A NEW MILLENNIUM OF PASSIVE TREATMENT OF ACID ROCK DRAINAGE: ADVANCES IN DESIGN AND CONSTRUCTION SINCE 1988[1]

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Abstract. The history of passive treatment of acid rock drainage dates back over 20 years. It is only recently that engineers and scientists have been able to discern how Mother Nature has been immobilizing metals in natural wetlands and to mimic her handiwork. Since 1988 (when engineers and scientists gathered at two major technical conferences in Pittsburgh and Chattanooga), the geochemistry of metal precipitation in oxidizing and reducing environments has become better understood and the capacity of passive treatment systems for mine drainage has reached levels of 1,200 gpm. Systems operating in tropical and alpine environments indicate that this technology has broad application. While there have been advances, a "cook book" approach to design has yet to be realized. However, a staged design protocol of laboratory, bench-, and pilot-scale testing has yielded full-scale designs that have been functioning as intended. Future advancements needed include a focus on sulfate removal and the recovery of resources that might make this already economical water treatment method even more so.

Additional Key Words: Constructed wetlands, acid mine drainage, heavy metals, sulfate reduction

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Introduction

It has been over twenty years since the pioneering work of a group of researchers at Wright State University documented water quality improvements in a natural *Sphagnum* bog in Ohio that was receiving low pH, metal laden water (Huntsman et al., 1978). Independently, a group at West Virginia University found similar results at the Tub Run Bog (Lang et al., 1982). Subsequently, researchers, practitioners and engineers focused on developing the promising technology of using "constructed wetlands" to treat acid mine drainage (AMD) or acid rock drainage (ARD). But the term "wetland", besides carrying legal and regulatory baggage, does not quite describe structures like "anoxic limestone drains" or "successive alkalinity producing systems;" hence, the term "passive treatment" was coined.

After 20-odd years and the celebration of a new millennium, a retrospective look at the technology is appropriate to examine milestones and advancements to better focus efforts at achieving further improvements.

Definition of Passive Treatment

There are many technologies for treating AMD/ARD. To properly focus the discussion, the following definition of passive treatment is proposed:

> **Passive treatment** is a process of sequentially removing metals and/or acidity in a natural-looking man-made bio-system that capitalizes on ecological and geochemical reactions. The process requires no power and no chemicals after construction and lasts for decades with minimal human help.

It is a *sequential* process because no single treatment cell type works in every situation or with every AMD/ARD geochemistry. It is an *ecological/geochemical* process because most of the reactions (with the exception of limestone dissolution) that occur in passive treatment systems are biologically assisted. Lastly, it is a *removal* process because the system must involve the filtration or immobilization of the metal precipitates that are formed. Otherwise, they would be flushed out of the system and the degree of water quality improvement would be compromised.

A truly passive system should also function for many years, without a major retrofit to replenish construction materials, and be able to function without using electrical power. Benning and Ott (1997) described a volunteer passive system outside of an abandoned lead-zinc mine in Ireland that has apparently been functioning unattended for over 120 years. Ideally, a passive treatment system should be designed to last for at least several decades.

The proposed definition excludes some proven technologies such as semi-passive alkalinity dosing units (Aquafix ™ and Chemstream ™), limestone sand and diversion wells, among others. Because it is a "treatment" process definition per se, it also excludes AMD/ARD prevention methods such as alkaline or organic additions to overburden and mine waste, the backfilling of mines with coal combustion byproducts and water exclusion caps and covers.

This narrowed definition does not suggest that the above technologies be avoided. Rather, they are all viable weapons in the arsenal of AMD/ARD mitigation methods that can be used with or without passive treatment to achieve post-mining water quality goals.

A Short History of Passive Treatment

The early work on passive treatment was initially focused on AMD/ARD from coal mines, primarily in the Eastern US. A number of research groups evolved, including: the former U.S. Bureau of Mines, the Tennessee Valley Authority, and various academic communities including Penn State, West Virginia University, and the Colorado School of Mines (Wildeman et al., 1993 and Hedin, 2002). As of 1988, all seemed to agree that there were a number of biogeochemical mechanisms involved in metals removal and water quality improvements in wetland type environments (either natural or man-made), but there was some disagreement on which mechanisms were the most important. For coal mine systems characterized by moderate amounts of iron and manganese, aerobic systems dominated by plants and limestone appeared to be the best means of raising pH (via photosynthesis and neutralization reactions) and precipitating iron through hydrolysis reactions. Researchers out West, primarily Wildeman, Klusman, and Cohen at the Colorado School of Mines, considered sulfate reducing bioreactor (SRB) systems the most appropriate for metal mine AMD/ARD. According to personal observations by the authors, two "camps" had evolved, each thinking that they had the magic bullet.

The ASSMR Conference in Durango, Colorado in 1991 was important, for the different "camps" collaborated for the first time, presenting a short course on passive treatment. Each camp had the opportunity to present its case and view what the other camp's approach had to offer. The course was well attended and many participants stayed after its official end, despite long trips home. It is safe to say that both camps came to recognize the strengths and weaknesses of the two approaches and how the two could be integrated into hybrid systems to treat a variety of AMD/ARD situations.

Passive Treatment Milestones

The following milestones are presented in a somewhat chronological order, based on publication dates and personal observations. The milestones presented are solely the views of the authors and are not all inclusive, for the number of talented scientists, engineers, professors, and students, both in America and internationally, that have contributed to advancing the state of the art probably number in the hundreds.

Natural Systems

Certainly, Mother Nature provided the first milestone in passive treatment, as evidenced by the occurrences of bog iron ore that was smelted in prehistoric furnaces and the pyrite found in coal beds. Observations of *sphagnum*-dominated natural systems by the Wright State and West Virginia University groups set the stage for future advancements. Many researchers, including Sobolewski (1997), Wildeman and Pavlik (2000) and others have documented the ability of natural wetlands to remediate AMD/ARD.

Aerobic Wetlands

Research at the USBM, TVA, West Virginia University, and Penn State during the 1980s refocused the wetland work towards cattail-dominated systems. While working for the former U.S. Bureau of Mines, Bob Hedin and Bob Nairn developed the concept of measuring aerobic wetland cell performance by using mass balance accounting in about 1992 (Hedin, 2002). They noticed distinct performance differences in aerobic cells treating net acidic and net alkaline AMD/ARD containing iron and manganese. They further developed empirical mass loading/removal factors (mass load in – mass load out = net removed) per unit surface area for iron and manganese. These are typically reported as “gdm” factors for grams per day per square meter of wetland surface. This milestone was the foundation for future design efforts that made engineering and geochemical sense.

Anoxic Limestone Drains (ALDs)

The hydrolysis of iron consumes alkalinity. Consequently, AMD/ARD that is net acidic is more difficult to treat passively than that which is net alkaline. Alkalinity can be added through limestone dissolution if the AMD/ARD has a low dissolved oxygen concentration and the iron is ferrous. Turner and McCoy (1990) reported the successful field application of this concept in an “anoxic limestone drain” in Tennessee. Independently, Greg Brodie and Cindy Britt of the TVA identified an “accidental” ALD at the IMP-1 site in Alabama, where an abandoned haul road constructed out of limestone rock sub-base was providing alkalinity to an aerobic wetland cell receiving seepage from a coal slurry pond that would have otherwise failed. Subsequently, TVA developed detailed design criteria for ALDs which were shared with the passive treatment community (Brodie et al., 1993).

Simplified Flow Chart for Aerobic Wetland Design.

In the late 1980s, the design methods for aerobic passive treatment cells for iron removal were still under development. Brodie (1991) sorted out the empirical relationships in a milestone design flow chart that provided the foundation for a more-comprehensive design flow chart subsequently developed by Hedin and Nairn at the former US Bureau of Mines as shown in Figure 1.

This figure, in one form or another continues to guide engineers and practitioners in the passive treatment cell design process and thus qualifies as a milestone. It has been modified by the authors to include the passive treatment of heavy metal-bearing AMD/ARD based on our observations since 1988. It reflects how far the technology has matured toward a “cook book” approach to passive treatment design.

Big Five Pilot Tests, Colorado

The results of pilot tests conducted by the Colorado School of Mines at the Big Five Tunnel in Idaho Springs, Colorado spawned the first anaerobic sulfate reducing bioreactors (SRB) for dealing with heavy metals (Wildeman et al., 1993). The tests were funded by the EPA’s Risk Reduction Laboratory in Cincinnati under its Emerging Technology Program and provided the foundation research for the implementation of larger systems.

The Big Five pilot tests were originally designed on the premise that the minimum size of a wetland “ecosystem” was about 200 square feet (18.6 m^2). Subsequently, it was determined that plants per se were not required for bacterial sulfate reduction and that the bacterial ecosystem could be much smaller. This finding spawned the concept of lab-scale tests for biochemical concept evaluations and bench size bioreactors the size of trashcans that could be used to economically test a variety of SRB configurations.

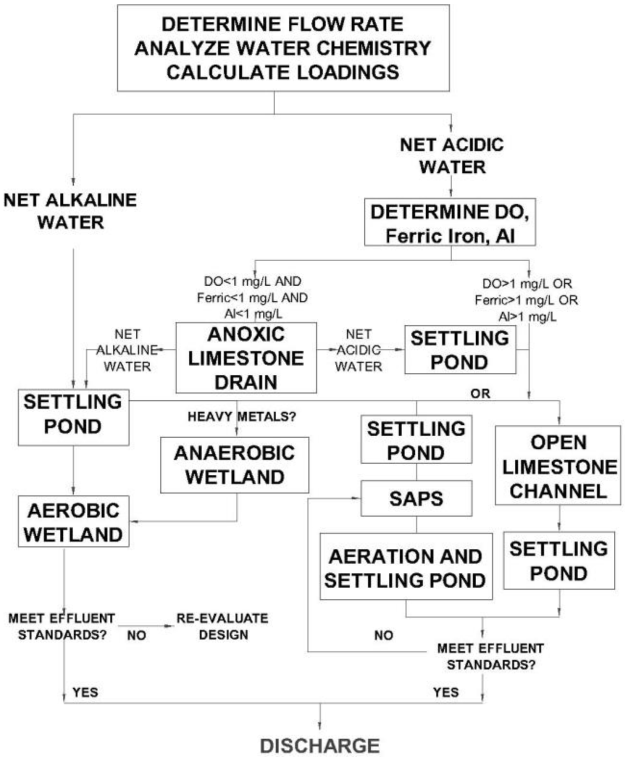

Figure 1. Flow Chart for Selecting a Passive AMD Treatment System Based on Water Chemistry and Flow (Adapted from Hedin et al., 1994).

The development of "phased" design of passive treatment systems was a milestone that would subsequently minimize large system failures.

<u>The Fabius Coal Mine "Hard Rock" Wetland, Alabama</u>

From 1991 to 1993, Greg Brodie of TVA designed and constructed the biggest passive treatment system up to that time at the Fabius Coal Mine. He affectionately called it the Mother of All Wetlands (MAW), and it involved collecting AMD/ARD from two sources, routing it through ALDs, settling ponds, and aerobic wetland cells dominated by plants. It is a milestone due to its size (16 acres/6.5 hectares), its complexity, and the design average flow rate of about 600 gallons per minute (37.9 liters/sec). Over ten years later, it is still operating as designed with reportedly little maintenance (Brodie, 2001).

Successive Alkalinity Producing Systems (SAPS)

Kepler and McCleary (1994) first reported the successful implementation of a SAPS at the ICARD/ASSMR Joint Meeting in Pittsburgh. The major limitation with ALDs was their inability to accept oxygenated water containing ferric iron. The SAPS concept surmounted this problem by combining the oxygen-stripping capability of a sulfate reducing bioreactor with the alkalinity generating capability of an ALD in a vertical flow configured SAPS. Kepler and McCleary constructed three SAPS in Jefferson County, Pennsylvania within the Mill Creek (Clarion River Basin) watershed during the period from October 1991 to July 1992. A fourth SAPS was completed in August 1994.

The development of the SAPS was an important passive treatment milestone. It bridged the gap between ALDs and SRBs with a hybrid cell that could be used alone or in combination with other or similar cells to treat a wider range of AMD/ARD chemistries in situations where the net acidic water was oxygenated.

West Fork Sulfate Reducing Bioreactor (SRB) System, Missouri

In 1995, after nearly two years of bench and pilot studies and permitting effort, the first large scale sulfate reducing bioreactor system was constructed at an active lead mine in Missouri (Gusek et al., 1998). The 4.5-acre (1.8 hectare), multi-celled system treats 1,200 gpm (76 liters/sec) of pumped mine water containing lead and zinc down to stringent discharge limits of 30 parts per billion lead. The total cost of designing, permitting, and constructing the system in 1995 was about $700,000. It is a milestone due to its high flow rate and cost-effective innovative design that won several awards for engineering excellence in 1998.

Biotic Manganese Removal

Stillings et al. (1988) reported on the removal of iron and manganese in Typha-dominated wetlands 10 months after construction. Vail, et al. (1988) reported on the activity of manganese-oxidizing bacteria. Wildeman et al. (1993) reported on pilot studies whose results suggested that limestone cobbles worked better than non-limestone cobbles in removing manganese. Wildeman further theorized that photosynthesis was the primary mechanism responsible for pH increases in algae-dominated treatment cells. This early work was supported by field observations and measurements in 1994 by Phillips et al. Robbins et al. (1999) contributed to the understanding of manganese removal in passive treatment system by identifying 13 different biological mechanisms capable of passively immobilizing manganese in the Shade constructed wetland in Pennsylvania. Collectively, these advancements comprise a milestone in the understanding of manganese removal in wetland environments.

Open Limestone Channels

Brant and Ziemkiewicz (1995) were the first to report on the ability of hydroxide-armored limestone to provide bicarbonate alkalinity in an open channel. Herron (1998) observed similar conditions in the field in Colorado. This is a milestone because it refuted a long-held belief that hydroxide armoring in open channels resulted in complete limestone blinding and offered little opportunity for alkalinity addition. The introduction of the concept opened the door for future investigations to determine the conditions most appropriate for its application, some of which are ongoing (Rose and Lourenso, 2000).

Conference Participation

Measuring participation in technical conferences associated with mined land reclamation is one method of gauging research activity in passive treatment and is thus an indication of advancements in the state of the art. The technical papers devoted to passive treatment at three major conferences in the last 20 years were tallied. The conferences were:

- W.V. Surface Mine Drainage Task Force Symposium (WV)
- ASSMR/ASMR Meetings (ASMR)
- International Conference on Acid Rock Drainage (ICARD)
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As stated in the abstract, 1988 was a watershed year for the presentation of papers on the topic of passive treatment. Since then, generally speaking, the West Virginia Surface Mine Drainage Task Force Symposium has supplied a steady forum for this topic providing about three to four papers per year, which represents 20 to 25 percent of the program.

Table 1. Summary of the number of papers presented that were devoted to passive treatment of AMD/ARD

Year	WV	ASMR	ICARD
1981	1	N/H	N/H
1982	1	N/H	N/H
1983	0	N/H	N/H
1984	1	0	N/H
1985	0	0	N/H
1986	2	0	N/H
1987	3	1	N/H
1988	22- Joint Meeting		(16)[1]
1989	4	2	N/H
1990	12 –Joint Meeting		N/H
1991	3	10	15
1992	7	10	N/H
1993	4	3	N/H
1994	20 - Joint Meeting		
1995	4	6	N/H
1996	4	18	N/H
1997	4	6	8
1998	4	11	N/H
1999	2	14	N/H
2000	1	12	14
2001	4	10	N/H

(1) The First International Conference on Constructed Wetlands for Wastewater Treatment in Chattanooga, TN, published in Hammer (1989).

(N/H = Not Held)

Passive treatment papers in ASMR proceedings have been less on a percentage basis (e.g., about 12 percent of the 2001 ASMR papers addressed the topic), but have provided a steady source of information over the past 14 years since 1988, providing the largest number of papers among the three venues. Passive treatment papers in the last ICARD proceedings ranged from 7 percent in 1997 to 9 percent in 2000.

These crude statistics suggest that research interest in passive treatment has remained fairly constant in the last dozen or so years. Perhaps it means that research funding on the topic or the number of workers in the field (who publish regularly) are constant. The authors interpret the statistics to suggest that an understanding of passive treatment methods is still evolving and that "cook book" designs for all AMD/ARD sources are not yet feasible, so research continues.

Challenges

The community of researchers, scientists and engineers has come a long way since 1988, but there are many challenges that remain before passive treatment implementation graduates from being an art to becoming a science. Overcoming some of the challenges may require shifts in thinking that go further "outside the box", perhaps to thinking "outside the building in which the box is housed". It is that attitude that allowed us to reach the milestones previously discussed. Here are some of the milestones that lie ahead.

Aluminum Hydroxide Clogging

SAPS and ALDs are prone to clogging when they are exposed to elevated concentrations of aluminum. SAPS have been retrofitted so that they can be flushed (Kepler, 1997), but this maintenance activity detracts from the passive nature of these units. Pre-treatment for aluminum removal with open limestone channels may not be practical in most situations. Preliminary results from bench and pilot scale test programs at four sites below has shown that AMD/ARD with elevated aluminum concentrations can be treated in a sulfate reducing environment:

- Brewer Gold Mine, SC (113 to 220 mg of aluminum per liter)
- Smolnik Mine, Slovakia (120 mg of aluminum per liter)
- Fran Mine, Pennsylvania (200 mg of aluminum per liter)
- Dixon Run No. 3 Mine, PA (28 to 40 mg of aluminum per liter)

The two SRB pilot cells at Brewer were operated for 18 months without aluminum hydroxide clogging; the pilot cell at Smolnik was run for about 9 months, and the Dixon Run pilot has been operating since November 2000 without hydroxide fouling (although it was observed at startup and subsequently remedied).

The Fran Mine bench scale test (five cells) was operated for 18 weeks in 2001. Bench cell biopsies at the conclusion of that period did not reveal aluminum hydroxide accumulations although other unidentified aluminum compounds were likely present. Whole water analysis of the final effluents revealed that dissolved silica concentrations decreased after the AMD/ARD was passed through the mostly organic substrates. Detailed geochemical modeling of the data is planned.

These preliminary results suggest that aluminum clogging situations might be avoided in sulfate reducing cells by encouraging the precipitation of aluminum compounds other than gibbsite. However, uncertainty of long term sulfate reducing cell performance under aluminum loading needs to be assessed further for this challenge to be overcome.

Cost Control, Long Term Maintenance

Most systems require periodic inspection and some maintenance as currently designed. Problems include plugging of discharge points with branches and trash, iron precipitate accumulations, and other difficulties. But these are short-term design issues. Despite the attractive economics of passive treatment compared to the active treatment alternative, minimizing long-term maintenance costs of a passive system is a major design challenge. The ultimate goal would be a system that is totally self-sustaining. Non-limestone based systems comprised of aerobic cells treating net neutral or alkaline water containing iron and manganese have a good chance of meeting this goal. However, net acidic waters that require SRB or SAPS units will require periodic replacement of organic and limestone substrate components under current technology. Rendering these systems self-sustaining might require a paradigm shift that incorporates a nearly endless supply of carbon: perhaps raw or partially digested municipal sewage. Economic analyses that include life-cycle costs will probably be required to grapple with this issue.

Space Limitations

As civilization encroaches on previously mined and reclaimed land, the open spaces available for constructing passive treatment systems will become even more restricted. In mountainous terrain, the problem is even more immediate. How can the footprints of passive treatment systems be shrunk to fit in tighter spaces? Is stacking an answer? Can the systems be installed in the underground mine voids through boreholes? Will hybrid systems that use industrial organic wastes as nutrient feed stock for SRB systems become acceptable practice?

Each situation will be different of course, but the type of technology required to address this challenge is a development milestone that lies ahead.

Underground In-Mine Treatment Systems

One of the beauties of SRB systems is that they do not require plants to operate. All that is needed is a carbon source and an SRB arranged in a manner that encourages bacterial growth in concert with managed loading of AMD/ARD. In areas where land surface favorable to passive treatment system construction is at a premium due to steep terrain or the encroachment of civilization, building passive treatment systems in abandoned underground mine voids (using the mine void itself as the containment "vessel") is an attractive possibility that has been realized in only one study at a metal mine in Montana (Canty, 1999).

Two challenges to overcome to implement this technology include the placement of large volumes of solid organic matter into mine voids through boreholes and the procurement of inexpensive organic material like forestry or paper waste and animal manure (SRB inoculum). The introduction of animal manure (even in small amounts) into ground water (i.e., a mine pool) will be a regulatory hurdle that may prove to be difficult to surmount. Carefully controlled field tests in small mines will probably be required.

Overcoming the Stigma of Failures

There is nothing more embarrassing than admitting failure. In the case of passive treatment, it is far too easy to blame the technology: "those wetlands just don't work". A number of factors can combine to cause some passive treatment systems to fail or at least not work as well as intended (Gusek, 2001):

- No Design – e.g., "Just build a swamp here, fill that pond over there with manure and it will be good enough."
- Inadequate Design – undersized for load, applying the wrong geochemical approach, phased design lacking, complex geochemistry, improper startup and operational procedures.
- Inadequate Maintenance – low maintenance does not mean "NO" maintenance.

- Last Minute Design Changes – departure from well-conceived construction specifications to respond to a field fit conditions can affect system performance – experience helps.

Note that the word “design” occurs in three of the above points. Thus, when a particular system fails, it may be inappropriately attributed to the technology, not the design. Overcoming this challenge will be facilitated by communication among “operators” of failed systems who may be embarrassed over the waste of time and precious funding. Constant retrofitting may not be the answer either. Retreating to a bench- or pilot-scale test to determine the best retrofit design to implement may prove to be the best approach to overcoming this challenge.

Sulfate

Many SRB systems achieve some measure of sulfate reduction, but interest in a passive method that addresses sulfate alone is probably the biggest technological hurdle facing the passive treatment research and design community. What are the limiting factors for bacterial sulfate reduction and how might they be overcome passively? Sulfate reducing bacteria are poisoned by excess amounts of sulfide ion or dissolved hydrogen sulfide, which is analogous to humans suffocating in the carbon dioxide we exhale. Zero valent iron or other sacrificial metals may hold the key to overcoming this technological challenge. Noxious odors from SRB cells are a design challenge that is typically met by balancing the dissolved metal load with the rate of sulfate reduction.

Resource Recovery

Passive treatment systems have the ability to immobilize all kinds of metals in the form of oxides, sulfides, and carbonates, and perhaps even silicates. Today, the residual materials from such systems are considered wastes requiring disposal. Hedin (1998) reported on the concept of recovering iron oxides from passive treatment systems. To many, the mention of the mineral siderite (iron carbonate) conjures up acid-base accounting nightmares. However, siderite is an iron ore that is self-coking; it fueled the early days of industrial revolution in England. Intentionally creating siderite in a passive treatment environment is a technological challenge that might alleviate a sludge disposal problem and recover a valuable resource.

No Cook Book

Net alkaline or mildly acid AMD/ARD are conducive to "cook book" designs as evidenced by the successful application of the design decision tree shown in Figure 1. However, for AMD/ARD with more complex geochemistry that includes heavy metals, selenium, arsenic and cyanide, a cook book design is highly unlikely. This aspect of design needs to be merged with the infinite variety of construction materials that must be procured locally to properly control construction costs. These materials might include: wood chips, limestone, sawdust, animal manure, and even paper waste. The effects of grain size distribution add another layer of complexity; is a coarse or fine-grained material better? The answer will be different at each passive treatment site and it will be difficult to categorize in a cook book.

Conclusions

The state of the art of passive treatment has advanced into a new millennium with a number of important milestones. These milestones have been achieved through the cooperation of researchers and engineers in government, academia, and private industry. It is the opinion of the authors that, when using good engineering design practices, the passive treatment of water that is net alkaline and contains minor concentrations of contaminants is becoming routine. The systems at West Fork in Missouri and the Fabius Coal Mine in Alabama testify to this opinion. A number of challenges remain; some may be surmountable, others not. Certainly these challenges become most obvious when the task is to treat water where the combined concentrations of iron and aluminum are above 300 mg/L. Regardless, the innovative thinking and the spirit of cooperation that has carried the technology to this point must be continued.

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