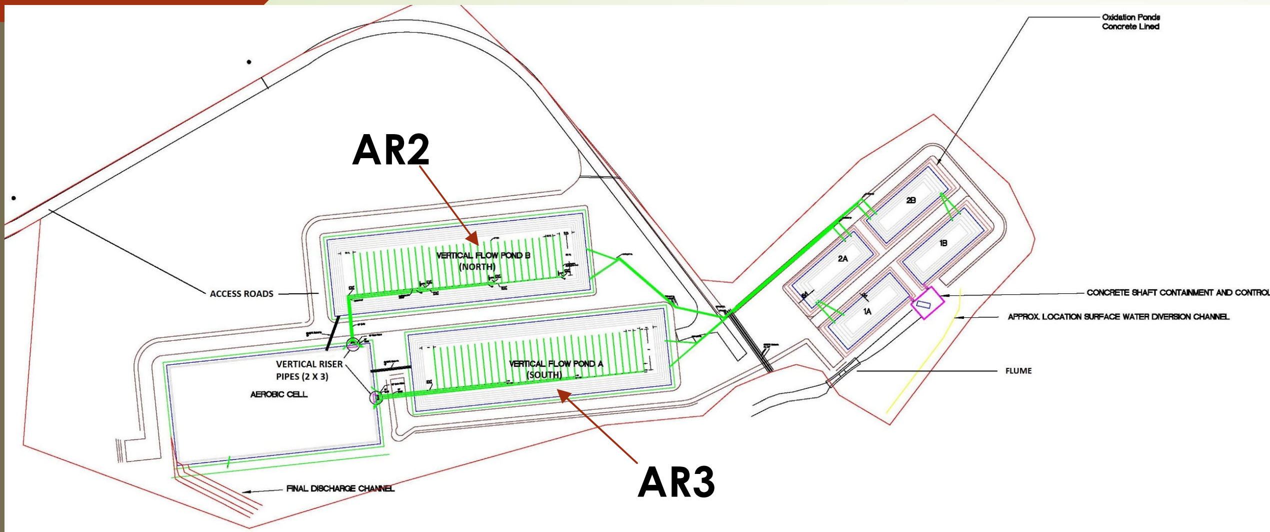


Enos PTS, Missouri

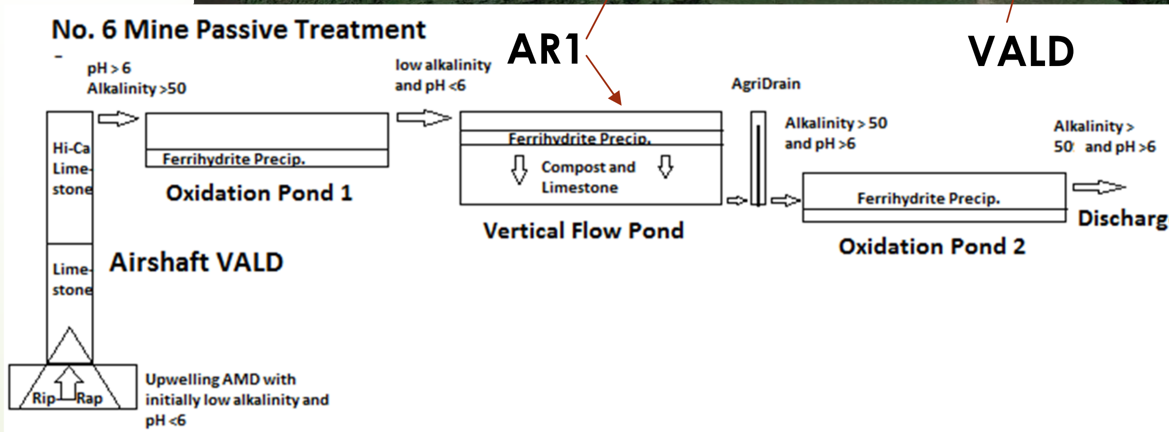


Midwestern VFPs Included in this Study

Hartford PTS, Arkansas



No. 6 Mine PTS, Arkansas



Midwestern VFPs Included in this Study

MO3 - L-Pit OLA* (Hybrid VFP), Missouri

* L-Pit OLA* (Hybrid VFP), Missouri

MO4 - East PTS OLA* (VFP), Missouri

Location, Type, Design Details, Construction and Rehab Dates Midwestern US Downflow VFPs

VFP ID	Location	System Type	Water Layer* (cm)	Compost Layer* (cm)	Limestone Layer* (cm)	Build Date (mo./yr.)	Operation (years)**	Compost Replacement Date (mo./yr.)
IL1	Carbondale, Illinois	Hybrid VFP/Bioreactor	30.0	180.0	60.9	12/2007	15.5	10/2013
IN1	Enos Corner, Indiana	Hybrid VFP/Bioreactor	90.0	90.0	60.9	12/2005	18.6	10/2009
IN2	Enos Corner, Indiana	Hybrid VFP/Bioreactor	90.0	90.0	60.9	12/2005	18.6	10/2012
IN3	Augusta, Indiana	Bioreactor	30.0	152.4	0.0	12/2008	14.4	N/A
MO1	Bevier, Missouri	SAPS1***	76.2	45.7	114.3	8/2001	21.8	3/2021
MO2	Bevier, Missouri	SAPS2***	76.2	45.7	114.3	8/2001	21.8	3/2021
MO3	Montrose, Missouri	Hybrid VFP/Bioreactor	30.5	137.2	76.2	5/2016	7.7	N/A
MO4	Montrose, Missouri	VFP	38.1	45.7	76.2	4/2017	6.8	N/A
MO5	Montrose, Missouri	VFP	15.2	45.7	76.2	4/2017	6.8	N/A
AR1	Huntington, Ark.	Hybrid VFP/Bioreactor	30.0	60.9	68.6	3/2009	11.2	N/A
AR2	Hartford, Arkansas	N. Hybrid VFP/Bioreactor	30.0	60.9	76.2	5/2015	8.0	N/A
AR3	Hartford, Arkansas	S. Hybrid VFP/Bioreactor	30.0	60.9	76.2	5/2015	8.0	N/A

* Water, compost, and limestone layer sum = hydraulic head; 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	Pool Area (m^2)	Hydraulic Head (cm)	Flow (LPM)	Water HRT (Hr.)	Compost HRT (Hr.)	Limestone HRT (Hr.)
IL1	Hybrid VFP	3521	255.9	85.05	202.8	316.0	110.5
IN1	Hybrid VFP	4016	225.9	599.4	95.0	25.3	19.7
IN2	Hybrid VFP	5487	225.9	599.4	130.9	35.4	27.4
IN3	Bioreactor	2394	167.4	70.41	161.8	152.7	0.0
MO1	SAPS1***	918	205.8	82.44	52.1	7.86	14.9
MO2	SAPS2***	1154	213.4	82.44	66.2	10.2	21.4
MO3	Hybrid VFP	1728	243.8	18.33	464.8	470.8	221.9
MO4	VFP	1103	160.0	30.85	216.9	70.2	125.8
MO5	VFP	1838	137.1	112.9	40.9	34.7	64.8
AR1	Hybrid VFP	2875	160.0	27.06	52.6	26.3	37.6
AR2	N. Hybrid VFP	3776	167.7	164.7	114.2	65.5	92.8
AR3	S. Hybrid VFP	3833	167.7	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.

Acidity Calculations

- Dissolved ferrous iron, ferric iron, manganese, and aluminum along with pH are used to calculate acidity from the formula:

- **Acidity = $50*((2*[Fe^{2+}]/55.85) + (3*[Fe^{3+}]/55.85) + (2*[Mn]/54.94) + (3*[Al]/26.98) + (1000*10^{-pH}))$**

- Calculated acidity values are reported as calcium carbonate equivalent (CCE). System performance is based on comparisons of net acidity where:

- **Net acidity = calculated acidity – total alkalinity**

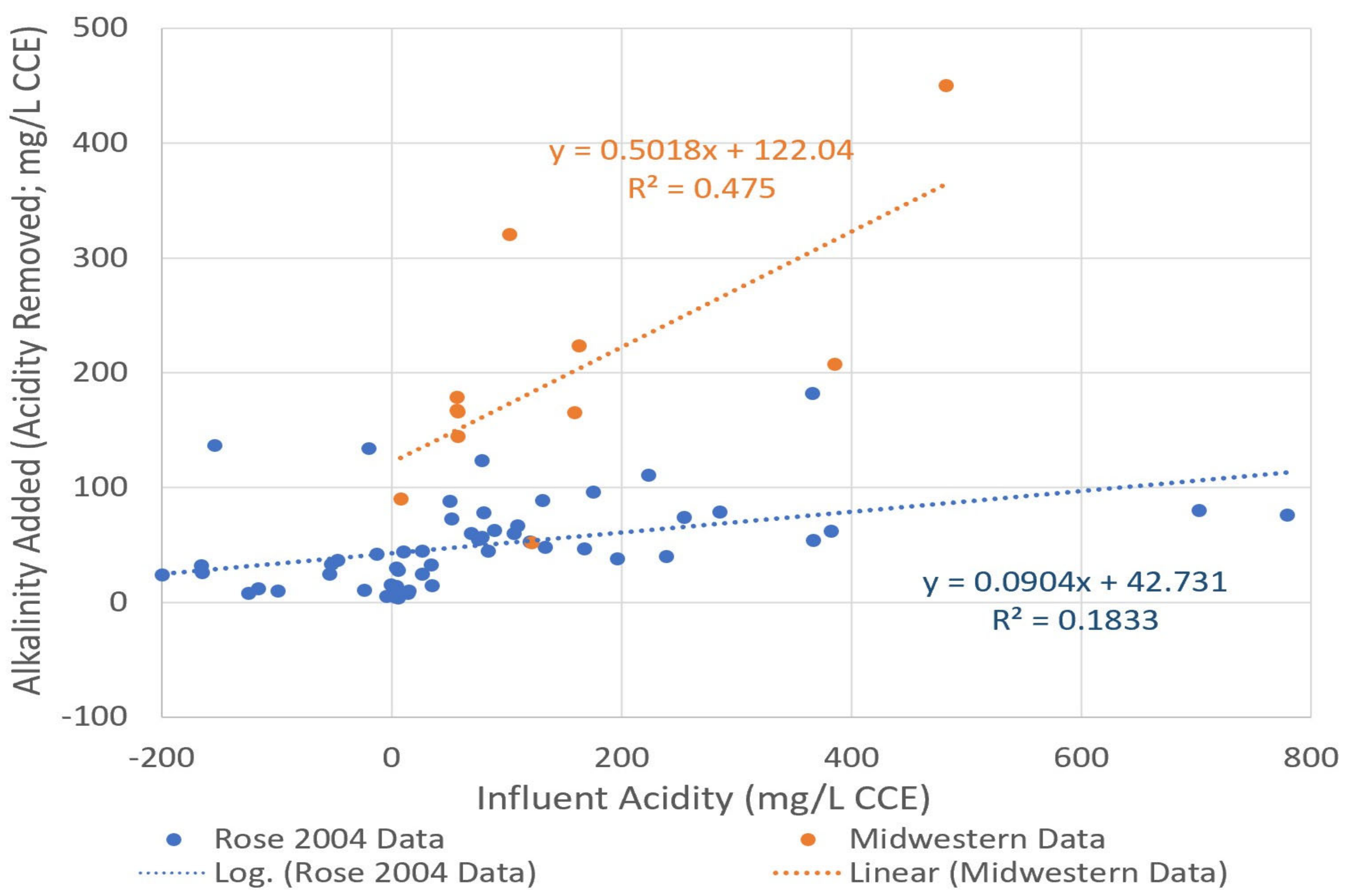
- In most cases, calculated acidity could be determined from field and laboratory values. If metal data is unavailable, lab (measured) acidity values were applied (lab acidity ~ net acidity = calculated acidity – total alkalinity).

Midwestern VFP’s: Selected Chemical Data

Cell ID	Type**	Net 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	n =
IL1	Hybrid	1,830.0	495.9	37.34	122.3	127.7	32.78	0.756	92.7	70
IN1	Hybrid	57.2	14.8	2.32	0.96	4.43	2.44	0.143	- 87.8	56
IN2	Hybrid	57.2	14.8	2.32	0.96	4.27	2.43	0.140	-109.2	56
IN3	Bioreactor	482.5	110.5	10.95	8.05	2.61	6.78	0.250	32.0	42
MO1	SAPS1	385.2	154.5	8.08	1.73	154.0	8.00	0.222	177.3	20
MO2	SAPS2	163.0	15.1	8.62	0.79	36.08	7.67	0.147	-60.9	20
MO3	Hybrid	102.2	52.0	19.71	1.82	8.45	6.24	0.115	-218.2	8
MO4	VFP	129.2	129.2	25.79	5.95	62.64	18.74	0.095	69.5	5
MO5	VFP	158.5	39.93	19.70	0.79	2.98	15.23	0.151	-7.3	5
AR1	Hybrid	7.45	3.14	2.02	0.033	0.54	1.77	0.027	-82.6	13
AR2	Hybrid	56.9	2.16	7.39	0.79	9.60	7.70	0.150	-110.8	5
AR3	Hybrid	56.9	2.16	7.39	0.79	0.90	5.70	0.195	-122.3	5

* Acidity values in mg/L calcium carbonate equivalent.

Performance of Conventional and Hybrid VFPs: Comparison to Rose (2004) Data



Loading Rate of Vertical Treatment Cells

- Loading rate is calculated using the pool area of the VFP (m^2), inlet AMD flow rate (LPM) and the pollutant concentration (mg/L). As an example, using the net acidity of the AMD at the VFP inlet:

- **Acidity Loading ($g/m^2/day$) = [1.44 * Net Acidity (mg/L) * Flow (LPM)]/Pool Area (m^3)]**

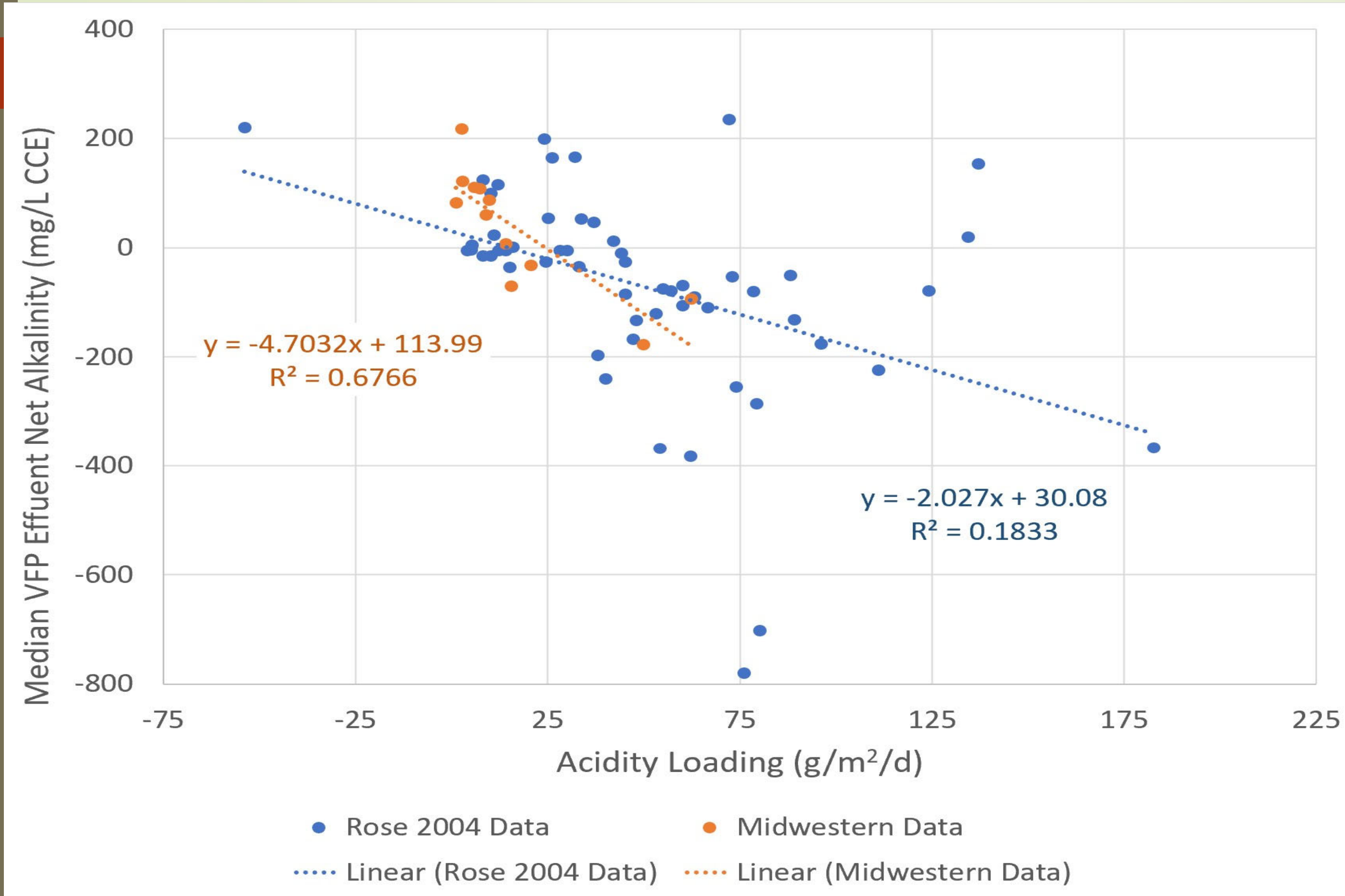
- Average acidity load for this study ranged from 2.62 to 62.25 $g/m^2/day$ and average acidity removal was between 2.14 and 58.71 $g/m^2/day$ (Table 3).
- Bioreactors IL1 and IN3 and MO1, the initial VFP of a 2-stage SAPS system, received the greatest acidity load with commensurate elevated metal loads.
- Several vertical flow systems produced slightly net acidic drainage [acidity load > acidity removal; bioreactors IL1, IN3, VFP MO1 (SAPS1), and hybrid VFPs MO4, MO5].
- In a SAPS system, the initial VFP is expected to produce net acid water as oxidation in the intervening oxidation ponds and/or aerobic wetland will produce lower pH drainage that assists in limestone dissolution in the follow-up VFP (SAPS2).

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

VFP ID	Type*	Acidity Load g/m²/d	Fe Load g/m²/d	Mn Load g/m²/d	Al Load g/m²/d	Cumulative Metal Load g/m²/d	Acidity Removal Rate g/m2/d
IL1	Hybrid	62.25	16.86	1.27	4.17	22.46	58.71
IN1	Hybrid	9.75	3.18	0.489	0.205	3.93	34.79
IN2	Hybrid	7.13	2.33	0.358	0.150	2.88	20.95
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	2.52	14.09
MO3	Hybrid	2.62	0.795	0.107	0.030	0.931	2.14
MO4	VFP	15.33	5.20	1.04	0.240	6.59	12.53
MO5	VFP	14.02	3.53	0.032	0.161	5.44	14.67
AR1	Hybrid	1.01	0.426	0.274	0.004	0.704	13.07
AR2	Hybrid	5.90	0.561	0.422	0.069	1.05	12.93
AR3	Hybrid	2.72	0.259	0.195	0.032	0.486	5.70
VFP Average		**22.03**	**7.808**	**0.758**	**0.176**	**9.197**	**14.18**
Hybrid Average		**4.86**	**1.258**	**0.307**	**0.082**	**1.663**	**14.93**
Bioreactor Average		**41.34**	**10.771**	**0.866**	**2.256**	**13.973**	**38.90**

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

Performance of VFP Types – Areal Loading Considerations



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

- Hybrid VFPs and MO1 and bioreactor IN3 received the greatest acidity load with commensurate elevated metal loads.
- Sulfite ions discharging from a hybrid VFPs, and bioreactors may lead to additional alkalinity from sulfate reduction in deep portions of follow-up oxidation ponds.
- 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 shorter operation period when higher performance is expected.
- Construction of Appalachian VFPs predated most Midwestern VFPs. Midwestern VFP's benefited from lessons learned.

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 Bioreactors 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 lower R^2 value than the 2002/2004 data sets.
- 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.

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 could 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 lower TDS in the AMD source area.

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

The End -- Questions?