Prediction of Water Quality at Surface Coal Mines

Prepared by Members of the Prediction Workgroup
of the
Acid Drainage Technology Initiative (ADTI)

Edited by
Robert L. P. Kleinmann

Published by
The National Mine Land Reclamation Center
Located at West Virginia University in Morgantown, West Virginia

December 11, 2000

ADTI is a government/industry joint venture dedicated to the development and use of best science applications to the problem of acid mine drainage.

The National Energy Technology Laboratory of the U.S. Department of Energy prepared this document for publication. The U.S. Office of Surface Mining and the National Mining Association provided funds to offset the printing costs.

CHAPTER 1: INTRODUCTION AND RECOMMENDATIONS

by

Robert L. P. Kleinmann, Roger Hornberger, Bruce Leavitt, and David M. Hyman

THE NATURE OF THE PROBLEM

Nationwide, over 19,300 km (12,000 miles) of rivers and streams and over 730 km^2 (180,000 acres) of lakes and reservoirs are adversely affected by contaminated water draining from abandoned mines. The vast majority of this problem occurs in the eastern United States; EPA Region 3 (which includes Pennsylvania, West Virginia and Maryland) considers coal mine drainage to be its most significant non-point pollution problem. However, despite the magnitude of the problem, the situation is much better than it was 30 years ago, when the number of stream miles adversely affected was 50% worse. The improvement can be attributed to the reclamation of many abandoned operations, and to the regulatory requirements on coal mining operations, which now must both prevent acid mine drainage (AMD) generation and treat their effluent water during and after mining to meet effluent limits.

The regulatory authorities and the mining industry have worked hard to improve water quality during and after mining. A key component of this activity is predicting the post-reclamation water quality before mining occurs. The regulatory agencies make such predictions to aid in permitting decisions. Generally, where analysis indicates that poor post-reclamation water quality is anticipated, permits to mine are granted with restrictions (requiring the use of special preventive practices, such as alkaline additions, to overcome neutralization deficiencies, or deleting a coal seam or an area from the permit) or are denied altogether. The mining industry is generally required to demonstrate that no pollution will result. Despite these efforts, AMD is common at reclaimed surface mines, in part because the task of predicting post-mining water quality is highly problematic. As a result, the industry spends over a million dollars a day chemically treating contaminated mine water. The industry can only afford the long-term liability of water treatment if it is planned for; unanticipated water treatment that must continue after mining and reclamation has been completed can bankrupt a company.

At surface coal mines where the overburden chemistry is dominated by either calcareous or highly pyritic strata, the prediction of post-reclamation water quality is relatively straightforward. However, at sites where neither clearly predominates, predicting post-reclamation water quality can be complex. Fifteen years ago, researchers found that at these more difficult-to-predict sites, overburden analysis procedures generally used to predict post-reclamation water quality at surface coal mines were no more effective than flipping a coin. Since then, a great deal of effort has gone into improving the procedures. Pennsylvania has compiled statistics indicating that overall, its permitting decisions are now accurate 98% of the time; that is to say, only a small percentage of the mines anticipated to produce neutral or alkaline water produce AMD. (It is not possible to estimate the number of mines not permitted to open in Pennsylvania because of anticipated AMD that, in fact, would have produced acceptable water.) Largely as a result of ADTI, other states are now beginning to similarly assess their permitting practices. However, even without the statistics from other states, it is clear to all of those working in the field that prediction of post-reclamation water quality has improved.

OUR OBJECTIVES

This report provides an overview of techniques, methods, and procedures that are being used to predict the quality of water that will be generated after a site is surface mined for coal, and then reclaimed. It was prepared by a subset (Group 1) of the Acid Drainage Technology Initiative (ADTI), which in turn is a coalition of State and Federal agencies, industry, academia, and consulting firms working together to promote communications and technology enhancement in the field of acid drainage. Group 1 is comprised of about 25 people, who focus on problems associated with predicting water quality, while Group 2 focuses on avoidance and remediation. Group 2 published a handbook in 1998 that should be considered as a companion volume to this one.

The objectives of this report are to provide a summary of the various options available to predict post-reclamation water quality at surface coal mines, including their relative strengths and limitations, and to promote the integrated use of the various methods. Ideally, this report will lead to an increased awareness and consideration of the various options that are available, and encourage both industry and regulatory agencies to use the most appropriate and cost-effective means of accurately predicting post-reclamation water quality. Recommendations are provided at the end of several of the chapters; these are summarized at the end of this chapter.

Currently, although similarities exist, each State's permitting agency has its own mine drainage prediction methodology. The amount and types of data required vary from state to state, including different requirements for documenting pre-mining water quality, overburden lithology and geochemical properties, and the proposed mining and reclamation plans. As a result, the degree of success in preventing AMD on new permits varies. This report incorporates the results of an informal survey of the mine drainage prediction processes and risk reduction techniques used by Alabama, Indiana, Illinois, Kentucky, Maryland, Ohio, Pennsylvania, Tennessee, Virginia, and West Virginia. The objective of this survey was to lay the groundwork for an extensive, long-term post-mortem regional analysis of mine permits relative to predicted post-mining water discharge quality, similar to what Pennsylvania has accomplished. This would allow local and regional variations to be factored into future recommendations. The authors hope that all of the regulatory agency personnel reviewing this document will learn ways in which they can improve the permitting process in their state, in part by incorporating successful techniques being used elsewhere.

It should be noted that this report presents only the components relevant to predicting water quality at surface mines at which coal is being mined. Although the general approach is similar, issues and interpretation of results can be quite different for hard rock operations and underground coal mining. Therefore, a separate volume will soon be produced that will focus on hard rock issues. In the future, a volume to predict the water quality from underground mines is also planned, once we have sufficient field validation of the technology being used.

FORMATION OF ACID MINE DRAINAGE

Acidity at coal mines is principally due to the oxidation of pyrite, FeS_2, which is commonly associated with the coal and surrounding strata. Coal owes its origins to the burial of organic matter in swamps; pyrite also forms in such environments. Several types of pyrite may be present, and the reactivity of the different forms can be significantly different due to the nature of their formation and the effect that grain size has on surface area.

Mining disrupts the rock strata and exposes the pyrite to air and water, allowing oxidation to take place. Oxidation of the sulfide component of the pyrite to sulfate produces 2 moles of acidity for every mole of pyrite. Sulfur may also be present in the rock as sulfate minerals, such as jarosite ($KFe_3(SO_4)_2(OH)_6$), or as organic sulfur. Some of the sulfate minerals can dissolve and form acid solutions, but the organic sulfur is organically bound with the coal and has little or no effect on acid potential. Acidity is also produced by the oxidation of the iron from Fe^{+2}, ferrous, to Fe^{+3}, ferric iron, and its subsequent hydrolysis. The acid water that results from all of these reactions leads to the dissolution of other common contaminants, such as aluminum and manganese, and occasionally other metals such as copper, zinc, and nickel.

At the same time, the rock strata typically include components that dissolve and produce alkalinity. In coal-bearing strata, alkalinity is principally represented by $CaCO_3$, either as limestone, calcareous cement or calcite, or as $CaMg(CO_3)_2$, dolomite. $FeCO_3$, siderite, is also commonly present but does not contribute alkalinity.

Although these minerals can oxidize and/or dissolve in the absence of mining, the disruption and displacement of the rock strata typically accelerates the processes. Accurately predicting post-reclamation water quality involves understanding how the mineral components will react in the mine environment and how the acid-forming reactions and the acid-neutralizing or alkalinity-generating reactions will balance at a given site. There are many complicating variables. For example, concentrations of pyrite and carbonate minerals vary both horizontally and vertically, so that accurately determining the amount of each at a site can be very difficult. The kinetics of the reactions change as the water quality changes (for example, as pyrite oxidizes and the pH drops). Reaction rates are also affected by such variables as climate, the activity of iron-oxidizing bacteria, the rate of diffusion of oxygen, water infiltration rates, atmospheric chemistry within the mine spoil, the degree of compaction, pyrite and carbonate mineral grain size and morphology, the relative locations of the pyritic and calcareous rocks, and the location of the water table.

Prediction of water quality involves measuring the most important variables, making certain assumptions relative to less-important variables, extrapolating from what has been learned through experience at other sites, and sometimes conducting laboratory simulations to evaluate kinetic aspects. Generally, one attempts to predict whether the site will produce acidic or alkaline drainage, though sites that produce alkaline water may still require chemical treatment or special handling, due to the level of metal contaminants present.

METHODS OF PREDICTION

Most frequently, prediction of post-reclamation water quality at surface coal mines involves analysis of overburden samples. These samples can be analyzed using one of several static tests, which involve determining and comparing the amount of potentially acidic and alkaline constituents in the rock. There are also kinetic tests, which are principally leaching methods in which rock samples from the proposed mine site are subjected to simulated weathering conditions and the leachate is analyzed in a laboratory for mine drainage quality parameters. These kinetic tests may be conducted in an apparatus in the laboratory or in the field, and the test results may be evaluated independently of static tests or integrated with static test results on the same rock samples. Other methods of prediction include the use of geophysical and/or geochemical procedures.

As an alternative approach, the prediction of drainage quality from the natural background water quality at the site or from the chemistry of water at an adjacent mined site involves scientific inference and common sense. If representative samples of surface and ground water are collected on or near a proposed site, it is reasonable to assume that they should indicate something about the geology of the site and the quality of the mine drainage that will be produced after mining. For example, within areas of the Appalachian Coal basin of the eastern United States where major stratigraphic sections of carbonate rocks are present, surface and ground water will have a relatively high concentration of alkalinity, particularly in the head waters of small tributaries and in springs and ground water seeps. If the springs, seeps and tributary samples on or near a proposed mine site have low buffering capacity, it is less likely that carbonate rock will be present to produce alkaline drainage or to neutralize AMD. However, a major problem in relying solely upon background water quality is that significant sections of potentially acidic strata may be present on site, but not reflected in the pre-mining water quality. This occurs because the high acidity only results after the pyrite or other acid-producing minerals are exposed to increased oxidation and weathering during mining.

The use of mine water quality at nearby sites is a very similar, and generally more useful, technique. Post-mining discharges, highwall seeps, and pit waters at adjacent active, reclaimed, or abandoned sites can provide good indications of whether future mine drainage is likely to be highly alkaline, highly acidic or somewhat neutral, if adequate stratigraphic correlations of coal seams and overburden lithologic units can be made. Discharges from active or abandoned underground mines are of some value, but not as useful as surface mine data. Such data can be compiled from state agency permit files of active or completed sites. At least two major problems may impede the accurate prediction of proposed mine site drainage quality from nearby sites. One is that the proposed mine site may have significantly different overburden chemistry due to facies changes, differences in depths of weathering or other local-scale geologic variations. A second is that the existing water quality may reflect past mining and reclamation practices. For example, the existing reclaimed site may have coal preparation plant refuse or large amounts of alkaline additives, such as flyash, buried in the backfill, both of which will skew the water quality one way or the other. These potential interpretation problems are discussed in more detail in chapter 3.

Static and kinetic tests incorporate chemical analyses performed on rock samples from the actual mine site. A critical point is that these methods are only valid if the rock samples are truly representative of the site where mining is proposed. Rock samples may be collected from exploration boreholes or other sources (e.g. exposed highwalls). Both static and kinetic tests produce site-specific geochemical evaluations of potential acidity or alkalinity, and possibly other parameters of predicted water quality. The major difference between static and kinetic tests is that static tests provide measurements of the amount of selected chemical constituents <u>in</u> the rock sample (e.g. total sulfur, neutralization potential), while kinetic tests provide measurements of the amount of selected chemical constituents that come <u>out</u> of the rock samples in leachate (e.g. acidity and iron concentrations) under specified conditions. The total amount of an element or mineral (e.g. sulfur or pyrite) in the rock sample may not be directly proportional to the amount of the associated parameter (e.g. sulfate or iron) in the simulated effluent produced in a leaching test or actual mine drainage in the field. This is due to reaction kinetics, mineral solubility controls, crystallinity and morphology of the minerals, and other physical, chemical, and biological factors. However, both static and kinetic tests have potential value, provided that their limitations are recognized when interpreting the results.

In this report, we focus primarily on the static test that is most commonly used to predict mine drainage quality in the eastern United States, namely acid-base accounting (ABA). This method involves a comparison of the maximum potential acidity (MPA), typically calculated from the total sulfur in the sample, to the neutralization potential (NP). Other static tests have been developed and employed for use in coal mine drainage prediction, but ABA is the most routinely used method for coal mine drainage prediction. A recent innovation, Evolved Gas Analysis (EGA), also deserves mention as it has the potential to fill a gap between static and kinetic tests, since it is a static test that provides some information that can be used to factor in reaction kinetics. In addition, geochemical logging techniques adapted from the oil and gas industry can be used to provide an instantaneous analysis that simulates ABA. All of these methods are discussed in Chapter 4.

Kinetic tests are most appropriately used when the results of static tests falls between the regions defined (by practice) as acid or alkaline. The most commonly used kinetic tests for mine drainage prediction involve either leaching columns or humidity cells. These tests have been used, evaluated, and compared in many coal mine drainage prediction studies, but are in fact only occasionally used by the mining industry and state regulatory agencies in the Appalachian Coal Basin. Other kinetic test methods, such as the Soxhlet reactor, have also been used in prediction efforts, but even less frequently than humidity cells and leaching columns. Kinetic test methods are more routinely used by the metal mining industry and regulatory agencies in the western U.S. and Canada. Barriers to their use in the eastern United States include their expense and the time (months) needed to obtain results, as well as the fact that they have not had the widespread field validation that ABA has had.

Kinetic tests incorporate dynamic elements of the physical, chemical, and biological processes involved in the weathering of mine rock, and attempt to simulate the kinetics of the chemical reactions that control the production of acidic or alkaline mine drainage. Factors that may be incorporated include: size, shape and structure of the apparatus; volume and placement of the rock samples in the apparatus; particle size; mineralogy; antecedent storage conditions; interleach storage conditions; rock to water ratio; leaching solution composition; leaching interval; pore gas composition and nature of bacterial populations. If the critical physical, chemical and biological conditions are proportionally representative of the natural environment, the water quality of the leachate may be used to predict or estimate the water quality from the proposed mine site. Unfortunately, kinetic test procedures are necessarily simplifications of the natural environment, and it is easy to be fooled by laboratory procedures that underestimate or overestimate some component of the real world. These issues are addressed in detail in Chapter 5. In addition, the validity of kinetic tests, like static tests, depends on how well the samples represent the site. It is important to remember that despite apparently precise laboratory analyses, test results may not accurately predict mine drainage quality.

To summarize, this report provides information on numerous methods to predict post-reclamation water quality at surface coal mines. The various advantages, disadvantages and assumptions of the principal methods are discussed; these must be understood by anyone selecting or interpreting the results from these techniques. This array of prediction methods is analogous to a collection of tools in a toolbox. The choice of which tool to use is ideally a function of site-specific circumstances, but in the past, the decision has often been dictated more by familiarity with the test and the ability of practitioners to extrapolate the test results to mine scale decisions. In the context of compliance and enforcement, when the only tool in your toolbox is a hammer, everything begins to look like a nail. It is the hope of the ADTI participants that, with sufficient information, practitioners will feel comfortable using tools that are more appropriate, rather than just familiar. Regulatory agencies and the mining industry should both consider and promote the proper use of all mine drainage prediction tools, and to become comfortable using them in concert to optimize the odds of accurately predicting the effects of mining a given site in a particular manner.

RECOMMENDATIONS

The use of ABA for accurate prediction of mine water quality depends on obtaining representative samples of the geologic materials that will be disturbed. Geologic variability within a site must be captured through the use of a sufficient number of samples. The effect of weathering on the sampled strata must be considered; the absence of carbonate minerals or pyrite in the top 20 feet of overburden sampled is likely not representative of the same strata at greater depths. Studies in Pennsylvania have shown that an absolute minimum of three and more typically six or seven holes are needed per 100 acres in order to capture the geologic variability of a site. The collective experience of the ADTI Coal sector underscores Pennsylvania's findings, though of course each site is different and it is hard to generalize. However, Pennsylvania has also found that their sampling requirement can be entirely waived if water quality is good at adjacent mines that have extracted the same coal seam. In fact, they have found that the most effective predictor of AMD potential has been previous mining in the same seam and general location as the proposed operation.

If the strata are adequately sampled, overburden analysis, and in particular, ABA, works well in most overburden. However, an overburden analysis located between analytical results clearly associated with alkaline discharges and those that are clearly associated with acidic discharges is said to fall within a *gray zone*. The uncertainty is caused by variability in rock strata and the ability to adequately represent those strata with a limited volume of sample material, as well as sources of error in the analytical procedures.

For example, the presence of the mineral siderite has long been known to cause false levels of alkalinity to be reported in ABA results. In addition, the subjective fizz test has been shown to result in significant lab-to-lab variability in ABA test results on the same sample. Chapter 4 contains a modification of the ABA procedure that eliminates these two sources of error. The ADTI Coal sector strongly recommends to all operators, researches, and regulators that these ABA modifications be adopted. The authors believe that broad application of this methodology will result in fewer mines that produce acidic discharges, and allow for the safe permitting of mines that would not have been permitted utilizing the old procedure.

It is also necessary to define the gray zone. The ADTI coal sector recommends that strata with a neutralization potential (NP) less than 10 tons/1000 tons or a net neutralization potential (NNP) less than

0 tons/1000 tons be considered potentially acid producing. Strata with an NP greater than 21 tons/1000 tons or an NNP greater than 12 tons/1000 tons can be considered alkaline. The gray zone is the defined region between these values. These values are based on the ABA procedure currently used in the U.S., and their derivation is discussed in chapter 4. As the ABA modifications recommended in this text are applied in the field, it is anticipated that the accuracy of predictions should improve. These values should therefore be re-assessed once the modified test procedures have been adopted. It is anticipated that the elimination of the siderite problem and the elimination of subjectivity in the fizz test should reduce the size of the undecided gray zone, and lower the break points for the generation of an alkaline discharge.

Dynamic or kinetic testing, in which the rock samples are subjected to mild to severe weathering under laboratory conditions, are described in detail in Chapter 5. While kinetic tests have been utilized to make permitting decisions, the time and effort required for such testing have generally limited their applicability. In addition, the lack of standardization has also caused problems. The Chapter 5 recommendations should correct the latter problem; presumably, this will allow kinetic tests to be used when clarification of the likelihood of acid generation for sites in the defined gray zone is necessary.

Finally, it should be emphasized that regardless of whether one is preparing or reviewing a permit, the unique character and condition of each mine site precludes a simple cookbook approach. If site characterization is adequate, it is generally possible to predict post-mining water quality. This evaluation should then be factored into a consideration of whether this predicted water quality is likely to have unacceptable effects on local water quality, and if so, whether anything can be done during mining and reclamation to allow it to proceed without such adverse effects.