AN OVERVIEW OF MODERN SHALE GAS DEVELOPMENT IN THE UNITED STATES

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Natural gas production from tight shale formations, known as "shale gas", is one of the most rapidly expanding trends in onshore domestic oil and gas exploration and production today. In some cases, this has included bringing drilling and production to regions of the country that have seen little or no activity in the past. New oil and gas developments bring change to the environmental and socio-economic landscape, particularly in those areas where gas development is new. With these changes have come questions about the nature of shale gas development, the potential environmental impacts, and the ability of the current regulatory structure to deal with this development. Both regulators and policy makers need objective sources of information upon which to base answers to these questions and to make decisions about how to manage the challenges that may accompany shale gas development.

This paper responds to these needs by describing the importance of shale gas in meeting the future energy needs of the United States (U.S.) and providing an overview of modern shale gas development. It also presents a summary of regulations applicable to the natural gas production industry, and details the environmental considerations related to shale gas development.

Natural Gas Basics

Natural gas is a mixture of light-end, flammable hydrocarbons primarily composed of methane (CH_4),[1] but also containing lesser percentages of butane, ethane, propane, and other gases. It is odorless, colorless, and, when ignited, releases a significant amount of energy.[2] Natural gas is burns cleanly and emits much smaller quantities of potentially harmful emissions than either coal or oil.[3]

Natural gas is found in rock formations (reservoirs) beneath the earth's surface; in some cases it may be associated with oil deposits. Once extracted, the natural gas is processed to eliminate other gases, water, sand, and impurities. Some hydrocarbon gases, such as butane and propane, are captured and marketed separately. Once it has been purified, the natural gas is distributed through a system of pipelines across thousands of miles[4] to its endpoints for residential, commercial, industrial, and transportation use.

The widespread use of natural gas—in the industrial, residential, and commercial sectors—is largely due to its versatility. Its high BTU content and well-developed infrastructure make it a

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[1] Chemistry and Technology of Fuels and Oils. 2000. Volume 36, Number 2, pp. 82-88. March 2000.

[2] NaturalGas.org. *Overview of Natural Gas*. Background. www.naturalgas.org/overview/background.asp. Accessed: September 2008.

[3] EIA. 1999. *Natural Gas 1998: Issues and Trends*. http://www.eia.doe.gov/pub/oil_gas/natural_gas/analysis_publications/natural_gas_1998_issues_trends/pdf/it98.pdf. Accessed: April 1999.

[4] EIA. *About U.S. Natural Gas Pipelines – Transporting Natural Gas*. www.eia.doe.gov/pub/oil_gas/natural_gas/analysis_publications/ngpipeline. Accessed: September 2008.

versatile fuel, useful for many applications, from electrical generation to residential heating. In addition, it is efficient and clean burning, the cleanest of all of the fossil fuels.[5],[6], [7],[8] With the current emphasis on the potential effects of air emissions on global climate change, air quality, and visibility, cleaner fuels like natural gas are an important part of our nation's energy future.[9]

Another factor that makes natural gas an attractive energy source is its reliability. Eighty-four percent of the natural gas consumed in the U.S. is produced here, and 98 percent is produced in North America.[10] Thus, the supply of natural gas is not dependent on unstable foreign countries and the delivery system is less subject to interruption.

The Role of Natural Gas in the United States' Energy Portfolio

Natural gas plays a key role in meeting U.S. energy demands. Natural gas, coal and oil supply about 85 percent of the nation's energy (Exhibit 1[11]), with natural gas supplying about 22 percent of the total.[12] Proportionally, this is expected to remain fairly constant for the next twenty years. The National Petroleum Council estimates that the U.S. has more than 1,530 Tcf of technically recoverable natural gas, including 204 Tcf of proven reserves (reserves are the discovered, economically recoverable fraction of the original gas-in-place).[13] Given that one Tcf is one trillion cubic feet, the proven reserves alone could provide heating energy to 3,060 homes, generate 204 billion kilowatt-hours of electricity, or fuel 2,448,000,000 natural gas-powered vehicles for one year.[14] At U.S. production rates for 2008, the current resource estimate provides enough natural gas to supply the U.S. for the next 82 years.[15]

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[5] EIA. 2007. *International Energy Outlook 2007, Chapter 4: Natural Gas*. http://tonto.eia.doe.gov/FTPROOT/forecasting/0484(2007).pdf. May 2007.

[6] EIA. 2008. *Annual Energy Outlook 2008 with Projections to 2030*. http://www.eia.doe.gov/oiaf/aeo/pdf/0383(2008).pdf. June 2008.

[7] NaturalGas.org. 2008. *Natural Gas and the Environment*. http://www.naturalgas.org/environment/naturalgas.asp. Accessed: September 2008.

[8] American Clean Skies Foundation. *Natural Gas Myth vs. Fact*. www.cleanskies.org. Accessed: September 2008.

[9] American Clean Skies Foundation. *U.S. Fuel Goals*. www.cleanskies.org. Accessed: September 2008.

[10] EIA. 2008. *Natural Gas Year-In-Review 2007.* http://www.eia.doe.gov/pub/oil_gas/natural_gas/feature_articles/2008/ngyir2007/ngyir2007.pdf. Accessed: March 2008.

[11] EIA. 2008. *Annual Energy Outlook 2008 with Projections to 2030*. http://www.eia.doe.gov/oiaf/aeo/pdf/0383(2008).pdf. Accessed: June 2008.

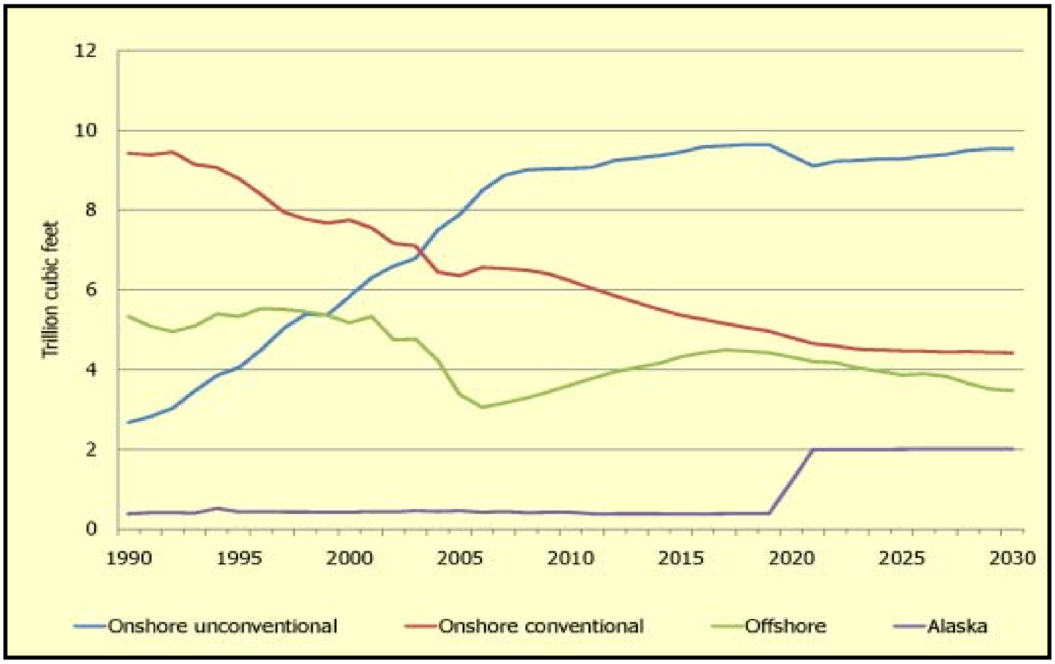
[12] EIA. 2008. *Annual Energy Outlook 2008 with Projections to 2030*. http://www.eia.doe.gov/oiaf/aeo/pdf/0383(2008).pdf. June 2008.

[13] National Petroleum Council. 2008. 118th meeting of the National Petroleum Council. September 17, 2008.

[14] Department of Energy. 2003. *Rocky Mountain States Natural Gas – Resource Potential and Prerequisites to Expanded Production*. http://fossil.energy.gov/programs/oilgas/publications/naturalgas_general/rockymtn_final.pdf. DOE/FE-0460. Accessed: September 2003.

[15] Navigant Consulting. 2008. *North American Natural Gas Supply Assessment*. Prepared for American Clean Skies Foundation. July 4, 2008.

EXHIBIT 2: NATURAL GAS PRODUCTION BY SOURCE (TCF/YEAR)



Source: EIA, 2008

Unconventional Gas

Much of the technically recoverable natural gas in North America is present in unconventional reservoirs such as tight sands, shale, and coal beds.[16] Over the last decade, production from unconventional sources has increased almost 65 percent, from 5.4 Tcf/year in 1998 to 8.9 Tcf/year in 2007. This means unconventional production now accounts for 46 percent of the total U.S. manufacture.[17] Overall, unconventional natural gas is anticipated to become an ever increasing portion of the U.S. proven reserves, constituting the bulk of the U. S. natural gas supply for the next twenty years (Exhibit 2[18]), while production from conventional gas resources is declining.[19]

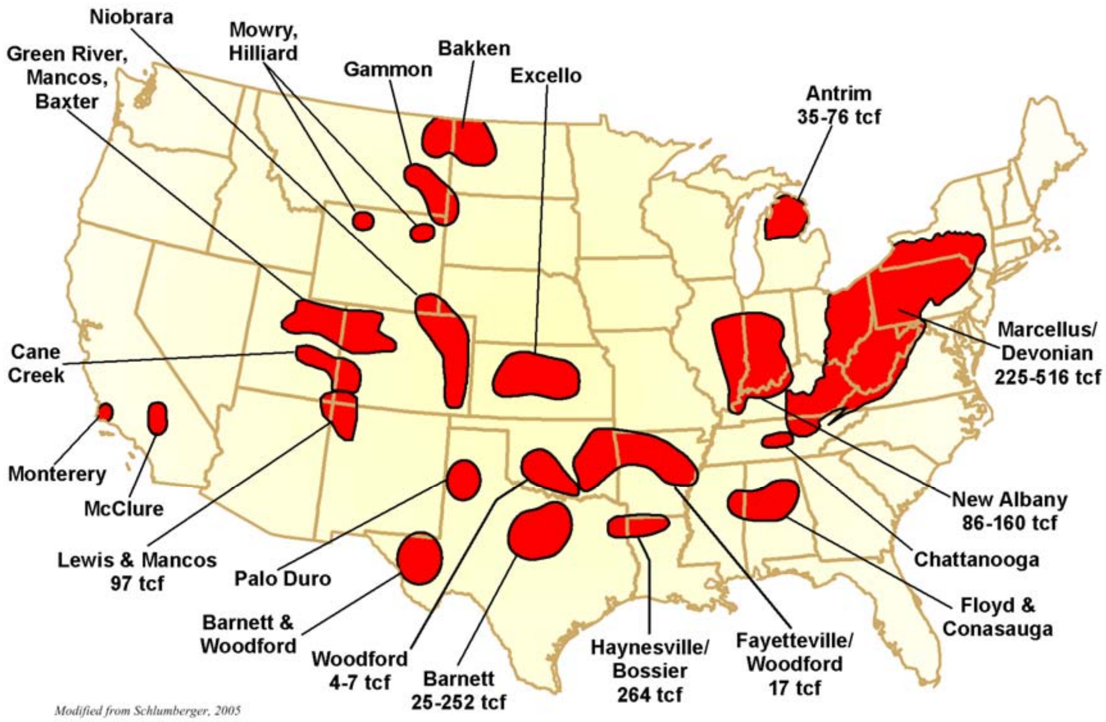
[16] EIA. 2007. *International Energy Outlook, Chapter 4: Natural Gas*. http://tonto.eia.doe.gov/FTPROOT/forecasting/0484(2007).pdf. Accessed: May 2007.

[17] Navigant Consulting. 2008. *North American Natural Gas Supply Assessment*. Prepared for American Clean Skies Foundation. July 4, 2008.

[18] EIA. 2008. *Annual Energy Outlook 2008 with Projections to 2030*. http://www.eia.doe.gov/oiaf/aeo/pdf/0383(2008).pdf. Accessed: June 2008.

[19] EIA. 2008. *Annual Energy Outlook 2008 with Projections to 2030*. http://www.eia.doe.gov/oiaf/aeo/pdf/0383(2008).pdf. Accessed: June 2008.

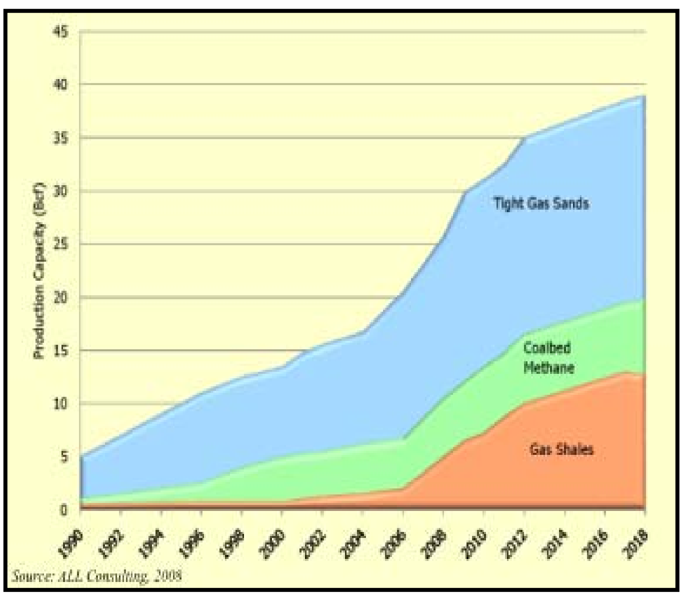
EXHIBIT 3: SHALE GAS PLAYS IN THE UNITED STATES



The Role of Shale Gas in Unconventional Gas

A key factor in this increase in production from unconventional resources has been the development of shale gas. The lower forty-eight states have a wide distribution of highly organic shales capable of containing vast resources of natural gas (Exhibit 3[20]). This potential for production in the twenty-one known onshore shale basins, coupled with other unconventional gas plays, is expected to contribute significantly to the U.S. domestic energy outlook. Exhibit 4[21] shows the projected contribution of shale gas to the overall unconventional gas production in the U.S. in terms of Bcf per day.

EXHIBIT 4: UNITED STATES UNCONVENTIONAL GAS OUTLOOK



Three factors have come together in recent years to make shale gas production

[20] Modified from: Frantz, J.K. and Jochen, V. 2005. Schlumberger. *Shale Gas White Paper*. 05-OF299. Schlumberger Marketing Communications. October 2005.

[21] ALL Consulting, 2008. U.S. Unconventional Gas Outlook.

economically viable: technological advances in 1) horizontal drilling and 2) hydraulic fracturing, plus 3) rapid increases in natural gas prices as a result of significant supply and demand pressures. Horizontal drilling and hydraulic fracturing have not only dramatically improved daily production rates, but have increased the total ultimate recovery potential of individual wells to as high as 54 percent in one experimental case in Texas.[22] Without these advances in the pre-existing technology, many unconventional natural gas plays would not be economical. As recently as the late 1990s, only 40 drilling rigs (6 percent) in the U.S. were capable of onshore horizontal drilling; that number grew to 519 rigs (28 percent) by May of 2008.[23]

Since 1998, annual production has consistently exceeded EIA's forecasts of unconventional gas production. A great deal of this increase is attributable to shale gas production, particularly from the Barnett Shale in Texas. Already, the fledgling Barnett Shale play in Texas produces 6 percent of all natural gas produced in the lower forty-eight states.[24] The potential for most other shale gas plays in the U.S. is just emerging. Taking this into consideration, Navigant (2008) has projected that the U.S. total natural gas resources (proven plus unproven technically recoverable) are 1,680 Tcf to 2,247 Tcf, or 88 to 118 years of production at 2007 production levels. Of that, shale gas is expected to provide 28 percent, or more, of the estimated production.[25]

Analysts have estimated that by 2011 most new reserves growth (50 to 60 percent or approximately 3 Bcf/d) will come from unconventional shale gas reservoirs.[26] Total annual production volumes of 3 to 4 Tcf may be sustainable for decades. An additional benefit of shale gas plays is that many exist in areas previously developed for natural gas production and, therefore, much of the necessary pipeline infrastructure is already in place. Many of these areas are also near the nation's population centers thus facilitating transportation to consumers.

EXHIBIT 5: MARCELLUS SHALE

Source: ALL Consulting, 2008

SHALE GAS DEVELOPMENT IN THE UNITED STATES

Shale formations across the U.S. have been used to produce natural gas in small but continuous volumes since the earliest years of gas

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22 Williams, P. 2008. American Clean Skies. *A Vast Ocean of Natural Gas*. p 44-50. Summer 2008.

23 EIA. 2008. *Is U.S. Natural Gas Production Increasing*? http://tonto.eia.doe.gov/energy_in_brief/natural_gas_production.cfm. Accessed: June 11, 2008

24 EIA. 2008. *Is U.S. Natural Gas Production Increasing*? http://tonto.eia.doe.gov/energy_in_brief/natural_gas_production.cfm. Accessed: June 11, 2008.

25 Navigant Consulting. 2008. *North American Natural Gas Supply Assessment*. Prepared for American Clean Skies Foundation. July 4, 2008.

26 Navigant Consulting. 2008. *North American Natural Gas Supply Assessment*. Prepared for American Clean Skies Foundation. July 4, 2008.

development.[27] By the 1930s, gas from the Antrim Shale in Michigan had experienced moderate cultivation, and in the 1980s, it grew to nearly 9,000 wells.[28]

It was also during the 1980s that the nation's most active natural gas play initially kicked off in the area near Fort Worth, Texas.[29] The play was the Barnett Shale and its success grabbed the industry's attention. Large-scale hydraulic fracturing, a process first developed in Texas in the 1950s, was first used on the Barnett in 1986; likewise, the first horizontal well in the Barnett was drilled in 1992.[30] Through continued improvements in the techniques and technology of hydraulic fracturing, development of the Barnett Shale has accelerated.[31] In the ensuing two decades, the science of shale gas extraction has matured into a sophisticated process which utilizes horizontal drilling and sequenced multi-stage hydraulic fracturing technologies. As the Barnett Shale play has matured, natural gas producers have been looking to apply the lessons learned there to other shale gas formations across the U.S. and Canada.[32]

The combination of sequenced hydraulic fracture treatments and horizontal well completions has been crucial to the expansion of shale gas development. Prior to the successful application of these two technologies in the Barnett Shale, similar resources in many basins were overlooked because production was not considered economically feasible.[33] The low natural permeability of shale has limited the production of gas shale resources because such low permeability allows only minor volumes of gas to flow naturally to a wellbore.[34] This characteristic of low matrix permeability represents a key difference between shale and other gas reservoirs, and must be overcome for gas shales to be economically viable.[35] Historically, operators have by-passed gas shale formations because of the combination of reduced economics and low permeability.[36]

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[27] Harper, J. 2008. Published by the Bureau of Topographic and Geologic Survey, Pennsylvania Department of Conservation and Natural Resources. Pennsylvania Geology. *The Marcellus Shale – An Old "New" Gas Reservoir in Pennsylvania*. v 28. no 1. Spring 2008.

[28] Harrison, W. Production History and Reservoir Characteristics of the Antrim Shale Gas Play, Michigan Basin. Western Michigan University. 2006.

[29] Hayden, J., and Pursell, D. 2005. Pickering Energy Partners Inc. *The Barnett Shale. Visitor's Guide to the Hottest Gas Play in the US.* October 2005.

[30] Hayden, J., and Pursell, D. 2005. Pickering Energy Partners Inc. *The Barnett Shale. Visitor's Guide to the Hottest Gas Play in the US*. October 2005.

[31] Halliburton Energy Services. 2008. *U.S. Shale Gas: An Unconventional Resource*. Unconventional Challenges. 2008.

[32] Hayden, J., and Pursell, D. 2005. Pickering Energy Partners Inc. *The Barnett Shale. Visitor's Guide to the Hottest Gas Play in the US.* October 2005.

[33] Harper, J. 2008. Published by the Bureau of Topographic and Geologic Survey, Pennsylvania Department of Conservation and Natural Resources. Pennsylvania Geology. *The Marcellus Shale – An Old "New" Gas Reservoir in Pennsylvania*. v 28. no 1. Spring 2008.

[34] Ameri, S., Aminian, K., Miller, J.A., Doricich, D., and Yost, A.B. A Systematic Approach for Economic Development of the Devonian Shale Gas Resources. SPE 14504.

[35] Halliburton Energy Services. 2008. *U.S. Shale Gas: An Unconventional Resource*. Unconventional Challenges. 2008.

[36] Airhart, M. Geology.com. The Barnett Shale Gas Boom: Igniting a Hunt for Unconventional Natural Gas Resources. Accessed: September 2008.

Shale Gas – Geology

Shale gas is natural gas produced from shale formations that typically function as both the reservoir and source rocks for the natural gas. In terms of its chemical makeup, shale gas is typically a dry gas composed primarily of methane (at least 90 percent methane), but some formations do produce wet gas. The Antrim and New Albany plays have typically produced water and gas.[37] Gas shales are organic-rich shale formations that were previously regarded only as source rocks and seals for gas accumulating in the strata near sandstone and carbonate reservoirs of traditional onshore gas development.[38] Shale is a sedimentary rock that is predominantly composed of consolidated clay sized particles. Shales are deposited as muds in low-energy environments such as tidal flats and deep water basins where the fine-grained clay particles fall out of suspension in the quiet waters. During the deposition of these very fine-grained sediments, there can also be accumulation of organic matter in the form of algae, plant, and animal derived organic debris.[39] The very fine sheet-like clay mineral grains and laminated layers of sediment result in a rock with permeability that is limited horizontally and extremely limited vertically This low permeability means that gas trapped in shale cannot move easily within the rock except over geologic expanses of time, i. e., millions of years. These units are often organic-rich and are thought to be the source beds for much of the hydrocarbons produced in these basins.[40]

Exhibit 5 shows a typical shale outcrop, revealing the natural bedding planes, or layers, of the shale and near vertical fractures that can cut across the naturally horizontal bedding planes. Although the vertical fissures shown in this picture are naturally occurring, artificial cracks induced by hydraulic fracture stimulation in the deep subsurface reservoir rock would have a similar appearance.

Shale Gas in the United States

Shale gas is present across much of the lower forty-eight States. Exhibit 3 shows the approximate locations of current producing gas shales. The most active shales to date are the Barnett Shale, the Haynesville Shale, the Antrim Shale, and the New Albany Shale.

Each of these gas shale basins is different and each has its unique set of exploration criteria and operational challenges. Because of these differences, the development of shale gas resources in each of these areas poses potential challenges to the surrounding communities and ecosystems For example the Antrim and New Albany Shales are shallower shales which produce significant volumes of formation water unlike most of the other gas shales. While development of the Fayetteville Shale is located in rural areas of north central Arkansas, development of the Barnett Shale is focused in the area of Forth Worth, Texas in an urban and suburban environment.
As new technologies are developed and refined, shale gas plays once believed to have limited economic viability are being re-evaluated. Exhibit 6 summarizes the key characteristics of select shale gas plays across the U.S. This Exhibit provides not only data related to the character of the

[37] Boyer, C., Kieschnick, J., Suarez-Rivera, R., Lewis, R., and Walter, G. 2006. Schlumberger. Oilfield Review. *Producing Gas from Its Source*. Autumn 2006.

[38] Frantz, J.K. and Jochen, V. 2005. Schlumberger. *Shale Gas White Paper*. 05-OF299. Schlumberger Marketing Communications. October 2005.

[39] Davis Jr, R. 1992. Depositional Systems: An Introduction to Sedimentology and Stratigraphy. Prentice Hall. 2nd Edition. 1992.

[40] Nuttal, B.C. 2007. Kentucky Geological Survey. Predicting Cumulative Production of Devonian Shale Gas Wells from Early Well Performance Data, Appalachian Basin of Eastern Kentucky. September 2007..

shale but also a means to compare some of the key characteristics for evaluating the different gas shale basins.

EXHIBIT 6. COMPARISON OF DATA FOR THE GAS SHALES IN THE UNITED STATES							
Gas Shale Basin	Barnett	Fayetteville	Haynesville	Marcellus	Woodford	Antrim	New Albany
Estimated Basin Area, square miles	5,000	9,000	9,000	95,000	11,000	12,000	43,500
Depth, ft	6, 500 - 8,500[42]	1,000 - 7,000[43]	10,500 - 13,500[44]	4,000 - 8,500[45]	6,000 – 11,000[46]	600 – 2,200[47]	500 – 2,000[48]
Net Thickness, ft	100-600[49]	20-200[50]	200[51]- 300[52]	50-200[53]	120-220[54]	70-12[55]	50-100[56]
Depth to Base of Treatable Water, ft	~1200	~500[57]	~400	~850	~400	~300	~400
Rock Column Thickness between Top of Pay and Bottom of Treatable Water	5,300–7,300	500 – 6,500	10,100 – 13,100	2,125 - 7650	5,600 – 10,600	300 – 1,900	100 – 1,600
Total Organic Carbon, %	4.5[58]	4.0-9.8[59]	0.5 – 4.0[60]	3-12[61]	1-14[62]	1-20[63]	1-25[64]
Total Porosity, %	4-5[65]	2-8[66]	8-9[67]	10[68]	3-9[69]	9[70]	10-14[71]
Gas Content, scf/ton	300-350[72]	60-220[73]	100-330[74]	60-100[75]	200-300[76]	40-100[77]	40-80[78]
Water Production, Barrels water/day	0[79]	0	0	0		5-500[80]	5-500[81]
Well spacing, Acres	60-160[82]	80-160	40-560[83]	40-160[84]	640[85]	40-160[86]	80[87]
Original Gas-In-Place, Tcf[88]	327	52	717	1,500	52	76	160
Recoverable Resources, Tcf[89]	44	41.6	251	262[90], 500[91]	11.4	20	19.2
Est. Gas Production, mcf/day/well	338[92]	530[93]	625-1,800[94]	3,100[95]	415[96]	125-200[97]	

Mcf = thousands of cubic feet of gas.
NOTE: Data derived from various sources and research analysis. Information from some basins was unable to be identified and confirmed at the time of this paper and has been left blank.
- for the Depth to base of treatable water data, the data was based on depth data from state oil and gas agencies and state geological survey data.

[42] Hayden, J., and Pursell, D. 2005. Pickering Energy Partners Inc. *The Barnett Shale. Visitor's Guide to the Hottest Gas Play in the US*. October 2005.

[43] Halliburton Energy Services. 2008. *U.S. Shale Gas: An Unconventional Resource*. Unconventional Challenges. 2008.

[44] Halliburton Energy Services. 2008. *U.S. Shale Gas: An Unconventional Resource*. Unconventional Challenges. 2008.

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[50] Hayden, J., and Pursell, D. 2005. Pickering Energy Partners Inc. *The Barnett Shale. Visitor's Guide to the Hottest Gas Play in the US*. October 2005.

[51] Boughal, K. 2008. *Unconventional Plays Grow in Number After Barnett Shale Blazed the Way*. World Oil Magazine. v 229. no 8. August 2008.

[52] Berman, A. 2008. *The Haynesville Shale Sizzles with the Barnett Cools*. World Oil Magazine. Volume 229 No.9. September 2008.

[53] Drilling Contractor. 2000. *Alabama Lawsuit Poses Threat to Hydraulic Fracturing Across U.S.* pp 42-43. January/February 2000.

[54] Haines, L. 2006. Supplement to Oil & Gas Investor. *Shale gas: Activity Builds in the Woodford Shale*. p 17. http://www.oilandgasinvestor.com/pdf/ShaleGas.pdf. January 2006.

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[56] Hayden, J., and Pursell, D. 2005. Pickering Energy Partners Inc. *The Barnett Shale. Visitor's Guide to the Hottest Gas Play in the US*. October 2005.

[57] Arkansas Oil and Gas Commission. 2008. Field Rules and Rule B-15.

[58] Hayden, J., and Pursell, D. 2005. Pickering Energy Partners Inc. *The Barnett Shale. Visitor's Guide to the Hottest Gas Play in the US*. October 2005.

[59] Hayden, J., and Pursell, D. 2005. Pickering Energy Partners Inc. *The Barnett Shale. Visitor's Guide to the Hottest Gas Play in the US*. October 2005.

[60] Berman, A. 2008. *The Haynesville Shale Sizzles while the Barnett Cools.* World Oil Magazine. v 229. no 9. September 2008.

[61] Nyahay, R., Leone, J., Smith, L., Martin, J., and Jarvie, D. 2007. *Update on Regional Assessment of Gas Potential in the Devonian Marcellus and Ordovician Utica Shales of New York.* http://www.searchanddiscovery.net/documents/2007/07101nyahay/index.htm. October 1, 2007.

[62] Cardott, B. 2004. Oklahoma Geological Survey. *Overview of Unconventional Energy Resources of Oklahoma*. http://www.ogs.ou.edu/fossilfuels/coalpdfs/UnconventionalPresentation.pdf. March 9, 2004.

[63] Hayden, J., and Pursell, D. 2005. Pickering Energy Partners Inc. *The Barnett Shale. Visitor's Guide to the Hottest Gas Play in the US*. October 2005.

[64] Hayden, J., and Pursell, D. 2005. Pickering Energy Partners Inc. *The Barnett Shale. Visitor's Guide to the Hottest Gas Play in the US*. October 2005.

[65] Hayden, J., and Pursell, D. 2005. Pickering Energy Partners Inc. *The Barnett Shale. Visitor's Guide to the Hottest Gas Play in the US*. October 2005.

[66] Hayden, J., and Pursell, D. 2005. Pickering Energy Partners Inc. *The Barnett Shale. Visitor's Guide to the Hottest Gas Play in the US*. October 2005.

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[68] Soeder, D.J. 1986. *Porosity and Permeability of Eastern Devonian Gas Shale*. SPE Formation Evaluation. v 3. Issue 1. January 1, 1986.

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[74] Petroleum Listing Services. 2008. *Other Players Reporting Haynesville Success.* August 15, 2008.

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[84] Sumi, L. 2008. Oil and Gas Accountability Project (OGAP). *Shale Gas: Focus on the Marcellus Shale.* http://www.earthworksaction.org/pubs/OGAPMarcellusShaleReport-6-12-08.pdf. May 2008.

[85] Sumi, L. 2008. Oil and Gas Accountability Project (OGAP). *Shale Gas: Focus on the Marcellus Shale*. http://www.earthworksaction.org/pubs/OGAPMarcellusShaleReport-6-12-08.pdf. May 2008.

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[87] Hayden, J., and Pursell, D. 2005. Pickering Energy Partners Inc. *The Barnett Shale. Visitor's Guide to the Hottest Gas Play in the US.* October 2005.

[88] Navigant Consulting. 2008. *North American Natural Gas Supply Assessment.* Prepared for American Clean Skies Foundation. July 4, 2008.

[89] Navigant Consulting. 2008. *North American Natural Gas Supply Assessment.* Prepared for American Clean Skies Foundation. July 4, 2008.

[90] Navigant Consulting. 2008. *North American Natural Gas Supply Assessment.* Prepared for American Clean Skies Foundation. July 4, 2008.

[91] Engelder, T and Lash, G.G. 2008. *Marcellus Shale Play's Vast Resource Potential Creating Stir in Appalachia*. The American Oil & Gas Reporter. May 2008.

[92] Williams, P. 2008. American Clean Skies. *A Vast Ocean of Natural Gas*. p 44-50. Summer 2008.

[93] Williams, P. 2008. American Clean Skies. *A Vast Ocean of Natural Gas*. p 44-50. Summer 2008.

[94] Gas Leases. 2008. Chesapeake Energy CEO: *Haynesville Shale is Fourth Largest in the World.* http://gas-lease.org/2008/07/06/chesapeake-energy-ceo-haynesville-shale-is-fourth-largest-in-the-world/. July 6, 2008.

[95] Engelder, T and Lash, G.G. 2008. *Marcellus Shale Play's Vast Resource Potential Creating Stir in Appalachia*. The American Oil & Gas Reporter. May 2008.

[96] Williams, P. 2008. American Clean Skies. *A Vast Ocean of Natural Gas*. p 44-50. Summer 2008.

[97] US Energy Investor. 2005. *Discovering Outstanding Investment Opportunities in the US Energy Sector*. Issue 3. January 1, 2005.

REGULATORY FRAMEWORK

The development and production of oil and gas in the U.S., including shale gas, are regulated under a complex set of federal, state, and local laws that address every aspect of exploration and operation. All of the laws, regulations, and permits that apply to conventional oil and gas exploration and production activities also apply to shale gas development. The U.S. Environmental Protection Agency (EPA) administers most of the federal laws, but development on federally-owned land is managed primarily by the Bureau of Land Management (part of the Department of the Interior) and the U.S. Forest Service (part of the U.S. Department of Agriculture). In addition, each state in which oil and gas is produced has one or more regulatory agencies that administrate wells, including their design, location, spacing, operation, and abandonment, as well as environmental activities and discharges, including water management and disposal, waste management and disposal, air emissions, underground injection, wildlife impacts, surface disturbance, and worker health and safety. Many of the federal laws are implemented by the states under agreements and plans approved by the appropriate federal agencies.

Federal and State Environmental Laws Governing Shale Gas Development

A series of federal laws govern most environmental aspects of shale gas development. For example, the Clean Water Act regulates surface discharges of water associated with shale gas drilling and production, as well as storm water runoff from production sites. The Safe Drinking Water Act directs the underground injection of fluids from shale gas activities. The Clean Air Act limits air emissions from engines, gas processing equipment, and other sources associated with drilling and production. The National Environmental Policy Act (NEPA) requires that exploration and production on federal lands be thoroughly analyzed for environmental impacts.

However, federal agencies do not have the resources to administer all of these environmental programs for all the oil and gas sites around the country. In addition, federal regulation may not always be the most effective way of assuring the desired level of environmental protection. Therefore, most of these federal laws have provisions for granting primacy to the states, which have usually developed their own sets of regulations. By statute, states may adopt these standards of their own, but they must be at least as protective as the federal principles they replace—they may actually be more protective in order to address local conditions. Once these programs are approved by the relevant federal agency (usually EPA), the state then has primacy jurisdiction.

State regulation of the environmental practices related to shale gas development can more easily address the regional and state-specific character of the activities, compared to one-size-fits-all management at the federal level.[41] Some of these factors include: geology, hydrology, climate, topography, industry characteristics, development history, state legal structures, population density, and local economics. The state agencies that regulate environmental practices and monitor and enforce their laws and regulations may be located in the Department of Natural Resources (such as in Ohio) or in the Department of Environmental Protection (such as in Pennsylvania). The Texas Railroad Commission regulates oil and gas activity in the nation's largest oil and gas producing state, home to the Barnett Shale. The names and organizational structures vary, but the functions are very similar. Often, multiple agencies are involved, having jurisdiction over different activities and aspects of development.

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[41] Interstate Oil and Gas Compact Commission (IOGCC). *Issues. States' Rights*. http://www.iogcc.state.ok.us/states-rights. Accessed: September 2008.

These state agencies not only implement and enforce federal laws; they also have their own sets of state laws to administer, which often add additional levels of environmental protection and requirements. Also, several states have their own versions of the federal NEPA law, requiring environmental assessments and reviews at the state level and extending those reviews beyond federal lands to state and private lands.

The regulation of shale gas drilling and production is a cradle-to-grave approach, and states have many tools at their disposal to assure that shale gas operations do not adversely impact the environment. They have broad powers to regulate, permit, and enforce all activities—from drilling and fracturing of the well, to production operations, to managing and disposing of wastes, to abandoning and plugging the well. Different states take different approaches to this regulation and enforcement, but their laws generally give the state oil and gas director or the agency the discretion to require whatever is necessary to protect the human health and the environment.[42] In addition, most have a general prohibition against pollution from oil and gas drilling and production.[43] A majority of the state requirements are written into rules or regulations; however some are added to permits on a case-by-case basis as a result of environmental review, on-the-ground inspections, public comments, or commission hearings.

States require developers to obtain a permit before drilling and operating a gas well. The application for this permit includes data about the well location, construction, operation and reclamation. If the well is to be fractured, information about the fracturing program is included in the application.[44] Agency staff members review the application for compliance with regulations and to assure adequate environmental safeguards, and if necessary, perform a site inspection before permit approval. Most states require notice to affected landowners and/or the public and provide the opportunity for objections to drilling permits. Any protestations are then investigated by the agencies for evidence of possible adverse impacts from drilling. Most states have implemented safeguards even beyond these: most require operators to post a bond or other financial security when obtaining a drilling permit to insure compliance with the state regulations and to make sure that there are funds to properly plug the well once production ceases; and many obligate producers to notify the state agencies of any significant new activity through a "sundry notice" or a new permit application so that the agency is aware of that activity and can review it.[45]

State oil and gas environmental programs are also periodically reviewed against a set of guidelines developed by an independent body of state, industry, and environmental stakeholders, known as

[42] An example of this type of provision is the following from Pennsylvania's statute: "[T]he department shall have the authority to issue such orders as are necessary to aid in the enforcement of the provisions of [the oil and gas] act". (58 P.S. section 601.503.).

[43] An example of such language can be found in New York's rules, which state: "The drilling, casing and completion program adopted for any well shall be such as to prevent pollution. Pollution of the land and/or of surface or ground fresh water resulting from exploration or drilling is prohibited." (5 NYCRR Part 554). Another example is the requirement in the rules of the Texas Railroad Commission: "No person conducting activities subject to regulation by the commission may cause or allow pollution of surface or subsurface water in the state." (TAC 16.1.3.8).

[44] See, for example, West Virginia Code Section 22-6-6 (c)(11) which states, "Every permit application filed under this section shall be verified and shall contain the following:…If the proposed well work is to stimulate an oil or gas well, specifications in accordance with the data requirements of … this article".

[45] See, for example, Louisiana Statewide Order 29-B, section 105, or Texas Administrative Code 16.1.3.5.

STRONGER (State Review of Oil and Natural Gas Environmental Regulation).[46] Periodic evaluations of state and federal exploration and production waste management programs have proven useful in improving the effectiveness of those programs and increasing cooperation between federal and state regulatory agencies. To date, eighteen states have been reviewed under these review guidelines, several more than once. The STRONGER program has documented the effectiveness of and improvements in these state oil and gas environmental programs.[47,48] Before STRONGER, the Interstate Oil and Gas Compact Commission was responsible for state reviews using earlier versions of the guidelines.

The organization of regulatory agencies within the different oil and gas producing states varies considerably. Some states have several agencies that may oversee some facet of oil and gas operations, particularly environmental requirements. In different states, these agencies may be located in sundry departments or divisions within their respective governments. These various approaches have developed over time within each state, and each state tries to create a structure that best serves its citizenry and all of the industries that it must oversee. The one constant is that each oil and gas producing state has one agency with primary responsibility for permitting wells and overseeing general operations. While these agencies may work with other agencies in the regulatory process, they serve as a central organizing body and a useful source of information about the various agencies that may have jurisdiction over oil and gas activities.

Local Regulation

In addition to state and federal requirements, additional requirements regarding oil and gas operations may be imposed by other levels of government in specific locations. Entities such as cities, counties, tribes, and regional water authorities may each set operational requirements that affect the location and operation of wells or require permits and approvals over and above those at the federal or state level.

When operations occur in or near populated areas, local governments may establish ordinances to protect the environment and the general welfare of its citizens. These local ordinances frequently require additional permits for control of issues such as well placement in flood zones, noise level, set backs from residences or other protected sites, site house-keeping, and traffic. For example, ordinances may set limits on the noise levels that may be generated during both daytime and nighttime operations.[49,50,51,52]

In some cases, regional river authorities that have jurisdiction in multiple states have also been established. These federally established river authorities have been created to protect the water

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[46] State Review of Oil and Natural Gas Regulations (STRONGER). http://www.strongerinc.org. Accessed: September 2008.

[47] STRONGER. *List of State Reviews*. http://www.strongerinc.org/reviews/reviews.asp. Accessed: September 2008.

[48] STRONGER. *History of STRONGER - Helping To Make An Experiment Work*. http://www.strongerinc.org/about/history.asp. Accessed: September 2008..

[49] Southlake, Texas Gas Well Ordinance. Article IV. Gas and Oil Well Drilling and Production.

[50] Richard Hills Texas Gas Well Ordinance. Ordinance No. 996-04. September 14, 2004.

[51] Haltom City Ordinance No. 0-2004-026-15. November 22, 2004.

[52] Fort Worth, Texas Ordinance No. 16986-06-2006. June 21, 2006.

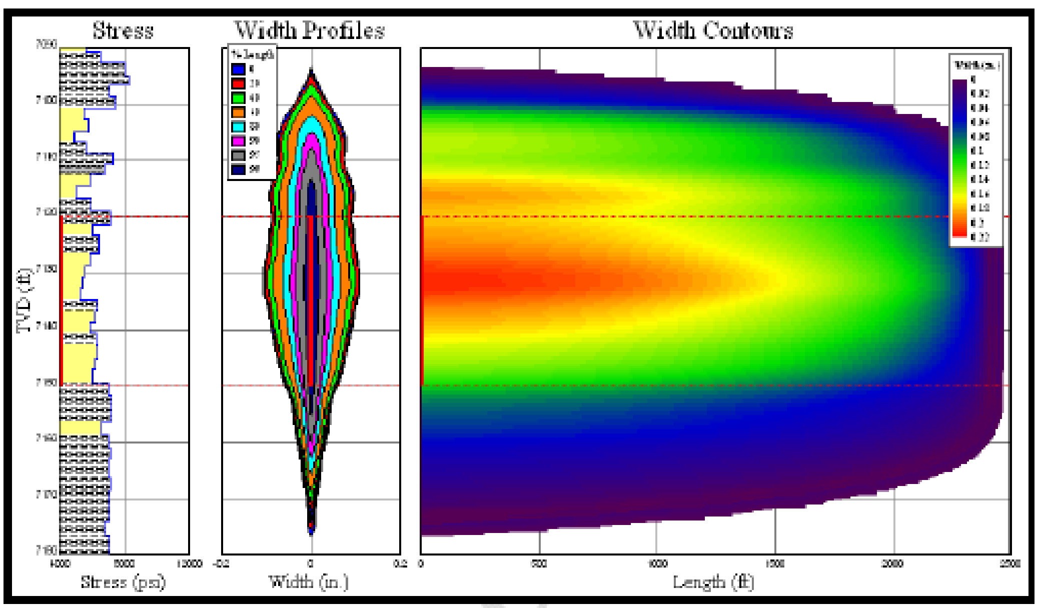
quality of the entire river basin and to govern uses of the water.[53] Additional approvals and permits may be required for operations in these river basins. For example, the Delaware River Basin Commission covers parts of New York, Pennsylvania, New Jersey and Delaware.[54] Natural gas operators wishing to withdraw water for consumptive use in this basin must first receive a permit from the DRBC.

Environmental Considerations

The development of shale gas resources has been dependent on several concomitant improvements in technology. These improvements directly affect the environmental considerations associated with shale gas development.

Hydraulic fracturing techniques have grown to be carefully engineered processes employed to generate a more extensive network of fractures and thereby produce a larger portion of the in-place natural gas. This innovation has transformed shale gas into a bona fide economic resource play and has led to the drilling of many more shale gas wells and to increased attention on potential environmental effects.

EXHIBIT 9: OUTPUT OF HYDRAULIC FRACTURE SIMULATION MODEL



Source: Chesapeake Energy Corporation, 2008.

At the same time, horizontal drilling has become more economical, faster, more accurate, and more wide-spread. With horizontal drilling, operators can access and drain larger volumes of the shale reservoir from a single well. The combination of opening up larger volumes of the reservoir and being able to reach out long distances means that only a fraction of the wells are needed to drain

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[53] Susquehanna River Basin Commission. *Regulation of Projects*. 18 CFR 801, 806, 807, and 808. http://srbc.net/policies/docs/srbc_regulation_of_projects.PDF. Effective: February 20, 2007. Accessed: September 2008

[54] Delaware River Basin Commission Basin. Administrative Manual Part III. Water Quality Regulations. 18 CFR PART 410. http://www.state.nj.us/drbc/regs/WQRegs_071608.pdf. September 12, 2008

the gas from a given field area. Fewer wells translate into fewer impacts from land disturbance, noise, water use, traffic, and air emissions.

Fluid handling techniques have also evolved to make routine drilling and stimulation work less impactful on the local environment and especially less prone to accidental releases to land, water, and air.

Hydraulic Fracturing

Fracturing is a formation stimulation technique used to create additional permeability in a producing reservoir, thus allowing gas to flow more readily to the wellbore. Fracturing has become the industry standard.[55] Recent developments in hydraulic fracturing include pumping large volumes of low-viscosity; nearly pure water/sand slurry into the shale to induce new fractures and augment existing fractures in the shale. Modern refinements in hydraulic fracturing technology make it an extremely sophisticated engineering process designed to emplace fracture networks into specific reservoir units. Hydraulic fracturing treatments are carefully tailored to the specific parameters of the target shale including thickness, local stress conditions, compressibility, and rigidity. Local conditions are used in computer models to design site-specific hydraulic fracturing treatments and optimize the new fractures as shown in Exhibit 9. Both shale gas reservoirs and the intervals to be fractured are typically thick, so it is often more effective to separate the hydraulic fracturing process into several stages, each focused on a consistent portion of the reservoir. Each stage of the job will be isolated within the borehole so that the full capacity of the fracturing equipment can be applied to the single reservoir unit.[56] This can be done in vertical or horizontal wells to great effect.

Before operators or service companies perform a hydraulic fracture treatment of a well (either vertical or horizontal), they conduct a series of tests to ensure that the well, well-head equipment, and fracturing equipment are in proper working order and will safely withstand the fracture treatment pressures and pump rates. It should be noted that minimum construction requirements are typically mandated by state oil and gas regulatory agencies to make sure that the well construction and fracture treatment design are protective of environmental resources and are safe for operation.

EXHIBIT 10: FRACTURE TREATMENT CENTRAL CONTROL VAN

Source: ALL Consulting, 2008

A fracture stimulation is closely monitored by many specialists (Fayetteville Shale - Arkansas)

After testing surface equipment, the hydraulic fracturing process begins with the pumping of a “rock-acid”—often hydrochloric acid (HCl)—treatment to clean the near-wellbore area which may

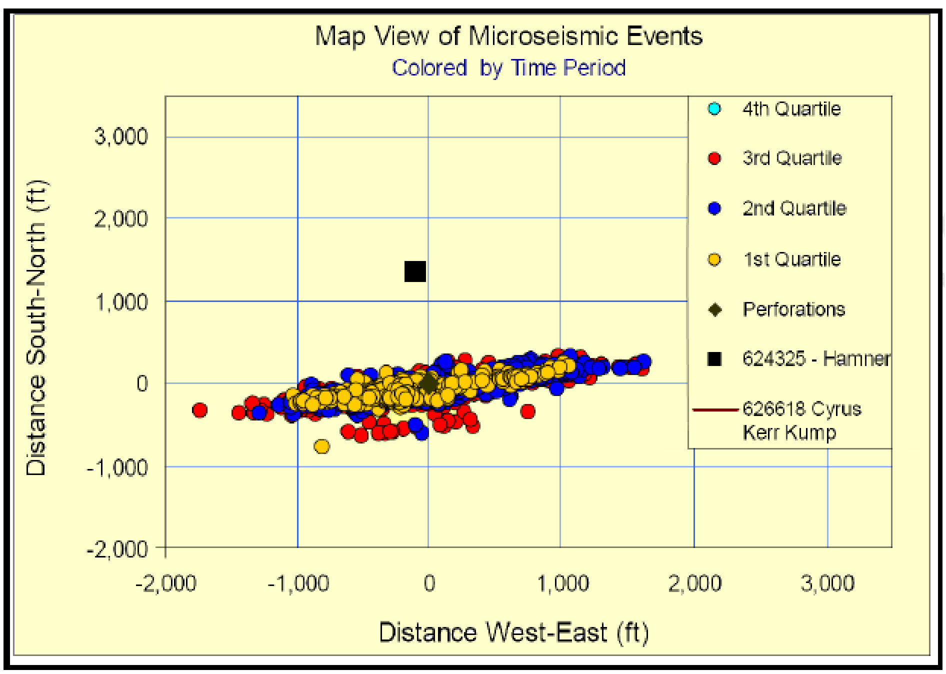
[55] Boyer, C., Kieschnick, J., Suarez-Rivera, R., Lewis, R., and Walter, G. 2006. Schlumberger. Oilfield Review. *Producing Gas from Its Source*. Pp 36-49. Autumn 2006.
[56] Ketter, A.A., Daniels,J.L., Heinze, J.R., and Waters, G. *A Field Study Optimizing Completion Strategies for Fracture Initiation in Barnett Shale Horizontal Wells*. SPE 103232.

have become plugged with drilling mud and cement. The next step is a slug of "slickwater" which combines water with a friction-reducing chemical additive allowing the water to be pumped faster into the formation. Slickwater hydraulic fractures treatments work best in low-permeability reservoirs, and have been the primary instrument in opening up unconventional plays like the Texas Barnett Shale.[57] In addition to the cost advantage, slickwater hydraulic fractures treatments require less cleanup, provide longer fractures, and carry proppant farther into the fracture network.

After the first water slug, the operator begins the fracturing process by pumping a large volume of slickwater with fine sand at a low volume. Subsequent steps include the application of slickwater volumes with coarser sand proppant that keep fractures closer to the well-bore open. The last step is a flush to remove proppant from the equipment and well-bore. After the flush, the next treatment stage is begun on a new portion of the bore-hole that contains its own specific reservoir parameters including thickness, local stress conditions, compressibility, and rigidity.

The staged fracturing treatments are closely monitored by technicians from service and operating companies (Exhibit 10). By fracturing discrete intervals of the wellbore (either horizontal or vertical), the operator is able to make modifications to accommodate local changes in the shale reservoir including lithology, natural splitting, rigidity, and changes in the stress regime.

EXHIBIT 11: MICRO SEISMIC MAPPING OF FRACTURES IN A TREATMENT



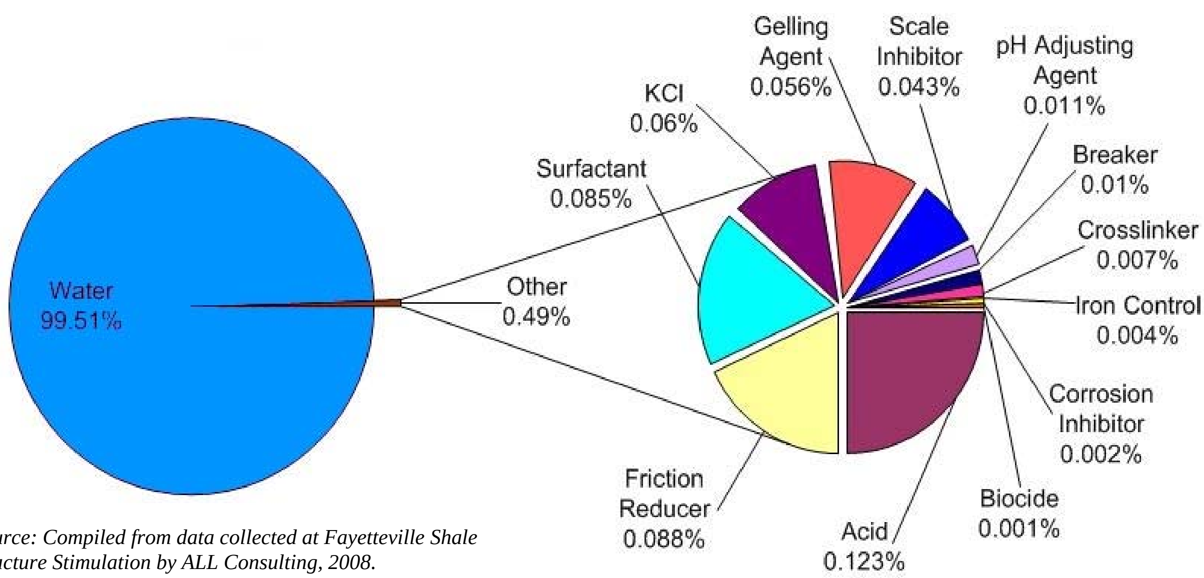
Source: Oilfield Service Company

[57] Palisch, T., M. Vincent, and P. Handren, 2008. *Slickwater Fracturing – Food for Thought.* SPE Paper 115766, September 2008.

Fracturing stages are determined with the help of numerical simulators to predict fracture performance in the shale reservoir. Engineers and geologists can manipulate the simulator and evaluate the effect on fissure height, length, and orientation.[58] Predictions from the simulator can be used to monitor and evaluate the results of the fracture job. Monitoring can also be done in real-time at the well by way of micro-seismic mapping (Exhibit 11). This technology can locate the fracture tips in an east-west and north-south direction from the bore-hole and track their growth as the job proceeds and more steps are completed. Of particular importance is the growth of fractures in the vertical direction. Operators take particular care to ensure that they do not migrate out of the shale reservoir and extend into adjacent water-bearing units. Such fissures can ruin the economics of a shale gas well.

During the fracturing treatment, a number of chemicals are added to the water-sand mix. Each chemical compound serves a specifically engineered purpose such as reducing viscosity or bacterial growth or bio-fouling reservoir surfaces. The make-up of fracturing fluid will vary from one basin to another and from one contractor to another. Exhibit 12 below graphically demonstrates the relative amounts of the components in a fracture fluid used recently on the Fayetteville Shale; this fluid is 99.5 percent water with less than 0.5 percent other compounds. Any toxicity of the components, such as acid, is greatly reduced by dilution in the pumped fluid and by the reaction of the acid with the rock in the subsurface that converts the acid into salts.[59]

EXHIBIT 12: VOLUMETRIC COMPOSITION OF A SHALE GAS FRACTURE FLUID



Source: Compiled from data collected at Fayetteville Shale Fracture Stimulation by ALL Consulting, 2008.

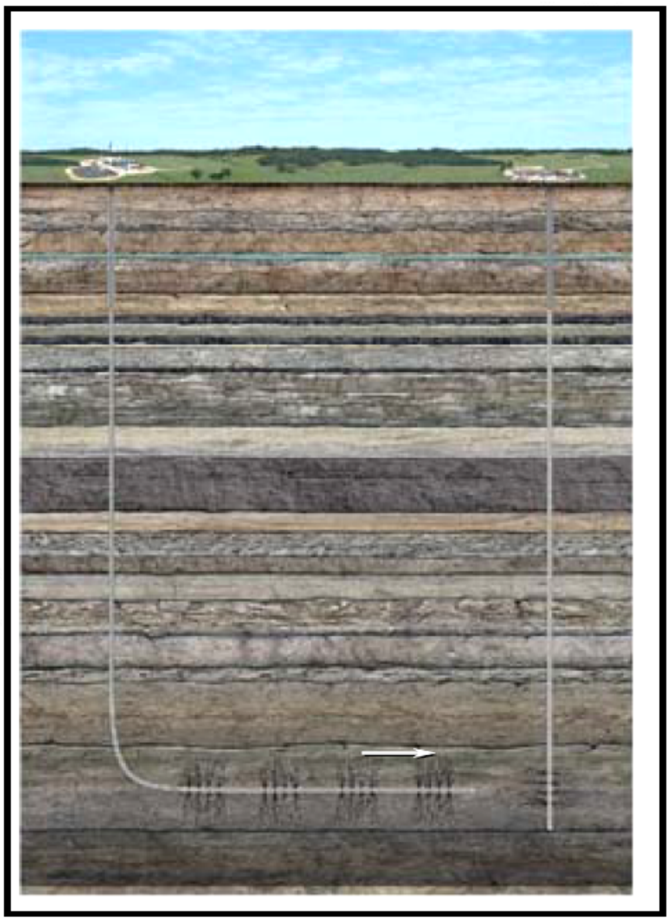
[58] Meyer & Associates, Inc. *User's Guide for the Meyer Fracturing Simulators.* Sixth Edition

[59] Parshall, J. 2008. *Barnett Shale Showcases Tight-gas Development*. Journal of Petroleum Technology. September 19, 2008.

Horizontal Drilling

Modern drilling technology has progressed to the point of allowing the driller to turn corners by making the drill bit progress on a horizontal track while accurately staying within a narrow directional and vertical window. Because the horizontal portion is easily controlled, the well is able to drain shale gas resources from a geographical area that is much larger than a single vertical well in the same shale formation. Exhibit 13 illustrates how horizontal drilling provides more drainage in a shale gas development than does a vertical well. Using the Marcellus Shale play in Pennsylvania as an example, a vertical well may only drain a cylinder of shale 1,320 feet in diameter and as little as 50 feet high . By comparison, a horizontal well may extend from 2,000 to 6,000 feet in length and drain a volume up to 6,000 feet by 1,320 feet by 50 feet in thickness, an area about 4,000 times greater than that drained by a vertical well. The increase in drainage creates a number of important advantages for horizontal over vertical wells, particularly in terms of environmental concerns.

EXHIBIT 13: EXAMPLE HORIZONTAL WELL



Source: John Perez, Copyright ©, 2008

Using the similar Fayetteville Shale as an example, analysis performed for the U. S. Department of the Interior[60] estimated that a shallow vertical shale gas well in Arkansas would have a 2.0 acre well pad and 0.10 miles of road and 0.55 miles of utility corridor resulting in a total of 4.8 acres of disturbance per well. The same study identified a horizontal shale gas well that occupies a well-pad of approximately 3.5 acres plus roads and utilities resulting in a total of 6.9 acres. The horizontal well has the ability to drain at least four times the acreage of a vertical well, meaning that horizontal shale gas development results in roughly one-third (19.2 acres versus 6.9 acres) the disturbed acres. This means less landscaping and vegetation destroyed, wildlife habitat disturbed, soil erosion and compaction done, and general construction needed. Co-locating several horizontal wells on a single pad will further shrink the number of disturbed acres.

Reducing the number of producing wells in a field will also reduce the need for field personnel and routine truck traffic within the field. Fewer wells will require fewer maintenance crews traveling county roads. Produced water will still need to be transported to central management facilities but if there are fewer well sites with more production, it may become economical to transport the water to the facility by pipeline rather than by truck. Pipelines require ground

[60] U.S. Department of the Interior. 2008. *Reasonably Foreseeable Development Scenario for Fluid Minerals : Arkansas.* Prepared for the Bureau of Land Management Eastern States Jackson Field Office. March 2008.

disturbance but the total amount is small and the time of disturbance is short until the trenches can be filled and re-vegetated. Furthermore, pipelines can be built with an assortment of safety features such as automatic cutoff valves along the pipeline to isolate the line if pressures drop (indicating a leak) and trip-wires laid on top of the pipelines that will break if the pipeline is severed by earth-moving equipment.[61]

Like traffic, noise can be reduced by use of these fewer horizontal wells. If a shale gas field only has one-quarter the number of wells, noise and dust from drilling and equipment will be much less. These impacts can be further reduced as required by mitigation strategies such as sound walls and spraying gravel roads with dust-suppressant during dry periods. Then again, dust and noise are not issues in most rural locations, and mitigation may not be needed.

Other potential environment impacts from drilling can also be alleviated. Wastes such as used mud and produced water are managed by routine, on-site containment of these fluids as described in the next section. Refuse volume and other possible impacts can be further cut by reducing the number of wells and locating the wells on the same pad or nearby pads. Co-locating multiple wells on the same pad will encourage the use of closed mud systems to maintain mud quality from well to well and cut down on waste by re-using mud. The use of steel tanks for mud management allows the operator to segregate specialty muds that might only be used over short intervals and then the tank can be moved to another well.[62] Because the shale contains few water zones and is prone to damage during mud-drilling, some Marcellus wells are drilled with air; in addition, air drilling is considerably faster. Air drilling is not appropriate in all locations, but when it is, it generates a low volume of dry drilling wastes that can be more easily managed than wet refuse.[63]

Water Availability

The drilling and hydraulic fracturing of a typical horizontal shale gas well is estimated to require between 3,000,000 and 4,000,000 gallons of water. Surface water withdrawals of necessary volumes to drill and stimulate gas shale wells in some regions of the country represent a relatively minor volume of the total water resource use in that area; however, operators need this water when drilling, and require that the water be procured over a relatively short period of time. Operators are also employing alternatives, such as making using seasonal changes in river flow to capture water when surface water flows are greatest. Utilizing seasonal flow differences allows planning of withdrawals to avoid potential impacts to municipal drinking water supplies and to aquatic or riparian communities.

Because the development of gas shale is new in some areas, these water needs may challenge supplies and infrastructure. As operators look to develop new shale gas plays, communication with local water planning agencies can help operators and communities to harmoniously coexist and effectively manage local water resources. Understanding local water needs can help operators

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[61] Several contractors supply this form of protection for pipelines in sensitive locations. For example, Westminster International Ltd, 2008. Pipeline Leak Detection System, website: http://www.wgplc.com/international/pdfs/Westminster%20Pipeline%20Security%20Leak%20Detection.pdf Accessed: November 2008.

[62] For example, Baker Hughes Drilling Fluids offer a number of specialty muds for specific situations http://www.bakerhughesdirect.com/cgi/bhdf/resources/ExternalFileHandler.jsp?channelId=-4195539&path=private/BHDF/public/about/index.html Accessed: November 2008.

[63] Schlumberger Oilfield Glossary, 2008. http://www.glossary.oilfield.slb.com/Display.cfm?Term=air%20drilling Accessed: November 2008.

develop a water storage or management plan that will meet with acceptance in neighboring communities. Although the water needed for drilling an individual well may represent a small volume over a large area, the withdrawals may have a cumulative impact to watersheds over the short term. This potential impact can be avoided by working with local water resource managers to develop a plan outlining when and where withdrawals will occur (i.e. avoiding headwaters tributaries, small surface water bodies, or other sensitive sources). In some basins, one key to the successful development of shale gas is the identification of water supplies capable of meeting the needs of a development company for drilling and fracturing water without interfering with community needs. While a variety of options exist, the conditions of obtaining water are complex and vary by region and even within a region such that developers will also need to understand local water laws.[64]

Fluid Management

A variety of waste fluids are generated on site at shale gas wells. During drilling, used mud and saturated cuttings are produced and must be managed. The volume of mud roughly correlates with the size of the well drilled, so a horizontal Marcellus well may generate twice as much drilling waste as a single vertical well; however, as discussed above, it will replace four such holes. Drilling wastes can be managed onsite either in pits or in steel tanks. Each pit is designed to keep liquids from infiltrating vulnerable water resources. On-site pits are a standard in the oil and gas industry but are not appropriate everywhere; they can be large and they disturb the land for an extended period of time. Steel tanks may be required to store drilling mud in some environments to minimize the size of the well site "footprint" or to provide extra protection for a sensitive environment. Steel tanks are not, of course, appropriate in every setting either. In rural areas where space is available at the well site for pits or ponds, steel tanks are usually not needed.

Horizontal drilling development has the power to reduce the number of well sites and to group them so that management facilities such as storage ponds can be used for several wells. Make-up water is used throughout the development process to drill the well and to form the basis of the hydraulic fracturing fluid. Large volumes of water may be needed and are often stored at the well site in pits or tanks. For example, surface water can be piped into the pit during high-water runoff periods and used during the year for drilling and fracture treatments in nearby wells. Exhibit 14 shows one of these large storage ponds servicing the Marcellus development in Pennsylvania. Storage ponds are not suitable everywhere in the shale gas play; like steel tanks, they are appropriate in some locations and not in others.

EXHIBIT 14: CENTRAL WATER STORAGE POND

Source: ALL Consulting, 2008

Lined Fluid Retention Pit from the Marcellus Shale Development in Pennsylvania.

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[64] Weston, R.T. 2008. *Development of the Marcellus Shale-Water Resource Challenges.* Published by Kirkpatrick & Lockhart Preston Gates Ellis LLP. 2008.

After a hydraulic fracture treatment, when the pumping pressure has been relieved from the well, the water-based fracturing fluids begin to flow back through the well casing to the wellhead. This water is referred to as flowback water and consists of spent fracturing fluids and, in some cases, dissolved constituents from the formation itself (minerals present in the shales as well as brine waters that may be present within any natural pore space contained in the shale). The majority of flowback water is produced in a range of time from several hours to a couple of weeks. In various basins and shale gas plays, the extent of this volume of flowback water may account for less than 30 percent to more than 70 percent of the original fracture fluid volume.[65] In some cases, production of flowback water can continue for several months after gas production has begun.[66]

Natural formation waters that flow to the well are known as produced water. Regardless of the source of water, flowback or formation water, these waters that are produced back through the wellhead with the gas represent a production stream that must be managed and are collectively referred to as produced water.

Gas shale operators manage produced water through a variety of mechanisms including: underground injection, treatment and discharge, and recycling. Underground injection is not possible in every play area as suitable injection zones may not be available. Similar to a producing reservoir, there must be a porous and permeable formation capable of receiving injected fluids near the play area. If such is not locally available, it may be possible to transport the produced water to a more distant injection site. Treatment of produced waters may be feasible through either self-contained systems at well sites or fields or through municipal waste water treatment plants or commercial treatment facilities. The availability of municipal or commercial treatment plants may be limited to larger urban areas where treatment facilities with sufficient available capacity already exist; as in underground injection, transportation to treatment facilities may or may not be practical.[67]

Lead Author Biographical Sketch

Dan Arthur is a founding member and the Managing Partner of ALL Consulting. Mr. Arthur earned his bachelors degree in Petroleum Engineering from the University of Missouri-Rolla. He is a recognized authority on environmental issues pertaining to unconventional resource development and production. Mr. Arthur has served or is currently serving as the lead researcher on several significant projects involving unconventional resources; environmental considerations pertaining to shale gas development; produced water management and recycling; access to federal lands; and low impact natural gas and oil development. Has previously managed U.S. Department of Energy (DOE) funded research projects involving the development of best management practices utilizing GIS technologies for efficient environmental protection during unconventional resource Development and Production; research to develop a national primer on coal bed methane; research to develop a Handbook on the preparation and review of environmental documents for CBM development; and research with the Ground Water Protection Research Foundation (GWPRF) and funded by DOE and BLM involving analysis of produced water management alternatives and beneficial uses of coal bed methane produced water. Mr. Arthur has published many articles and reports and has made numerous presentations on environmental, energy, and technology issues.

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[65] Personal communication with numerous operator and service companies in a variety of shale gas plays.

[66] Willberg, D.M., Steinsberger, N., Hoover, R., Card, R.J., and Queen, J. 1998. *Optimization of Fracture Cleanup Using Flowback Analysis*. SPE 39920-MS. 1998.

[67] Harper, J. 2008. Published by the Bureau of Topographic and Geologic Survey, Pennsylvania Department of Conservation and Natural Resources. Pennsylvania Geology. *The Marcellus Shale – An Old "New" Gas Reservoir in Pennsylvania*. v 28. no 1. Spring 2008.