THE BENEFITS OF COST-EFFECTIVE ENVIRONMENTAL BASELINE SAMPLING AND MONITORING PRACTICES IN ADVANCE OF COALBED METHANE PRODUCTION

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ABSTRACT

The currently favorable economic and technologic environment for increasing gas production in the U.S. portends an unprecedented boom in the drilling and development of shallow gas plays. Many operators contemplating developing such plays should be aware of the common regulatory, residential, legal, and operator concerns which have surfaced in areas where coalbed methane (CBM) is being produced. These concerns have cost operators millions of dollars spent to both assess the disputed impact of production practices and to settle claims against them. This does not include the hidden costs needed to manage in crisis and redirect a sparse labor pool to handle environmental issues. Many of the claims made against operators could have been foreseen and addressed in more cost-effective ways with a marginal amount of environmental baseline information. But in every case, the absence of baseline data led to considerable controversy and uncertainty regarding whom to blame for a variety of complaints. Fearing a loss of health and safety, local residents chose to blame operators and sought relief through litigation. In this context, prudent baseline measurement and monitoring practices are relatively easy and inexpensive to implement.

This article summarizes the typical environmental complaints commonly attributed to CBM operations in the San Juan, Black Warrior, and Powder River basins over the past two decades. It also provides selected examples of cost-effective methods which operators can use for planning and implementing baseline studies. Without such studies, the task of differentiating between environmental changes caused by production and those resulting from other causes becomes very difficult. Recommended methods focus on understanding production practices from a perspective of the potential impacts on the physical and geochemical properties of regional aquifers. Baseline measurements are best used for assessing risk and targeting areas where health, safety, and quality of life issues are paramount. There are also substantial secondary benefits to these measurements. The right information can help operators to constrain reservoir engineering models, detect reservoir compartmentation and anisotropy, verify the need for infill drilling, assess wellbore integrity, and predict the potential for souring gas reserves.

COMMON COMPLAINTS EXPRESSED BY REGULATORY AGENCIES AND RAISED DURING LITIGATION

The most common complaints attributed to CBM practices in the San Juan, Black Warrior, and Powder River basins have included the following: a. the loss of domestic water quantity; b. progressive deterioration of either surface or groundwater quality; and c. the emergence of potentially dangerous concentrations of free and dissolved methane in both water and soils. Each of these complaints can arise from a variety of causes. However, the following examples summarize information, contained in legal documents or published by regulatory agencies, attributing these problems to CBM production practices.

Loss of domestic water quantity

Several reasons have been proposed to explain declining yields in domestic water wells that may be completed in aquifers hundreds of feet above or below a producing coal horizon. A frequently quoted and widely held popular view is that drawing water from a coalbed aquifer is like drawing water from a glass through a straw. Lower the water level in the glass, and you will lower the water level in the straw. This simplistic view is reinforced by the misconception that local aquifers are of regional extent and that they are both vertically and laterally homogeneous. A more

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reasonable claim is that there are numerous types of permeable conduits that could connect coal seams with overlying and underlying aquifers. Examples cited are naturally-occurring fractures, fractures induced by either underground mining or hydraulic fracturing practices, and poorly-constructed producing or abandoned oil and gas wells. The most pressing concerns expressed by both state and federal regulators regard CBM production in the proximity of basin margins. It has been asserted that downdip production can lower water levels in domestic water wells completed near or within outcropping CBM producing horizons. Lowered water levels allegedly may also increase the risk for spontaneous coal combustion.

Deteriorating surface and groundwater quality

Changes in water quality attributed to CBM practices are usually cited to arise from induced changes in the oxidation state of water in wells. Assuming that migrating coalbed methane can bubble through a domestic water well, it can either displace free oxygen or generate conditions favorable for a chemically reducing environment. For example, bacterial consortia can assimilate the carbon in the organic methane molecule by forming simple building blocks for cell growth. Increasing methane concentrations can therefore accelerate the activity of bacterial consortia living in water. This can result in two effects. The first effect is to increase the amount of bacterial waste in water. Increased levels of bacterial cell matter and slime can turn clear water cloudy and cause it to appear unappetizing. The second effect is to lower free and chemically bound oxygen levels that bacteria consume for respiration.

A progressive loss of oxygen can promote the growth of iron-related bacteria (IRB) and sulfate-reducing bacteria (SRB) (Erlich, 1996). SRB will strip sulfate ions of their oxygen during respiration. The byproduct of this metabolic process is carbon dioxide and hydrogen sulfide gas. The presence of hydrogen sulfide gas is unmistakable. It emanates as an offensive odor usually described as similar to the smell of rotten eggs. Water containing dissolved hydrogen sulfide is mildly acidic, and can corrode faucets, shower heads, and appliances. IRB that reduce iron, on the other hand, allow iron to readily dissolve in water. Dissolved iron and sulfide ions can combine to form suspended particles of iron sulfide that will impart a dark gray color to water. When reduced water rich in dissolved iron exits a home's plumbing system and comes in abrupt contact with air, the iron will quickly oxidize and precipitate as insoluble, rust-colored iron hydroxide. This precipitate can stain porcelain fixtures, faucets, and even discolor laundry.

Bacteria can also be agents of chemical change in increasingly oxidized waters. Assuming aquifer water levels fall as a result of CBM production, a water pump operating in progressively shallow water will draw more oxygenated water that is in closer contact with air. If oxidation occurs in a well bore containing dissolved iron, then IRB that oxidize iron will convert it to an iron hydroxide precipitate. This imparts a rusty red color to water and, if present in large concentrations, will render water opaque. The water will also tend to have an unpleasant taste, commonly described as metallic.

Both chemical reduction and oxidation of domestic aquifers have also been cited to result from chemical reactions induced when produced waters, discharged at the surface, are allowed to infiltrate shallow aquifers. Surface discharge can also affect surface water chemistry by changing salinity or modifying historic concentrations of metal ions.

Emergence of free and dissolved methane

Methane seepage is the third and last type of complaint attributed to CBM production activities. Seeps pose the greatest potential safety hazard and engender the greatest fear among residents. Methane is an odorless and colorless gas that can lead to spontaneous explosions if allowed to reach concentrations of between 5% and 15% by volume in air. This range is defined by the lower and upper explosive limit of methane, respectively. Such concentrations can be reached in two ways: via exsolution of dissolved methane that is allowed to collect in an enclosed and unventilated space, or by the accumulation of free gas seeping to the surface.

Methane seeps can also physically displace normal oxygen levels in soil and kill vegetation. Extensive gas seeps can noticeably alter the vegetative landscape. Another physical effect of active gas seeps is that methane can behave as a carrier gas that transports undesired concentrations of buried hydrogen sulfide gas to the surface. In sufficiently high concentrations, sulfide gas brought to the surface can irritate skin and eyes and, in the worst possible scenario, can lead to loss of consciousness or death.

Litigators too easily explain the origin of dissolved methane in water wells and methane seeps as follows: desorption of gas from coal, responding to lowered hydrostatic pressures, releases large quantities of gas into the subsurface environment which was not there prior to development. Implied in such a statement is the idea that gas released from a coalbed methane reservoir has easy access to the surface and surrounding aquifers.

Both litigators and regulatory agencies have commonly identified four migration mechanisms to account for methane in domestic aquifers and for methane seeps. The first is vertical migration through large, natural fractures that extend vertically from the producing reservoir to the surface or domestic aquifer. The second pertains to gas migration along access paths provided by well bore conduits. In the San Juan Basin, for example, well installation practices conducted prior to the 1950s left the production casing annulus of deep oil and gas wells uncemented across both the shallower Fruitland Formation and overlying strata. Consequently, when CBM operations began in the 1980s, desorbed gas was free to migrate vertically from the Fruitland coal along the wellbore annulus and into shallow aquifer horizons (Beckstrom, 1993). Domestic water wells can also provide gas conduits to the surface. For example, domestic water wells completed in the Wyodak coal seam of the Powder River Basin are gravel packed. This may have been an appropriate completion method at the time. However, since CBM operations have begun there, water yield in several such wells has declined, and the gravel pack has provided a conduit for gas to migrate to the surface.

The final two gas seep mechanisms attributed to CBM production have been alleged to occur near basin margins where gas seeps emerge along the outcrop belt of producing coal seams. Methane liberated during production could migrate updip until it emanates from the outcrop or shallow subcrop. Alternatively, down-basin production could lower water levels near the outcrop and allow gas to be released at the surface via in-situ desorption of gas-saturated coal seams.

Historic and recent changes in water quantity, water quality, dissolved gas concentrations found in domestic water wells, or the perceived rate of methane seeps at the surface are naturally occurring phenomena. These can easily be attributed to numerous factors other than CBM production operations. CBM operators could not be assailed as easily if supported by data gathered in a baseline sampling program conducted prior to and during the onset of CBM production.

PRODUCTION-RELATED COMPLAINTS IMPACTING OPERATORS

Understanding the natural plumbing dynamics of regional coalbed aquifers, and both overlying and underlying aquifers within 100 feet of a CBM producing horizon, is essential. Operators are often surprised to find that their chosen drilling, completion, and production methods can result in the invasion of extra-formational water. Under the right conditions, significant local cross flow between aquifers can occur both within and outside of the immediate wellbore environment. At best, this can result in the unnecessary expense required to pump excess water. At worst, crossflow can alter the geochemical properties of a CBM reservoir. For example, cross flow can introduce dissolved sulfate into a reservoir causing sweet coalbed methane to turn increasingly sour. Significant costs can be incurred to monitor, control, blend, and process souring gas reserves. Cross flow can also introduce fluids that promote wellbore scaling or corrosion. To control these effects, expensive additives may have to be repeatedly injected into producing CBM wells and reservoirs.

CBM operators continually evaluate their drilling and production strategies. Questions of greatest economic importance relate to issues such as optimum well spacing, and the impact of infill drilling on correlative rights. Questions of this kind are usually left to the reservoir engineer to answer. Yet few operators realize that baseline sampling of the producing reservoir and temporal monitoring techniques provide powerful and useful tools for both constraining and supporting reservoir engineering models.

SETTING OBJECTIVES FOR A BASELINE SAMPLING AND MONITORING PROGRAM

Local and regional baseline analysis of aquifer properties should be conducted in two stages: a sampling and analysis program followed by a monitoring program. During initial sampling, a minimum amount of data should be collected to help operators define environmental risk (Cothern, 1996) and detect early warning signs of impending problems. Sampling results must be relevant to the three most common complaints attributed to CBM production: a. domestic water well quantity or yield; b. domestic water well quality; and c. the occurrence of free or dissolved methane. Subsequent monitoring should be conducted in sensitive areas to determine if there are statistically meaningful trends in the value of environmentally sensitive parameters which may correlate with CBM activities.

A cost-effective sampling program limits the scope of investigation by identifying three areas of greatest concern. First, are the "critical" areas where the risk of impacting local residents is greatest. Second, are the areas where water well problems unrelated to CBM production operations are already known to exist. And third, are the areas where either the risks of impacting production revenues or the opportunities for maximizing revenues are greatest.

Sampling should proceed using a randomized method for selecting sampling locations that are both within and outside of all three areas of interest. Such an approach minimizes possible bias, and allows objective comparison of geographic and time-varying trends through the use of accepted statistical hypothesis-testing methods (Ott, 1995). A sufficient number of samples should be collected to establish statistically meaningful "threshold" values of the environmental parameters that are most useful for warning operators of impending problems. Such threshold values should be defined and used to establish action triggers. Examples of actions to be taken might include additional sampling for more thorough analysis, or remediation. Threshold values can also be used to guide operators in establishing protocols to implement consistent drilling, completion, and production practices.

ESTABLISHING A BASELINE SAMPLING AND ANALYSIS COST HIERARCHY

The costs required for a baseline sampling and analysis program can be systematically minimized with advanced planning. Such planning should begin early in the leasing phase of a shallow gas prospect, and should be designed by a multidisciplinary team comprising members with different background training and responsibilities. For example, landmen, geologists, log analysts, reservoir engineers, and hydrologists can all participate in a baseline program at some time. Ideally, the team leader should be an individual who has good leadership skills and is comfortable working with multidisciplinary data. The team leader should be responsible for knowing where and how to retrieve baseline information in the event problems should arise.

A cost-effective baseline sampling program should consist of a pyramidal hierarchy of tasks performed sequentially. Each task can lead to a subsequent and more expensive level of analyses that may be required to satisfactorily characterize critical environmental parameters. Over the long term, the advantage of conducting such a staged program is that additional costs only need to be incurred if they are necessary. The optimum components comprising a baseline sampling and analysis hierarchy will now be discussed.

LOCAL AND REGIONAL RECONNAISSANCE

Compiling a variety of hydrologic, historic, and geologic data from a shallow gas basin is of paramount importance and offers the greatest benefits at the lowest cost. These data can provide 80% of the information needed to assess potential environmental impacts and the relative risk associated with shallow gas drilling and development activities. Such a reconnaissance task should be implemented to provide operators with the following information: a. a historical context for evaluating water quality and quantity delivered by various aquifers; b. a historical context for known gas seeps; c. a historical context for areas that may be affected by other potentially hazardous anthropogenic activities; d. a regional framework for determining "baseline" sampling areas; and e. a regional framework for designating "critical" areas at risk that should be sampled or monitored. The results of such an evaluation should be used to define specific requirements for spatial and ongoing temporal water and soil sampling plans.

Most basins have multiple aquifers among shallow, intermediate, and deep stratigraphic intervals. Their yield and water quality is usually highly variable, and problem areas are usually well known and documented. Much can be gained from collecting and assimilating publications specializing in various aspects of local and regional hydrology that are issued by municipal, state, and federal agencies. In western states, a State Engineer's Ground Water Division Office will also have permit records documenting the location, depth to completion, and water level data for many domestic and commercial water wells. These data need to be collected, assimilated into a data base when needed, and plotted to find areas that are either sparsely or densely drilled, and to identify the various aquifers utilized. Changes in the rate of drilling for water wells should also be noted because uncontrolled population growth can result in locally diminished aquifer yields. This is particularly true when domestic well water is increasingly used to irrigate lawns and gardens, or to fill swimming pools and ponds.

The best data comes from site-specific inspections. For example, when a landman is in a house negotiating a lease, that person should specifically inquire as to the water quality and yield at that residence. With just a little training, anyone can readily identify residential areas already experiencing water problems.

Nearly every location designated in lawsuits as having experienced problems with gas seeps due to CBM operations has historically been an area of active gas seeps. In most cases, those areas have been along outcrop belts where the producing formation is within 50 feet of the surface. Many real estate developments were built in such areas before anyone recognized that building a foundation on or immediately above a coal seam is a geologic hazard. This occurs in spite of local newspaper articles, many dating back to the mid-to-late 1800s, replete with reports of mining-related explosions, well house explosions, or even mysterious explosions in and around seep areas. Local ranchers are usually well aware of historic or recent gas seeps; someone just needs to ask them about it.

In other instances, gas seeps have surfaced in areas where the production casing of conventional oil and gas wells repeatedly lost integrity due to high shallow aquifer corrosion rates. Corrosive production field environments also affect pipelines, gathering lines, and production facility flow lines and tanks. A breach in any of these production-related infrastructures can charge shallow aquifers with hydrocarbons.

Aquifers can also be charged with hydrocarbons that have either migrated from deeper horizons over geologic time, or have been generated in-situ by hydrocarbon-generating bacteria. More than 20% of the world's gas reserves have been generated by subsurface bacteria, and a large percentage of these are found in shallow reservoirs (Wiese and Kvenvolden, 1994). Under the right conditions, landfills and leach fields can also be prolific sources of bacterial methane.

Other sources of historic groundwater contamination, such as those due to blowouts, leaks from gasoline station tanks, or other sources can easily be discovered by reviewing archived well files. In this context, it is necessary to identify and plot all wells in an area that are producing from deeper horizons. Under the right set of circumstances, any one of these could potentially be a source of aquifer contamination. A review of drilling records and mudlogs can also be an effective way to detect hydrocarbons that could affect aquifer quality. For example, shallow gas shows are often encountered while drilling to deeper horizons. When such gas shows predate any drilling in the area, they indicate that gas has migrated to shallow horizons over geologic time. Other drilling logs from the San Juan Basin, show that wells originally drilled to the Mesaverde or Dakota Formations in the 1940s encountered no shallow hydrocarbons. However, more recent drilling records from twin well locations drilled to the shallower Fruitland Formation indicate the presence of shallow gas. Such evidence is found in areas of the basin where a history of deep casing breach events, caused by electrochemical corrosion, charged shallow sands with hydrocarbons.

Abandoned surface and underground mines may provide another source of contamination that can impact local aquifers. Under the right conditions, the quality and composition of backfilled soils can affect groundwater quantity and quality for many years after reclamation efforts cease. Underground mines can cause differential subsidence at the surface that results in cracked roads, driveways, and foundations. These are clear indications of fracturing that could provide a path for gas to reach the surface. It is therefore necessary to collect the appropriate information from regulatory, state, and federal agencies that maintain records of resource exploitation activities that predate CBM development. For example, permitting data complying with the Surface Mining Control and Reclamation Act, the Bureau of Mines, the United States Geological Survey, and state Departments of Environmental Quality are all excellent sources for baseline hydrologic and geologic data.

Wireline logs record porous and permeable fairways in shallow aquifers that underlie residential areas. Such logs can help to differentiate aquifer horizons that are tapped by domestic water wells completed at different depths. Wherever possible, key marker beds should be identified and their distribution plotted on structure maps. Shallow structural and stratigraphic traps could potentially provide local reservoirs for shallow gas to accumulate. If shallow wireline logs are not available, long term efforts can be made to run calibrated gamma ray logs through casing throughout the CBM field area whenever a producing well needs repairs.

A variety of maps and images can be used to place the distribution of aquifers and possible natural gas seeps in a regional context. For example, surficial geologic maps, soil maps, topographic maps, and vegetation maps should all be reviewed before designing a sampling program. Remote sensing images and aerial photography provide valuable synoptic views of an area. For example, color infrared and color photography help identify evidence of current or historic coal burns. Spectral imagery can help identify areas where discharging aquifers (springs) may be transporting dissolved iron that oxidizes at the surface. These would be logical places to test for methane and sulfide gas.

Climatic data are of great value. Local airports and municipalities often keep accurate climatic records extending for decades and The National Oceanic and Atmospheric Agency compiles data that are available for downloading through the Internet. Analysis of local and regional precipitation trends will establish the ideal timing required to collect seasonal samples. Local aquifers are recharged during rainy seasons, when alluvial deposits are saturated, and when irrigation ditches are full. In semi-arid to arid environments, melting snow efficiently recharges local aquifers. Because recharge will significantly affect aquifer water levels, this variability will systematically influence analytical results. Such variability therefore needs to be documented. Sampling should also be conducted before soils freeze or after they thaw.

OBJECTIVE DESIGN OF A SAMPLING PROGRAM

Once the information gathered in reconnaissance studies has been analyzed to differentiate "baseline" areas from "critical" areas at risk, then it is time to design an aquifer characterization program. There are three important design components to every sampling program. These are a. documenting and implementing standardized sampling and analysis protocols; b. making provisions for quality assurance and control practices in the field and among laboratories used to provide analyses; and c. designing rigorous statistical tests to evaluate multiple hypotheses. Because it is beyond the scope of this article to discuss these in detail, helpful references are provided below (Koterba, Wilde, and Lapham, 1995, Mueller, Martin, and Lopes, 1997, Langmuir, 1996, and Shelton, 1994). However, operators should be aware that they will be inevitably accused of collecting biased information. Strict adherence to and documentation of objective sampling and analysis practices will help alleviate such concerns.

Both spatial and temporal samples should be collected to adequately characterize any site. Spatial sampling is used to define, compare, and contrast geographic patterns in data collected from local and regional aquifers. This requires designing a grid and using a grid spacing that is appropriate for capturing a minimum amount of information at a desired scale. Samples can be gathered at random anywhere inside the grid (an example of random stratified sampling). If statistical analysis of aquifer data is required, then the number of samples to be collected must also be designed. For example, a set of 24 samples can provide a reasonable estimate (within 20%) of the mean and variance for a single aquifer parameter. Design specifications for collecting temporal samples should be deferred until spatial surveys have been completed. Temporal sampling will help establish how the range of values for any given aquifer parameter will vary as a result of changing environmental conditions. The results of spatial and temporal sampling programs can then be used to design an aquifer monitoring program. Temporal sampling of producing CBM aquifers also provides a powerful means of assessing reservoir continuity and drainage patterns.

ANALYTICAL COMPONENTS OF A SAMPLING PROGRAM

A sampling program should quantify parameters that are useful for characterizing the quality of various aquifers identified in the reconnaissance program. A sampling hierarchy should be used to minimize the costs needed to fully quantify environmentally relevant properties of soils and aquifers. There can be three cost-based levels to a sampling hierarchy. These include the following: a. field sampling and analysis methods; b. standard laboratory analyses; and c. special laboratory analyses.

Field sampling and analysis methods

Field sampling methods are screening tools, and offer the most cost-effective means available to establish the potability, oxidation state, and general chemical properties of water in aquifers over a large area. Only a few hand-held field instruments need to be calibrated daily for these analyses. These are used to measure acidity (pH), redox potential (Eh), temperature, conductivity (used to determine the relative concentration of dissolved chemicals), and dissolved oxygen (dO). Other useful data pertain to observations made with the senses such as water color, clarity, and smell. It is relatively easy and inexpensive to collect hundreds of field samples in a single season among a variety of sites that include springs, water wells, CBM production wells, streams, surface reservoirs, irrigation ditches, and other sources of aquifer recharge. This prolific source of information can then be used to selectively target a smaller suite of samples slated for more expensive laboratory analyses.

Sampling of the ambient air above various soil and outcrop horizons also provides a good means for screening sites where soil gas probes should be installed. Such sampling is usually performed along specified transects where gas seeps have been informally documented or can logically be suspected to occur. These types of analyses are best conducted in areas both far from and within "critical" areas of potential risk. Outcrops, producing wells, and production facilities are common risk targets.

A variety of hand-held "sniffer" detectors are available for analysis of ambient air quality. These can also be used to analyze headspace gases of soil samples, gases liberated from water samples collected in springs and streams, or gases liberated when domestic well water is used to fill sinks or buckets. Of the available organic vapor analyzers (OVA), flame ionization devices (FID) offer the greatest sensitivity to low hydrocarbon concentrations. Many companies offering such services provide trained observers who can detect the surface manifestation of gas seeps. Alternatively, company personnel can be quickly trained to use rental equipment adequate for such activities. "Walking the ground" should be considered an important component of field analysis methods. Public education forums can help persuade residents to cooperate with an operator's efforts to randomly conduct sniffer surveys of residential basements and crawl spaces. Educating a concerned public prior to production activities should always be encouraged. Any excuse for two-way communication will provide valuable clues regarding water quality issues already facing a community.

It is usually quite difficult to make static water level measurements in domestic water wells.

Obtaining permission to access properties appears to be a significant problem in western states. Even if access is granted, many operators are leery of disassembling well heads for fear that they may be accused of damaging the well in some way. Other operators may opt to drill and maintain monitor wells at even higher costs. At the very least, operators should randomly inspect a specified number of domestic well heads. A surprisingly large number of wells are poorly constructed, lack sanitary seals, or have other obvious problems that can account for poor water quality and quantity.

Numerous plaintiffs who have complained of declining water yields and water quality were unaware that their "do-it-yourself" maintenance practices allowed them to innoculate their wells with bacteria. As a result, rich bacterial cultures growing in their wells were so prolific that thick slime coated the aquifer, thereby restricting aquifer yield. Poor well completions can also permit coliform bacteria, derived from animal fecal matter or leach fields, to invade and grow in water wells. Field sampling methods should therefore include sampling for bacteria (Cullimore, 1993).

Standard laboratory analysis methods

Once an area has been screened with data from field analyses, there are more detailed and expensive analyses which can be conducted on a relatively small number of targeted samples. Targeting strategies are most effective when based on statistical analysis of field data. Results of such analyses can be used to unambiguously differentiate among aquifers. Each aquifer can then be selectively sampled and analyzed for a variety of specified inorganic and organic constituents.

Wet chemical analyses are standard and relatively inexpensive. A typical suite of analytes includes the major ions as follows: calcium, magnesium, potassium, and sodium (positively charged ions) and carbonate, bicarbonate, sulfate, and chloride (negatively charged ions). Checking the charge balance between positively and negatively charged major ions is one good way to check quality control. Other analytes that are typically measured are iron and manganese, dissolved nitrogen compounds, and non-reactive ions such as bromine and fluorine. Some operators also measure the concentration of selected metals listed by the Resource Conservation and Recovery Act as potentially hazardous. It is also customary to measure other properties of water in the laboratory, such as pH and conductivity.

In the search for potential sources of hydrocarbon contamination, samples should be analyzed for the total concentration of dissolved organic carbon components. Benzene, toluene, ethyl benzene, and xylene (BTEX) analyses should be performed routinely as they are the best indicators of migrated petroleum or leaking sources of distillate and gasoline. Special samples are collected to determine the concentration of dissolved methane in water. Analysis of dissolved gas concentrations is particularly important because naturally-occurring bacterial methane is a common and ubiquitous constituent of basin margin aquifers.

Special laboratory analyses

If gaseous hydrocarbons are found to be dissolved in water samples or discovered to be emerging along seeps, it is important to characterize them. Chromatography and isotopic analyses are the best means available to assess the likely source of gas contaminants. Such measurements require special laboratory analyses which are reliably performed by only a handful of laboratories in the U.S. and around the world. Stable isotopic analyses of carbon, hydrogen and oxygen (Clark and Fritz, 1997) are the most expensive environmental measurements generally made in CBM production-related baseline studies. In some areas, the stable carbon isotopic content of methane is sufficient to distinguish between methane of thermogenic and bacteriogenic origin. However, there are many instances when the stable isotopic composition of carbon and hydrogen in methane, carbon in associated carbon dioxide, and the hydrogen and oxygen of associated water samples are all needed to adequately differentiate among potential gas sources. The stable isotopic composition of gas samples collected near or at the surface should be compared with stable isotopic analyses of methane collected from a select number of producing wells tapping all producing horizons.

CONCLUSION

In view of the controversial environmental concerns and negative popular perceptions that have plagued CBM development everywhere, baseline studies are a relatively minor cost of doing business. Operators should consider including the right to perform baseline testing of a lessor's water wells in their mineral lease. Baseline studies should then be carefully planned prior to and during the lease acquisition phase, and implemented prior to and during production. At the very least, simple work should be performed that includes testing a lessor's water wells, noting mechanical problems, determining water yield, detecting the presence of methane prior to production, and noting anecdotal evidence of methane discharges at the surface. At best, a more detailed sampling and analysis of groundwater chemistry will help operators to understand environmental conditions prior to production. Armed with the results of such studies, operators can better quantify the risks associated with production activities and prioritize the development of acreage positions. Delaying production in environmentally sensitive areas can provide ample time for establishing monitoring sites that can provide early warning signs of impending problems. Remediation costs will always be minimized when a program is in place to detect early warning signs and when contingency actions have been planned in advance. Operators who are sensitive to changes in the environment surrounding their producing fields are also in the best position to ward off needless litigation.

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