CASE STUDIES OF PASSIVE TREATMENT SYSTEMS: VERTICAL FLOW SYSTEMS [1]

Arthur W. Rose and Jonathan M. Dietz[2]

Abstract. As part of the Acid Drainage Technology Initiative (ADTI), case studies of 30 vertical flow systems (VFS or SAPS) have been compiled. Data includes inflow and outflow chemistry, flow rates, dimensions, design features and problems encountered. The increase in net alkalinity ranges widely, from 7 to 686 mg/L $CaCO_3$ (median 160 mg/L), but is positive for all systems. Systems having low influent acidity added little net alkalinity compared to units with high influent acidity. Increased retention time shows a correlation with increase in net alkalinity, suggesting that a standard retention time is not necessarily optimum. A regression of influent acidity loading vs. effluent alkalinity indicates that an acidity loading less than 40 $g/m^2/d$, on average, produces net alkaline effluent (r^2=0.55, p=0.0002). Similarly, 12 of the VFS had net acid effluent and are interpreted to be at the limit of VFS effectiveness. Most of the 12 units decrease acidity by between 25 and 50 $g/m^2/d$. These values are similar to the 25 $g/m^2/d$ determined by Dietz and Stidinger (1996). A value of 25 $g/m^2/d$ is suggested as a design criterion for VFS, in place of retention time. Results for several units suggest that this loading may be increased by addition of fine limestone to the compost layer, and multiple regressions suggest that pH and acidity may modify the expected effectiveness.

Multiple regressions show that net added alkalinity depends positively on influent Fe and negatively on Mn, as found by Jage et al. (2001), but also on H^+ (antilog pH) and retention time in compost. Many units have operated satisfactorily for 5 to 10 years, but regular inspections are desirable to correct minor problems. Thin spots in compost are deleterious because of channeling, and high-Fe inflows may suffer from accumulation of Fe precipitates in the VFS pond.

Additional key words: Acid mine drainage, SAPS, vertical flow wetlands.

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Introduction

Over the past 10 years, increasing numbers of passive systems have been constructed for treating acid mine drainage (AMD). These systems are constructed so that AMD flowing through them encounters chemical and microbial environments that neutralize the AMD and remove Fe, Al and other metals. In passive systems, relatively little attention is needed after construction, in contrast to the daily to weekly attention needed for active treatment systems such as those for addition of NaOH or lime. The general characteristics of passive systems have been discussed by Hedin et al. (1994), Skousen et al. (1998), Kepler and McCleary (1994), and Watzlaf et al. (2000).

Passive systems have shown variable success. Some systems have worked well for many years, and others have failed or declined markedly in effectiveness after months or years. Aerobic wetlands and anoxic limestone drains have been reviewed and the design parameters and limitations on water chemistry are extensively discussed (Hedin et al, 1994, Hedin and Watzlaf, 1994; Skousen et al., 1998; Watzlaf et al., 2000). However, for vertical flow systems, much less information has been published on successful vs. unsuccessful designs. Many workers have used retention time in the limestone as a sizing criterion, but this criterion has not been evaluated as an effective design approach in sizing vertical flow systems. Indeed, the dependence on log retention time found by Jage et al. (2001) suggests that retention times of hundreds of hours may have beneficial effects.

The purpose of this paper is to report information on 30 VFS, to identify key parameters and problems, and to suggest improved design criteria and features. Data on 9 additional VFS units (Filson 5/6, Glacial, Brandy Camp, Cold Stream A, B1, B2, Glenwhite, REM, Schnepp) have been obtained but not utilized in this paper because of limited sampling (only 3 to 5 sampling events) or data limited to the initial year when short-term effects are common. However, some helpful ideas have been suggested by these systems. The approach has been to collect information on as many systems as possible, and to compile these as "case studies" on a standard form. The compilation has grown out of the Acid Drainage Technology Initiative (ADTI), which is a collaborative program involving industry, federal and state regulators, and academic researchers (Hornberger et al., 2000). A handbook on avoidance and remediation technology has been published (Skousen et al., 1998), but the ADTI Passive Treatment Subgroup has

continued compilation efforts because this technology was judged to be in a state of rapid change. The current information is intended to lead to a more comprehensive summary on passive treatment technologies.

Compilation of Information on Vertical Flow Systems

Vertical flow systems (VFS) are also termed successive alkalinity producing systems (SAPS, Kepler and McCleary, 1994), vertical flow wetlands (VFW), vertical flow ponds (VFP) and reducing and alkalinity producing systems (RAPS, Watzlaf et al., 2000). They typically consist of a pond filled with influent AMD overlying of a layer of compost, which is in turn underlain by a layer of limestone aggregate with outflow through a set of perforated pipes, connected to outflow pipes on the lower side of the pond (Figure 1). Outflow from the vertical flow system typically flows into a pond and/or wetland in which Fe(II) oxidizes to Fe(III) and precipitates. Some systems are flushable in order to remove Al and Fe hydroxides that have accumulated within the limestone layer (Kepler and McCleary, 1997).
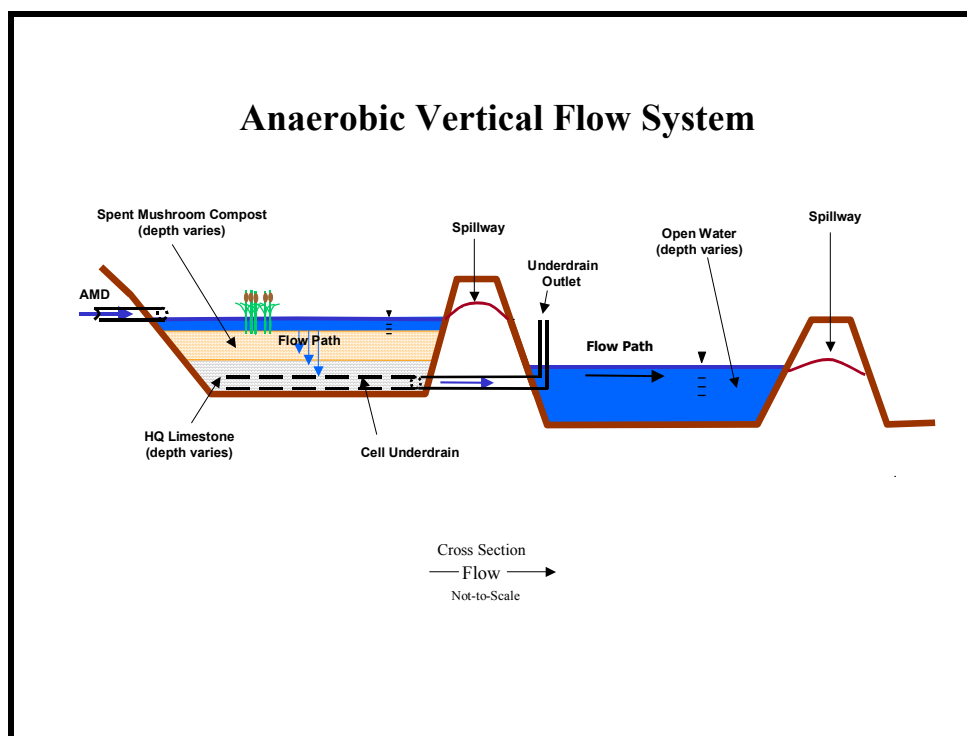

Figure 1. Diagram of a typical vertical flow system, with accompanying oxidation/settling pond.

Case studies on VFS have been contributed mainly by members of the ADTI Passive Treatment Subgroup, plus several others as indicated in the acknowledgments. In addition,

several sites were compiled from permit files of PA DEP.   Most sites were built at least partly with public funding, but a few are company-built facilities for which public data are available.

For VFS, the following types of information have been sought (though for some sites the data are incomplete):

1. Inflow and outflow chemistry over one or more years, preferably after the initial few months when short-term changes are common.

2. Flow rates tied to the chemical information, so that loadings can be calculated.

3. Date of construction, and the period of chemical and flow data collection. Data for the first 6 months of operation have usually been deleted because of short-term effects.

4. Size of the system, including surface dimensions, and thickness and/or mass of limestone and compost, plus a plan view showing dimensions, shape and sample sites.

5. Design features, such as size of limestone aggregate, presence of liners, underdrain characteristics, etc.

6. Cost of construction.

7. Location of facilities, designer, and other information allowing for later follow-up.

8. Problems encountered with the facility, such as decreased treatment over time, plugging, overflow, etc.

Basic physical information on the VFS sites is listed in Table 1.   A few comments on certain variables follow.

Length and width - These values are for the water surface dimensions, as far as can be determined.

Area.-   In most cases, area is computed from the length and width, but for a few systems of non-rectangular shape, the area has been calculated from a series of triangles.

Volume of limestone layer- Calculated from area and thickness of limestone, assuming a 2H:1V inward slope of pond walls, using the prismoidal formula and the thicknesses of the water, compost and limestone layers. It is possible that this calculation underestimates limestone if the margins of the limestone bed are steeper than 2:1.

Mass of limestone- Calculated from volume for most sites, assuming 50% porosity and a stone density of 2.5 g/cm^3, but for a few sites, the actual mass of stone was available.

Limestone diameter- The approximate maximum dimension of limestone fragments.

Retention time in limestone- Calculated from flow rate and limestone volume, assuming 50% porosity.

Retention time in compost- Calculated based on a porosity of 25 percent.

Source of data- See Table 1. This is the person or organization who provided the basic case study, though in some cases this was modified or extended by the authors.

Table 1. Data on SAPS systems

Name	Built	Flow L/min	Length m	Width m	Water depth m	Comp. Th. m	Ls. Th m	Area m2	Vol. ls m3	Mass ls. Mg	Ls dia. cm	Ret. T in Ls hr	Ret. T in Comp. hr	Cost $1,000	Source
Filson 1	94	116	35	12	1	0.5	0.65	420	85	106	1.3	6.1	7.5		D
Howe Bridge	10/91	144	45	25	1.5	0.15	0.6	1125	384	454	1.3	22.2	4.9	9	W,D,K
Pot Ridge TEST	10/95	76	37	36	0.76	0.3	1.83	1330	1505	2560	10.0	165.0	21.9	87.6	R
Pot Ridge C6	7/97	215	37	30	1.6	0.3	1.5	1110	773	966	10.0	30.0	6.5		R
Pot Ridge C10	10/97	215	35	28	1.6	0.3	1.5	980	641	801	10.0	24.8	5.7		R
Oven Run D1	95	323	79.2	15.2	1.5	0.3	0.91	1200	438	548		11.3	4.6		H,W
Oven Run D2	95	335	76.2	15.2	1.5	0.3	0.91	1158	419	524		10.4	4.3		H,W
Oven Run E1		500	135	26	1.5	0.3	0.91	3510	1948	2435		32.5	8.8	138	H,W
Oven Run E2		500	135	26	1.5	0.3	0.91	3510	1948	2435		32.5	8.8	137	H,W
Oven Run B1	99	817	286	28	0.6	0.3	0.91	8008	5766	12000	10.0	58.8	12.3	476	B
Oven Run B2	99	817	169	46	0.6	0.3	0.91	7774	6041	12000	10.0	61.6	11.9	476	B
Jennings	97	67	50	20		0.66	.45(1)	1000	344	345	2.5	42.8	41.0		W
Sommerville	95	95	45	30	1	0.4*(2)	0.4	1350	364	455		31.9	23.7		D
McKinley	96	57	30	20	0.4	0.15	0.4	600	183	229		26.8	6.6		D
Hortert	99	31	24.3	19.8	0.6	0.45		481	364	455	8.0	97.8	29.1	113.5	B
Harb-Walk.	11/99	42	21.3	19.2	1	0.15	0.91	409	174	740	9.0	34.5	6.1		Du
BEL1	96	190				1.37	0.46	395	63	79		3.6	11.9	32.3	Z
BEL2	96	185				1.07	0.76	498	199	249		14.3	12.0	32.3	Z
LLC2	95	100				1.07	0.46	295	103	129		16.3	13.2	20	Z
LLC3	95	100				1.07	0.46	357	120	150		20.1	15.9	20	Z
LLC4	95	100				1.07	0.46	197	51	64		11.8	8.8	20	Z
PMAC	96	4						223	75	94		625.0	0.0	32	Z
USC1	96	68				0.15	0.76	662	469	586		90.0	6.1	22.5	Z
USC2	96	70				0.15	0.76	395	248	310		50.0	3.5	22.5	Z
Rock Run #1	99	99	21.3	15.2		0.15	0.91	324	221	276		18.6	2.0	7.5	Mi
Rock Run #2	99	112	22.8	10.7		0.15	0.91	245	155	194		11.5	1.4	7.5	Mi
Maust #1	97	177	35	35	1	0.6	0.46	1225	353	1640	5.0	16.6	17.3	150	R
Maust #2	97	177	28.9	27.4	1	0.6	0.46	792	199	930	5.0	9.4	11.2	150	R
Lambert	97?	36	18.3	18.3	0.9	0.15	0.9	335	137	171		31.7	5.8		R

Sources: B = PA BAMR, D = Demchak, Du = Margaret Dunn and other of Stream Restoration Inc., H = William Hellier of PA DEP, Mi = Scott Miller and others of Ohio University, W = George Watzlaf and Candace Kairies of US DOE, R = A.W. Rose (in part from DEP files), Z= Carl Zipper of Virginia Tech Univ.
(1) Most limestone mixed with compost.
(2) Thickness highly variable

Chemical and flow data are listed in Table 2, as averages for the sites. In some cases, not all parameters were measured on every sampling date, but the averages of each parameter are assumed to represent the average behavior of the facility. For Howe Bridge three sets of data are available, for differing periods of time, from different individuals, and for Oven Run D, two sets of data are available. These provide some indication of sampling variability for these systems.

Throughout this paper, emphasis is on acidity and alkalinity as key parameters, rather than

Table 2. Chemical data from Vertical Flow Systems

Name	Period	N	Flow L/min	pH in	pH out	Acidity mg/L in	Acidity mg/L out	Alkal. mg/L in	Alkal. mg/L out	Iron mg/L in	Iron mg/L out	Manganese mg/L in	Manganese mg/L out	Aluminum mg/L in	Aluminum mg/L out	Calcium mg/L in	Calcium mg/L out	Sulfate mg/L in	Sulfate mg/L out
Filson 1	12/96-11/97	11	116	3.7	4.77	241	175	0	17	27.0	6.0	48.0	50.6	14.0	10.0	134	168	784	914
Howe Bridge W	1/92-9/00	41	144	5.8	5.89	323	106	31	56.8	193.0	73.7	38.0	36.0	0.0	0.0	193	240	1214	1102
Howe Bridge D	1/97-11/97	10	120	5.3	5.96	340	189	31	54	56.0	83.4	40.0	38.1			194	228	779	809
Howe Bridge K	11/91-10/96	70	163	3.1	5.8	180	80	0	65	208.0	48.0	35*	29*	0*	0*	199*	197*	1190*	1102*
Pot Ridge TEST	11/95-11/00	28	76	3.05	6.39	396	34	0	67	72.0	28.1	23.0	20.4	19.0	1.6	86	201	811	898
Pot Ridge C6	7/97=11/00	14	215	3.07	3.41	399	223	0	0	84.0	35.0	24.0	23.0	16.0	12.0	98	128	921	875
Pot Ridge C10	12/97-11/00	12	215	3.4	5.13	201	89	0	14	23.0	9.8	24.0	20.0	12.0	5.0	134	152	877	778
Oven Run D1W	10/95-9/00	14	367	4	5.57	114	9.9	0	28	38.0	3.0	29.0	28.2	1.8	0.9	297	323	1372	1358
Oven Run D1H	5/97-3/00	28	323	4.3	5.73	127	50	0	30	16.0	5.2	24.0	24.1	1.2	0.7			1322	1374
Oven Run D2 W	10/95-9/00	14	395	5.46	6.68	16	0		42	1.4	0.4	28.0	24.4	1.6	0.4	320	327	1340	1323
Oven Run D2 H	5/97-9/99	28	335	5.66	6.17	38	23	17	30	0.7	0.8	22.0	18.3	0.7	0.6			1292	1366
Oven Run E1	7/98-9/99	15	500*	3.04	4.34	217	84	0	13	16.0	10.7	11.0	11.4	15.0	9.6			900	944
Oven Run E2	7/98-9/99	14	500*	4.33	5.46	72	35	6	23	3.0	4.4	11.0	11.0	8.0	4.5			941	926
Oven Run B1	6/00-2/01	9	817	3	3.7	506	254	0	0	68.0	45.5	20.0	18.6	42.0	28.1			775	831
Oven Run B2	6/00-2/01	9	817	3.5	6.6	242	0	0	103	22.0	4.0	19.0	21.5	28.0	1.8			875	1104
Jennings	?	8	67	3.05	6.81	272	0	0	212	69.0	10.3	18.0	15.9	23.0	0.0	105	274	772	729
Sommerville	11/96-10/97	12	95	3.6	4.59	390	239	0	19	6.0	6.9	36.0	32.5	48.0	30.3	95	138	683	980
McKinley	12/96-11/97	10	57	3.9	6.53	101	4.1	3.2	65	5.0	0.4	36.0	17.2	2.1	0.3	160	179	717	691
Hortert	2/99-3/01	26	31	4.9	6.7	106	0	3.5	47	0.2	0.4	57.0	32.0	2.8	0.6	163	134	818	591
Harb-Walk (Ohiopyle)	12/99-5/01	13	42	5.9	6.8	205	4	18	104	92.0	21.0	19.5	17.0	0.1	0.1			891	875
BEL1		11	190	4.6	5	105	51.8	0.1	1.6	0.5	0.6	2.3	2.2					517	569
BEL2		11	185	5	6.2	52	5	1.6	42.5	0.6	0.4	2.2	2.1					680	541
LLC2		16	100	4.4	4.6	183	131	0.6	1.4	0.9	1.7	50.0	48.8					734	739
LLC3		16	100	4.6	5	131	120	1.4	2.7	1.7	1.7	49.0	46.4					739	670
LLC4		16	100	5	5.8	120	49.7	2.7	19.9	1.7	2.3	46.0	43.2					670	651
PMAC	6/97-3/99	48	4	4.4	6.5	196	2.8	2	153	122.0	15.5	10.3	10.3					1153	1107
USC1	2/97-6/99	19	68	4	4.7	256	196	0.1	8	1.1	1.2	35.0	31.6					686	508
USC2		19	70	5.1	6	44	0	29	54	0.8	0.7	19.0	16.0					540	283
Rock Run #1	8/00-5/01	10*	99	3.58	6.07	129	77.9	0	152	26.0	8.0	4.5	4.5	11.1	1.5	169*	253*	1013	986
Rock Run #2	8/00-5/01	10*	112	6.84	6.86	11.6	13.9	104	123	0.8	0.1	2.4	1.3	0.5	0.6	230*	235*	929	924
Maust #1	10/97-6/01	15*	177	3.17	7.08	154	0	0	184	23.7	0.8	15.1	9.4	2.6	0.0			570	474
Maust #2	10/97-6/01	14	177	6.8	7.23	0	0	187	234	0.8	0.6	9.8	6.9	<0.5	0.0			455	431
Lambert	2/00-5/01	14	36	4.6	7.39	66	0	17	169	8.8	0.8	14.3	6.8	7.6	0.0			838	674

*Fewer determinations than value of N

Fe, Al, pH, etc. Acidity and alkalinity express the total effect of the acid constituents and neutralization processes. They are independent of dissolved vs. total methods, and of sampling before vs. after an oxidation and settling pond. The term <u>net</u> alkalinity is used throughout to mean alkalinity minus acidity (mg/L $CaCO_3$). The term loading or loading rate is used for values in mass per unit time per unit area.

Effectiveness and Design Parameters for Vertical Flow Systems

Several parameters have been suggested for use in designing and in evaluating the effectiveness of VFS. Kepler and McCleary (1994) suggested that the expected increase in net alkalinity within a unit was 150-300 mg/L $CaCO_3$, and that additional units were needed if the influent exceeded this range. A minimum retention time of 14-16 hours has been suggested (Kepler and McCleary in Watzlaf and Hyman, 1995; Watzlaf et al., 2000). Hedin and Watzlaf (1994) provide equations for calculating the mass of limestone required in an ALD, assuming a 15-hour retention time. These equations have been used for designing the limestone layer of VFS. Dietz and Stidinger (1996) recommended a design criterion of 25 grams acidity/m^2/day to produce a long term net alkaline water in vertical flow systems. This recommendation was based on results from a controlled field study, which evaluated two small VFS located near Corsica, PA receiving different acidity loadings. Both VFW produced similar net alkaline effluent, but they found deteriorating compost layer conditions in the VFS removing the higher acidity loading of 62 grams acidity/m^2/day. Watzlaf et al. (2000) provided data on alkalinity generation rate for several VFS. Jage et al. (2000, 2001) showed that net alkalinity added could be predicted by a regression:

$$Alkadd = 43.12 \ln (T_r) + 0.75 Fe + 0.23 Ac^* - 58.45 \qquad (1)$$

where Alkadd is the net alkalinity added(mg/L $CaCO_3$), T_r is the residence time in the limestone layer (hrs), Fe is the influent Fe concentration (mg/L) and Ac* is the influent non-Mn acidity (mg/L $CaCO_3$) calculated from total acidity minus the manganese contribution to acidity (1.82*Mn in mg/L) because Mn acidity is not neutralized in these systems. Tables 2 and 3 list some measures of effectiveness for the systems.

Figure 2 illustrates the effect of influent acidity on effluent net alkalinity produced by VFS units. The significant trend indicates that as influent acidity increases, effluent net alkalinity
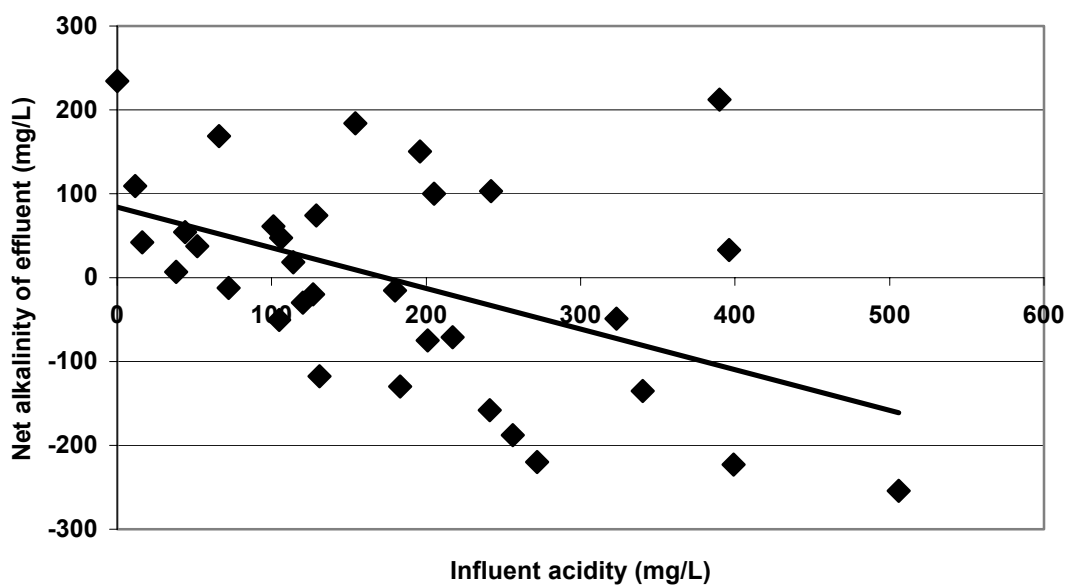
Figure 2. Net alkalinity of effluent vs. Acidity of influent, showing significant negative relation.
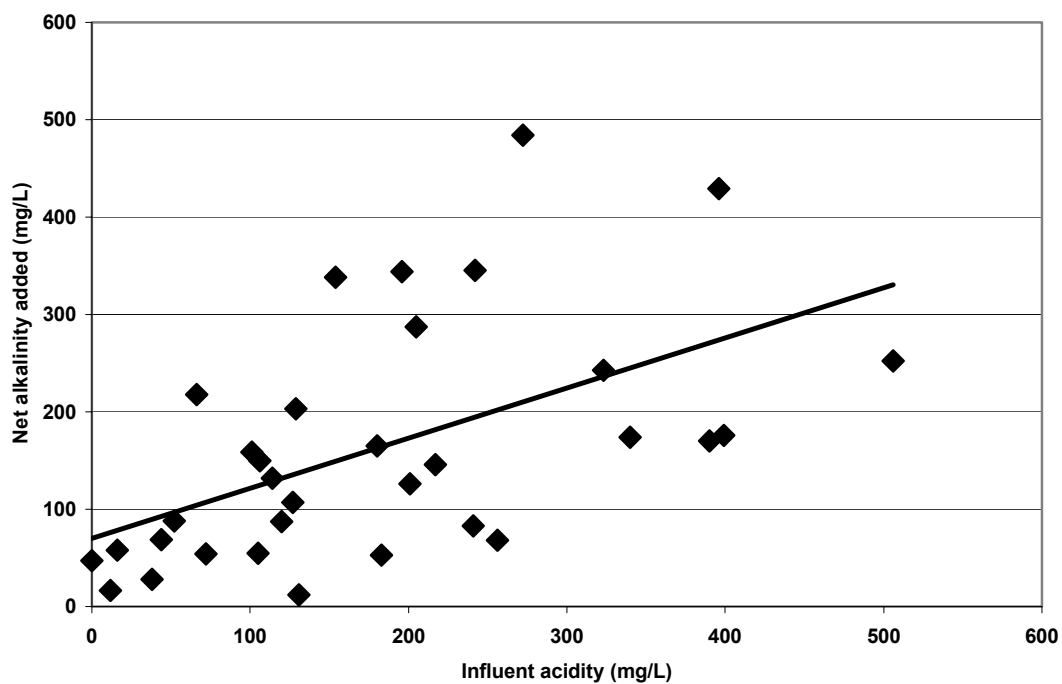

Figure 3. Net alkalinity added vs. acidity of effluent, showing significant positive correlation.

decreases, with an acid effluent occurring at an average influent acidity above 150 mg/L. However, several VFS with influent acidity greater than 150 mg/L produced net alkalinity in the

effluent, suggesting there may be some design difference in the VFS that resulted in this improved performance.

Figure 3 shows net added alkalinity as a function of influent acidity. The trend indicates that large amounts of alkalinity are added (acidity consumed) to influent with high acidity, and conversely, units with low influent acidity do not add much alkalinity. Evidently the processes in VFS do not operate uniformly for varying acidity. For this reason, a simple value of added alkalinity (i.e., 150-300 mg/L) is not a satisfactory design criterion.

Figure 4 illustrates the range of values for net added alkalinity (acidity removed plus effluent net alkalinity) by individual VFS units. All units added alkalinity, but the range varies widely, from 12 to 484 mg/L. The median alkalinity added is about 160 mg/L. Many of the values below 100 mg/L are from the second unit in a two-unit VFS. In some of these second units, the influent acidity is mainly Mn acidity. Evidently when effluent from the first unit has mainly Mn acidity, the second unit adds very little alkalinity. This phenomenon may be partly responsible for the correlation of Figure 3. Also, several of the double-unit VFS were designed with the idea that when the first unit eventually became less effective, the second unit would take up the load, so the second unit is not intended to have appreciable effectiveness in the first years.

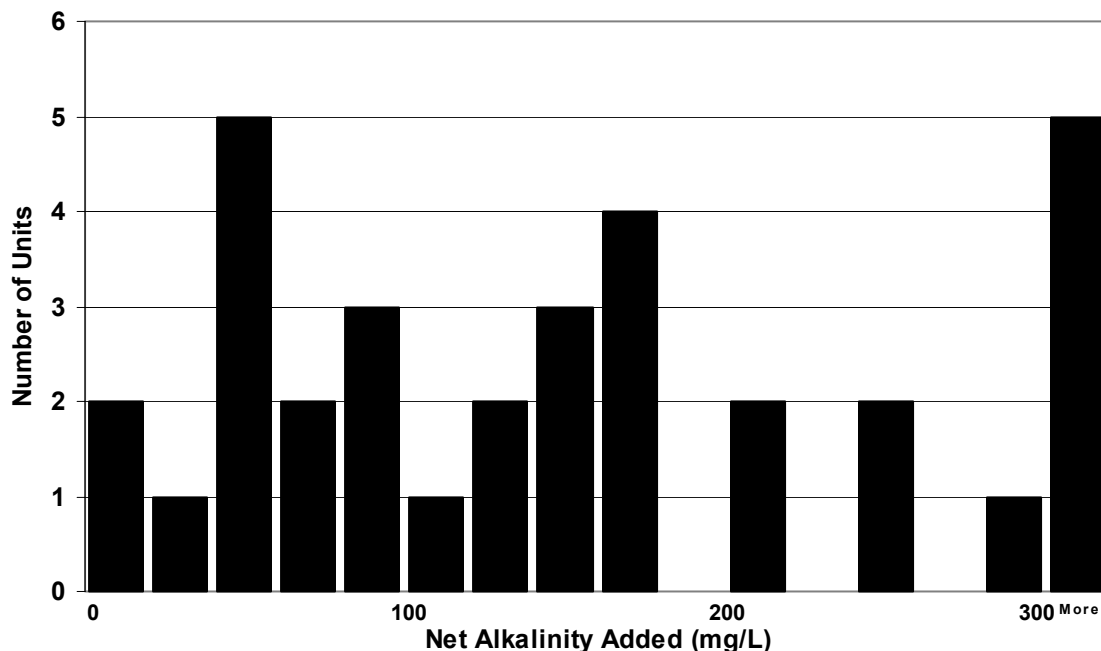Another possible design criterion is retention time. Our data shows no relation of effluent

Figure 4. Frequency distribution of net alkalinity added.

net alkalinity to retention time or log retention time. In fact, at similar retention times, an equal number of VFS produce net acidic as net alkaline effluent. Therefore, retention time is not a direct predictor for an alkaline effluent.

Net <u>added</u> alkalinity does show relations to log retention time. Jage et al. (2001) showed that alkalinity added (or acidity removed) was dependent on log retention time in limestone, up to times of hundreds of hours (see their Figure 2). Our data show a similar dependence of alkalinity added on log retention time in limestone (Figure 5). The correlation coefficient is 0.46, significant at the 1% level, though appreciable scatter exists. These data suggest that very long retention times could be beneficial for some waters.

The effect of log retention time on net added alkalinity contrasts with the leveling off in alkalinity gain after about 15 hours found for cubitainers (Watzlaf and Hedin, 1993) and field sites (Hedin and Watzlaf, 1994). However, their data were derived from only two influent waters, Howe Bridge and Morrison. Both of these waters have pH near 5, and partial pressure of CO_2 in the influent considerably exceeding atmospheric. The data of the present study, as well as that of Jage et al. (2001), suggest that for more acid waters, additional factors, such as influent acidity, coating of limestone by Al hydroxides or $CaSO_4$ or other factors, operate to slow the reaction rate and extend it over a longer period.
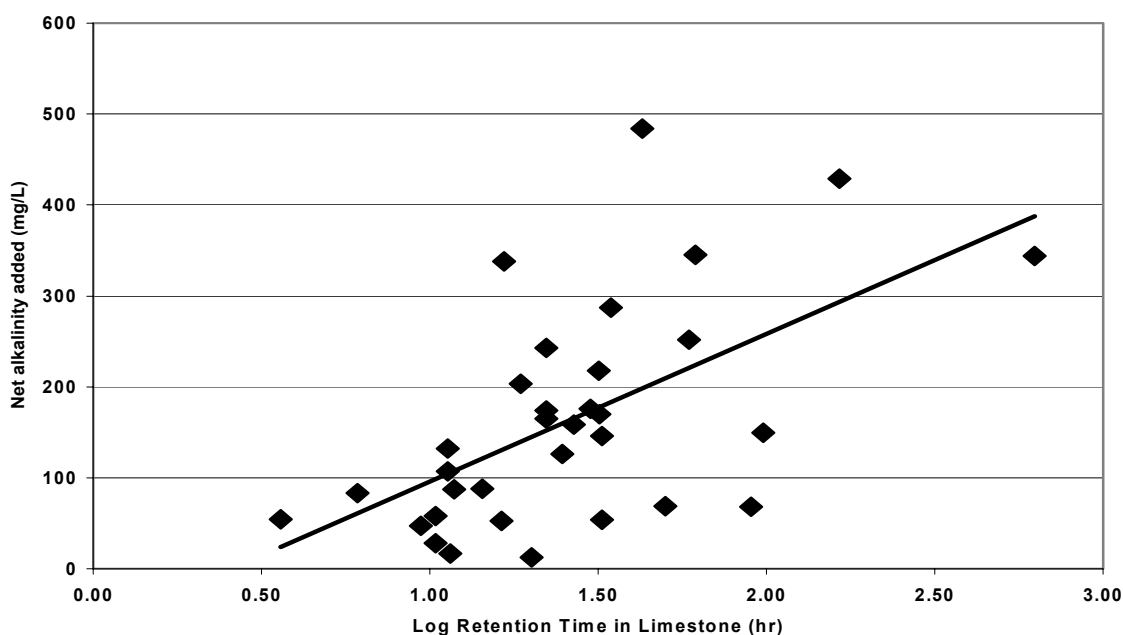

Figure 5. Net added alkalinity vs. log of retention time in limestone (hr.), showing positive correlation.

Increased retention time implies a larger volume (mass) of limestone for a given flow rate. If retention times of hundreds of hours might have benefit, then the optimum retention time must be evaluated economically (cost of additional limestone vs. benefits of additional acidity consumed). A retention time of 12-16 may be inadequate for many influent waters, as discussed later, and this parameter is not recommended as a primary design criterion. The cubitainer test of Watzlaf and Hedin (1993) may help identify sites requiring longer retention time, though effects of coating and other complicating factors may not become operative in short-term tests.

Use of Reaction Rates for Evaluation and Design

In evaluating the operation of VFS, it is appropriate to use rates of the chemical reactions, rather than just absolute concentrations of effluent. A simple method of evaluating reaction rates is to examine removal or generation rate based on a unit surface area or unit volume of the VFS. For example the rates can be evaluated as grams of alkalinity added or acidity consumed per day per square meter or cubic meter of VFS. Alternatively, one can examine the effect of varying acidity-loading rate ($g/m^2/d$) on effluent properties.

The net alkalinity of the effluent is found to be a clear function of the influent acidity loading rate in grams/m^2/day. Figure 6 shows this relation, along with the results of a linear regression.
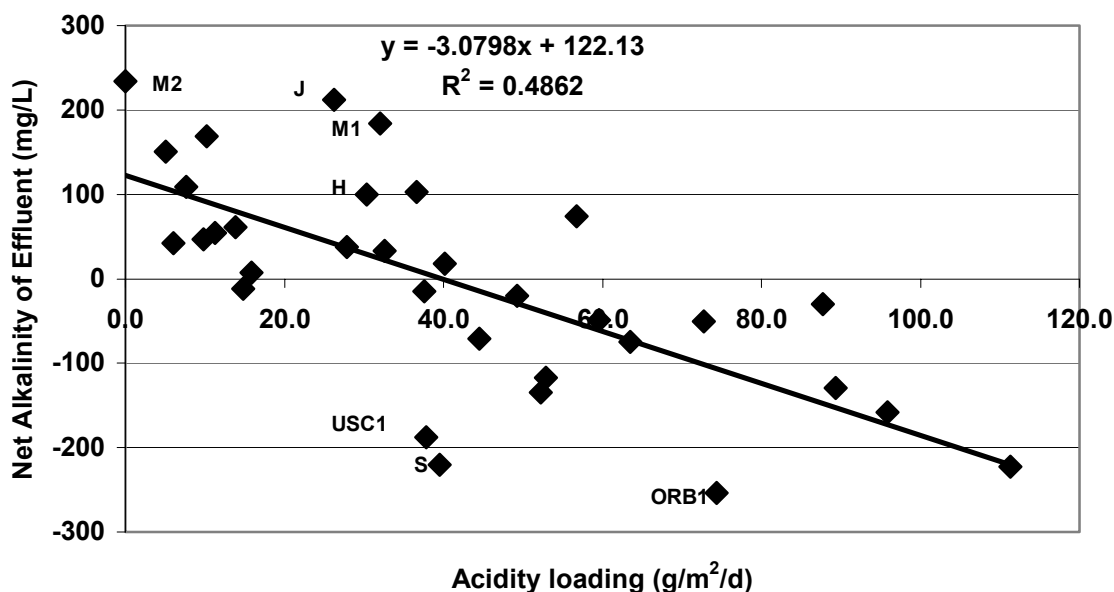

Figure 6. Net alkalinity of effluent vs. influent acidity loading, showing a negative relation and a value of 40 $g/m^2/d$ for generating alkaline effluent. M1, Maust 1; M2, Maust 2; J, Jennings; H, Harbison-Walker; S, Sommerville;, ORB1, Oven Run B1, USC1, USC1.

The effluent alkalinity decreases with increasing acidity loading rate.   The relation has an R^2 of 0.49, which is significant at about P=0.02.   The regression equation is:

$$Alk\ (mg/L) = -3.08\ AL(g/m^2/d) +122 \qquad (2)$$

where Alk is net effluent alkalinity and AL is acidity loading rate.   This regression predicts that a VFS will produce a net alkaline effluent, on average, when the loading is less than 40 $g/m^2/d$.

   Although the regression shows a strong relationship between acidity loading and net effluent alkalinity given the wide range of VFS designs (e.g., compost and limestone depths), the relation has considerable scatter.   Examination of the units with large deviations from the regression line indicates that additional factors may be involved.   The Sommerville and Oven Run B1 units show large negative deviations from the trend. The Sommerville unit was clearly observed to show vertical channeling (i.e., short-circuiting) through the compost layer (Demchak et al., 2001). The Oven Run B1 unit is also suspected of vertical channeling, in part because periodic flushing of the underdrain produces copious red-brown effluent and because the inflowing water appears to scour away the nearby compost (P. Milavec, personal communication).   No information is available on the characteristics of the USC1 site of Jage et al. (2000, 2001), which shows a similar large negative deviation. Note also that some second units in a system also tend to show negative deviations (Oven Run D2, Oven Run E2, LLC3), as previously discussed.

   Conversely, the Jennings, Maust 1, Maust 2 and Harbison units show large positive deviations from the trend.   At all four of these, limestone was mixed with the compost layer. It appears that this modification may increase the net effluent alkalinity produced by VFS. Thomas and Romanek (2001 and personal communication) also found markedly improved results in lab and field units with this modification.

   Deletion of the above 6 systems (Maust 1 and 2, Jennings, Harbison, Sommerville and Oven Run B1) improves the R^2 to 0.55, giving an equation of:

$$Alk.(mg/L) = -2.48\ AL\ (g/m^2/d) + 91.49 \qquad (3)$$

This model explains 55% of the effluent alkalinity variability in the data set, which is particularly intriguing given the range of influent chemistry, compost and limestone thickness, and retention times included in the data set (Table 1 and 2).

   The intercept for equation (3) is 37 $g/m^2/day$, which is the maximum acidity loading that produces a net alkaline water on an average basis.   The standard error of this regression (deviations from the regression line) is 69.6 mg/L, which can be used to calculate a 95%

confidence limit for the regression estimate (Dixon and Massey, 1951, p. 158-159). If the deviations are normally distributed, the 95% confidence limit is a conservative value above which the vast majority (97.5%) of all VFS units are expected to produce a net alkaline effluent greater than or equal to zero. This procedure yields an influent acidity loading of 25.6 $g/m^2/d$ for the VFS design, a value in close agreement with the 25 $g/m^2/d$ recommended by Dietz and Stidinger (1996).

Another parameter measuring the effectiveness of a VFS is alkalinity generation rate (R) in $g/m^2/d$, calculated from:

$$R = 1.44D_aQ/A \qquad\qquad\qquad (4)$$

where D_a is net alkalinity added (mg/L), Q is flow (L/min) and A is surface area of the VFS (m^2). Table 3 lists values of R for the sites. The values for this parameter range from 5 to 89 $g/m^2/d$, with a median of 34. This median appears to be a typical value for VFS, but the wide range requires further examination.

As noted above, many second units at a site add very little alkalinity, and their performance may be affected by an approach to calcite equilibrium, and other factors not evident in the more acid systems. Initial units treating AMD that is only slightly acid and generating net alkaline effluent may be affected by similar factors. However, fifteen of the VFS units had net acidic effluent. It can be inferred that these units are consuming acidity at the maximum possible rate for net acid conditions. Figure 7 shows the amount of acidity being consumed, on a loading basis, for these units with net acid effluent. Most of the units consume 25 to 50 $g/m^2/d$ of acidity. The rate of acidity reduction in these units is similar to the results for the regression of acidity loading vs. effluent alkalinity.

Based on these results, it is concluded that a rate of 25 $g/m^2/d$ is an appropriate conservative design criterion for standard VFS units. Addition of limestone to the compost may improve effectiveness above this rate, though further experimentation may be needed to ensure that this modification does not result in operational problems (e.g., plugging) for some influent mine drainage chemistries.

A comparison of this criterion with the retention time procedure, as presented by Hedin and Watzlaf (1994) for neutralization by limestone in ALD's, may be made using the equations presented on p. 193 of their paper. To simplify, the thickness of the limestone layer is assumed

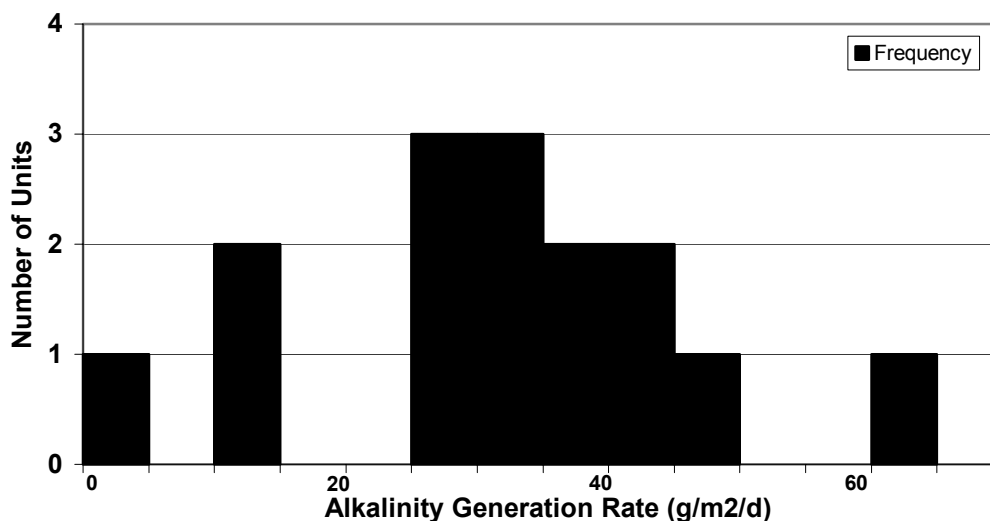| Name	Net Alkalinity out mg/L	Net Alkalinity added mg/L	Acidity Loading g/m2/d	Alkalinity Addition Rate g/m2/d
Filson 1	-158	83	95.8	33.0
Howe Bridge W	-49.2	242.8	59.5	44.8
Howe Bridge D	-135	174	52.2	26.7
Howe Bridge K	-15	165	37.6	34.4
Pot Ridge TEST	33	429	32.6	35.3
Pot Ridge C6	-223	176	111.3	49.1
Pot Ridge C10	-75	126	63.5	39.8
Oven Run D1W	18.1	132.1	40.2	46.5
Oven Run D1H	-20	107	49.2	41.5
Oven Run D2 W	42	58	6.1	22.0
Oven Run D2 H	7	28	15.8	11.7
Oven Run E1	-71	146	44.5	29.9
Oven Run E2	-12	54	14.8	11.1
Oven Run B1	-254	252	74.3	37.0
Oven Run B2	103	345	36.6	52.2
Sommerville	-220	170	39.5	17.2
Jennings	212	484	26.2	46.7
McKinley	60.9	158.7	13.8	21.7
Hortert	47	149.5	9.8	13.9
Harb-Walk(Ohiopyle)	100	287	30.3	42.4
BEL1	-50.2	54.7	72.7	37.9
BEL2	37.5	87.9	27.8	47.0
LLC2	-129.6	52.8	89.3	25.8
LLC3	-117.3	12.3	52.8	5.0
LLC4	-29.8	87.5	87.7	64.0
PMAC	150.2	344.2	5.1	8.9
USC1	-188	67.9	37.9	10.0
USC2	54	69	11.2	17.6
Rock Run #1	74.1	203.1	56.8	89.4
Rock Run #2	109.1	16.7	7.6	11.0
Maust #1	184	338	32.0	70.3
Maust #2	234	47	0.0	15.1
Lambert	169	218	10.2	33.7

Table 3. Effectiveness of Vertical Flow Systems

Figure 7. Frequency distribution of the alkalinity generation rate (acidity consumption rate) $(g/m^2/d)$ for all units with net acid effluent.   Most units add net alkalinity at a rate of 25 to 40 $g/m^2/d$.

to be 1 m, the retention time is 15 hr., the bulk pore volume is 50%, the design life is 25 years, and the bulk density of the bed is 1250 kg/m^3. One change in the calculation is that the variable C in their equation is designated as the influent net acidity to be neutralized rather than the effluent alkalinity, and the effluent is therefore taken to have zero net acidity.   Using these assumptions, the loading of systems with a 15-hour retention time is found to be 31 $g/m^2/d$ for an influent acidity of 50 mg/L, approximately the same as the design criterion proposed here. However, for higher influent acidities, the loading increases markedly, becoming 51 $g/m^2/d$ for 100 mg/L influent acidity, and 117 $g/m^2/d$ for 800 mg/l influent acidity.   Thus, the use of 15 hr retention time is adequate for low-acidity inflows, but appears undersized for higher acidity.

Results of Correlation and Multiple Regression

The effectiveness of VFS is likely to be dependent on more than the single design variable of acidity loading, though this appears to be a dominant parameter. Possible additional variables affecting performance include influent chemical parameters such as pH, Al, Fe(III) and Fe(II), Mn, Ca, SO_4, and physical parameters such as compost and limestone thickness, retention time, etc.   Also, many parameters may interact with other parameters in ways that are difficult to

visualize. For example, Jage and Zipper (2001,2000) showed that alkalinity added in a VFS was dependent on a combination of influent non-Mn acidity, Fe, and log retention time (eq. 1). They used a stepwise regression approach to identify these variables as the most important.

To identify parameters that may be important in the design of a VFS, we have examined our dataset using correlation analysis followed by stepwise regression.   Table 4 shows the results of correlation analysis for several effectiveness parameters (effluent net alkalinity, net added alkalinity, rate of net alkalinity addition).   The correlation coefficients indicate that effluent alkalinity is related positively to influent net alkalinity and negatively to influent acidity, acidity loading, non-manganese acidity, Al and Mn.

Net added alkalinity is correlated significantly to many variables. It correlates positively with H^+ (10^{-pH}), influent acidity, non-Mn acidity, Fe, Mn, Al, log retention time in limestone, and both retention time and log retention time in compost, and negatively to influent pH and Ca. These correlations are evaluated below by multiple regression.

The alkalinity generation rate R ($g/m^2/d$) correlates weakly with net added alkalinity and (negatively) with pH.   Evidently this rate variable incorporates in one parameter many of the factors showing correlations with alkalinity added.

Table 4. Correlation coefficients for effectiveness parameters				
Factors	N	Effluent Alkalinity	Alkalinity Added	Alk. Gen. Rate
pH	33	0.31	**-0.49**	**-0.36**
H^+	33	-0.16	**0.56**	0.31
Acidity in	33	**-0.57**	**0.56**	0.15
Acidity Loading	33	**-0.70**	-0.06	
Non-Mn Ac. in	33	**-0.48**	**0.60**	0.20
Alk. in	32	**0.39**	-0.28	-0.29
Alk. Added	33	0.33	1.00	**0.40**
Fe in	33	-0.02	**0.49**	0.17
Mn in	33	**-0.46**	-0.13	-0.20
Al in	24	**-0.48**	0.39	0.05
Ca in	15	0.24	**-0.55**	0.01
SO4 in	33	0.00	0.01	0.09
T_{ls}	33	0.20	0.34	-0.31
Log T_{ls}	33	0.08	**0.46**	-0.34
T_c	32	0.11	**0.52**	-0.06
Log T_c	32	0.06	**0.47**	-0.23

Bold entries are significant at 0.95 level (r>0.35 for N=33)

To sort out the interactions among variables, stepwise multiple regressions have been run for alkalinity added using the SAS Statistical System. Several qualifications of these regressions must be recognized. Most importantly, some systems have missing data, in particular for Al and Ca. If these variables are included in computing the regression, then fewer cases contribute to the result. For this reason, in most of the following regressions, these variables have not been included, and their effects are not represented, though they may be significant. Secondly, it has already been pointed out that systems with limestone added to the compost and those with channeling probably depart from the general behavior, but in these regressions, all systems are included. Inclusion of these systems probably increases the variance about the regression, but they have been included to increase the number of systems. Because of these and other effects, the regressions must be considered as indicative of effects and interactions, but should not be taken as final guides for design.

The final stepwise regression for Effluent Net Alkalinity (mg/L CaCO3) is:

Net Alk. = 143 + 1.17 x 10^4 H^+(M/L) - 0.52 Acidity(mg/L) - 2.10 AcidLoad(g/m^2/d)   (5)

This regression had as candidate variables influent H^+ (mol/L), acidity, acidity loading, non-Mn acidity, Fe, Mn, SO_4, retention time in limestone (T_l, hrs.), log T_l, retention time in compost (T_c, hrs) and log T_c. Variables were added stepwise (or could be removed) at a significance level of 0.10. The order in which variables entered was acidity loading, acidity, H+. The regression has $r^2 = 0.60$ (p<0.0001).

Equation (5) implies that for inflow with higher acidity, one should decrease the acidity loading (increase the area) in order to attain net alkaline effluent. Conversely, at higher H^+ (lower pH), one can attain net alkaline effluent with a higher acidity loading. These results may be explainable by the fact that reaction of $CaCO_3$ with H^+ is simple and rapid, but reaction with other components of acidity is less effective because of possible armoring by Al or Fe precipitates, or poisoning of the $CaCO_3$ surface by adsorption.

For net added alkalinity (mg/L $CaCO_3$) the following stepwise regression is found:

AlkAdd = 76.4 + 8.82x$10^4$$H^+$ + 0.89Fe - 1.83Mn+ 6.98 T_c   *$R^2 = 0.62$*   (6)

The order of variable entry was H^+, T_c, Fe, Mn. Additional trials with additional candidate variables gave slightly different results because of missing data (i.e, 9 units lacked Al values, 1 lacked influent alkalinity, 1 lacked thickness data). Because of these effects, the PMAC unit was not included in calculating equations (5) and (6), and Al and Ca effects were not evaluated.

The main difference from the results of Jage et al (2001) is the incorporation of H^+ in equation (6) and the lack of non-Mn acidity (but note the negative Mn effect). They included pH as a candidate variable but it is more appropriately included as H^+ (mol/L), which has concentration units analogous to alkalinity added. The inclusion of H^+ is logical because dissolution rate of $CaCO_3$ is strongly dependent on H^+ (Plummer et al., 1979).

Stepwise regression using alkalinity generation rate ($g/m^2/d$) as the dependent variable gave no significant variables, using the same candidate variables.

Problems and Lifetime

Although VFS are commonly designed for lives of 25 years or more, no unit has yet attained this age. However, one unit (Howe Bridge) is now 10 years old and is functioning nearly as well as when built. Another (Filson 1) performs satisfactorily after 7 years, 7 units are 6 years old, and 6 are 5 years old. One 6-year old unit (Sommerville) is understood to be failing by channeling, but others continue to work satisfactorily. Thus, well-designed units have the potential for a long life. However, a number of problems have been noted and suggest that some maintenance is necessary on these units, as well as improved design.

As noted above, channeling due to thin compost is known or suspected for at least two units. Because compost has much lower permeability than limestone aggregate, any thin spots in the compost layer allow preferential flow through the thin spot, leading to utilization of only a portion of the compost and limestone, and decreased retention time. At Sommerville, the thin area in the compost was apparently left after construction, whereas at Oven Run B1, rapid influent flow from a pipe is reported to have washed away compost near the inflow. These problems suggest that care should be taken to specify and verify a uniform thickness of compost, and to avoid processes that redistribute the compost. A related problem may be compost that is too thin. At a recently constructed flushable unit at Pot Ridge, brown water containing Fe precipitate is released on flushing. The inflow to this unit is very high in Fe (270 mg/L), and the compost is apparently either channeled or too thin. Because the compost must reduce all influent ferric iron in order to avoid armoring in the limestone layer, a thicker compost layer may be needed for high-Fe inflows.

Units receiving high-Fe inflow are also susceptible to precipitation of Fe in the VFS pond and accumulation of Fe precipitate on top of the compost. This accumulation decreases the

permeability of the system, requiring an increased head to accommodate the flow. Eventually the pond may overflow. This problem is reported for Howe Bridge, Filson 1 and Pot Ridge TEST (T.Morrow, personal commun.; Rose, 2001). To minimize this problem, the VFS should be preceded by an oxidation and settling pond/wetland to remove as much Fe as possible, and the water depth in the VFS should be minimized to shorten residence time. However, all the above units have such ponds and still have accumulated Fe precipitate that is impeding downflow. Periodic removal of the precipitate may be required, possibly by partial drainage followed by slurrying of the precipitate with a fire hose and removal by a sump pump.

Plugging of inflow and outflow pipes by Fe precipitate and by leaves and other trash can be a problem, leading to lack of inflow or overflow. Use of channels is preferable to pipes where feasible. Periodic inspection is needed to recognize such problems before they become serious.

The removal of Al precipitates from VFS by periodic flushing from the underdrain was proposed by Kepler and McCleary (1997). Only one of the case study units (Oven Run B) has used this design, and although Fe and Al precipitates are removed, the available data suggests that only a small proportion of the accumulation is flushed. The optimum flushing schedule is under study.

Conclusions

All the VFS in this study remove acidity from the inflowing AMD, and many of the units have operated successfully for 5 to 10 years. Some units exhibit minor maintenance problems, so a program of regular inspection and occasional maintenance is needed. The data clearly indicate that acidity loading ($g/m^2/d$) and net alkalinity addition rate ($g/m^2/d$) are more reliable design parameters than simple retention time or alkalinity added (mg/L). A sizing parameter of 25 $g/m^2/d$ for influent acidity is recommended for design of these units. However, several additional variables (pH, acidity, compost thickness, limestone in compost, etc.) may have at least a secondary influence on effectiveness and need further evaluation.

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