Hydraulic Fracturing Considerations for Natural Gas Wells of the Fayetteville Shale

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Lead Author Biographical Sketch

Dan Arthur is a founding member and the Managing Partner of ALL Consulting (www.all-llc.com). 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.

Abstract

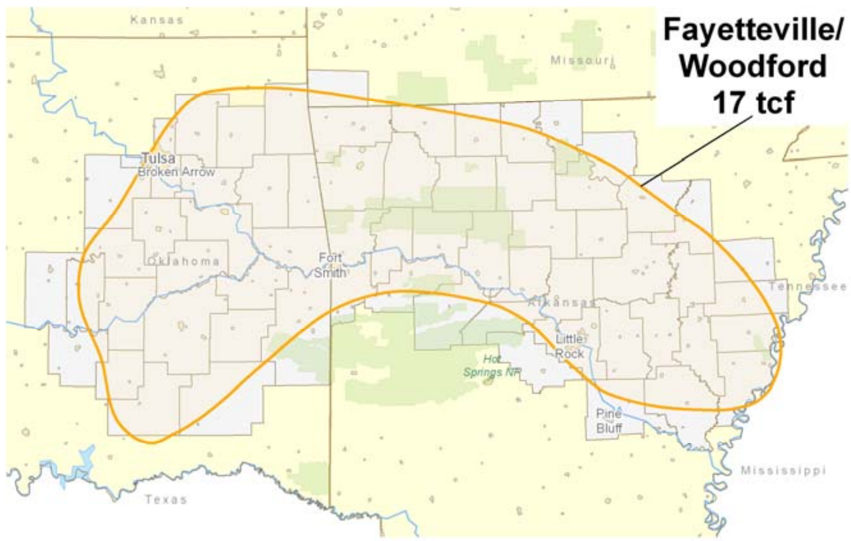
Hydraulic fracturing is a key component of the successful development model for shale gas plays. This paper will review the evolution of hydraulic fracturing, including environmental and regulatory considerations related to development of the Fayetteville Shale play. Technical and environmental considerations are presented applicable to hydraulic fracturing in the unconventional arena of gas shales with an emphasis on the Fayetteville Shale of the Arkoma Basin. Topics addressed in the paper will include discussion on why hydraulic fracturing is performed; the hydraulic fracturing process; applicable design and engineering aspects of well completions; geological considerations such as confinement of the fracturing process; potential risks to groundwater and underground sources of drinking water; and the composition of hydraulic fracturing fluids and associated technical considerations.

Introduction

Shale gas reservoir development is a growing source of natural gas reserves across the United States. A successful model for gas shale development that progressed in the Barnett Shale of the Fort Worth Basin is being expanded to other gas shale plays across the United States and Canada. Barnett Shale completion styles that led to the play's success involves development of the resource using horizontal wells and hydraulic fracturing. One shale gas play that has benefited from the success of the Barnett development model is the Fayetteville Shale of the Arkoma Basin (Exhibit 1). Wells for the Fayetteville Shale have the potential to be sources of natural gas for the next 30 years based on predicted average gas shale well life[1]. Development of the Fayetteville Shale is the focus of discussion in this paper. Modern development models for the Fayetteville Shale which use horizontal well drilling and hydraulic fracturing began to escalate in 2004[2].

This paper provides a summary of the hydraulic fracturing process, including a brief history of hydraulic fracturing as applied to shales and the activities associated with a hydraulic fracture treatment, including sourcing and disposing of fracturing fluids in Arkansas. Also incorporated in this paper is a discussion on the economic benefits associated with the Fayetteville Shale gas play.

Exhibit 1: Location of the Fayetteville Shale Play of the Arkoma Basin



Source: ALL Consulting, 2008

Unconventional development of energy resource plays, including coal beds, tight sands and shales has been a growing source of natural gas development in the United States in the last decade. Since 1998, unconventional natural gas production has increased nearly 65%. This increase in production has resulted in unconventional gas production becoming an increasingly larger piece of total domestic natural gas production in the United States, increasing from 28% in 1998 to 46% of total natural gas production in 2007[3].

The Fayetteville Shale in Arkansas shows great promise for continued development, partially because of successful technological advances in horizontal drilling and hydraulic fracturing. These

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1 K. Shirley. 2001. *Tax Break Rekindled Interest: Shale Gas Exciting Again.* AAPG Explorer March 2001.

2 AOGC, 2008, *Arkansas Oil and Gas Commission Gas Fayetteville Shale Gas Sales Summary* available online at http://www.aogc.state.ar.us/Fayprodinfo.htm, accessed on October 20th, 2008.

3 Navigant Consulting, Inc. 2008, *North American Natural Gas Supply Assessment*, Prepared for: American Clean Skies Foundation.

methodologies were tried and tested in the Barnett Shale of the Fort Worth basin. Due to the urban setting of Barnett Shale development in the Fort Worth basin, demand for reduced surface impacts forced developers to find a solution that would reduce the number of surface locations and disturbances, while providing the maximum amount of reservoir exposure. Laterals in the Barnett Shale can range from 1,500 feet (ft) to more than 5,000 ft. To date, laterals in the Fayetteville Shale have ranged from 1,850[4] ft to 3,000 ft in length[5]. Although considering trends in other plays, further reaching laterals could be drilled as the Fayetteville Shale play matures.

Shale gas plays are generally considered unconventional reservoirs because these formations contain gas-bearing rocks which have poor or limited natural permeability relative to the transmission of fluids to a wellbore[6]. As such, these resources require a means to increase their permeability through stimulation, specifically hydraulic fracturing[6]. Hydraulic fracturing has been proven to be a necessary component of successful gas shale development models.

Fayetteville Shale Outcrop in Fayetteville, AR

America's Gas Shales

Gas shales are organic-rich shale formations that were previously believed to function as source rocks and seals for gas accumulating in stratigraphically proximal sandstone and carbonate reservoirs of traditional onshore gas development[7]. Presence of gas in these shales has been evident since some of the earliest development of oil & gas resource. The first producing gas well in the U.S. was completed in 1821 in Devonian-aged shale near the town of Fredonia, New York[8].

Gas production from shales is gaining attention throughout the United States and active and developing plays extend beyond the Barnett Shale and Fayetteville Shale. Shale gas resources are located across the continental United States, offering abundant and available access to clean burning natural gas (Exhibit 2). Potential development of shale gas resources includes shales in a variety of basins, including Devonian Shales in the Appalachian Basin; Mowry Shale in the Powder River Basin; Mancos Shale in the Uinta Basin; Woodford Shale in the Ardmore Basin; Floyd/Neal Shale play in the Black Warrior Basin; Barnett Shale in the Permian Basin; New Albany Shale in the

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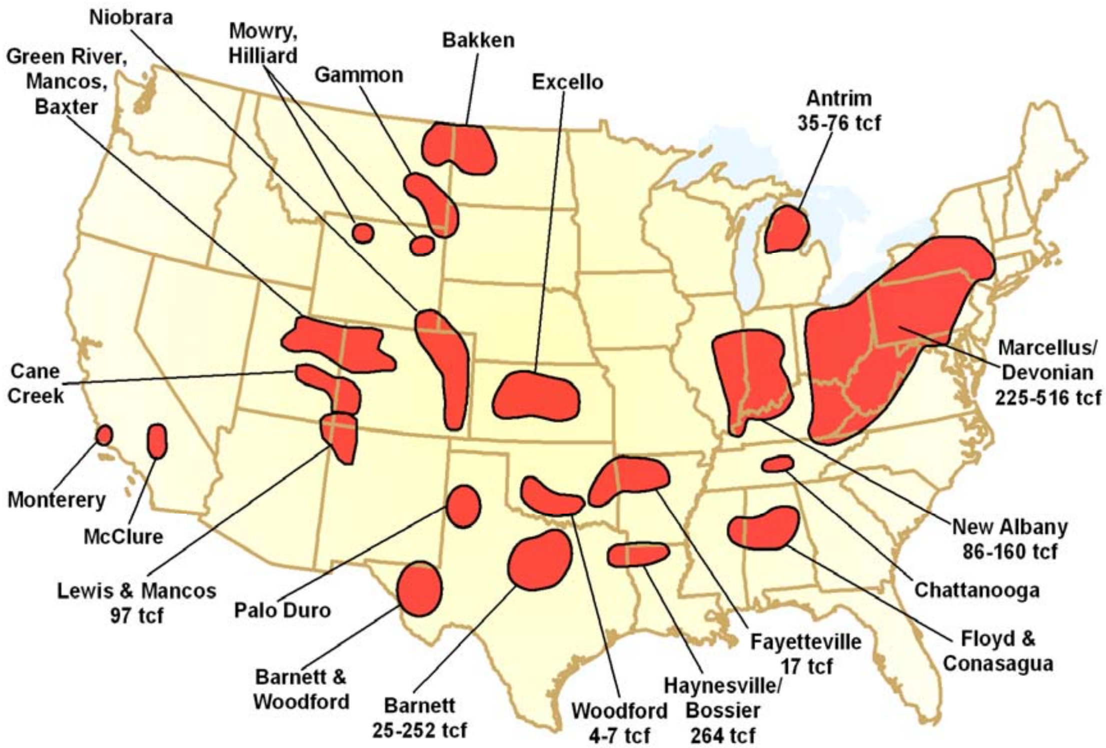
[4] Oil Online, 2005. *Southwestern Energy Provides Operational Update on Fayetteville Shale Play.* June 10th 2005.
[5] U.S. Department of Interior. 2008. Arkansas Reasonably Foreseeable Development Scenario for Fluid Minerals. March 2008.
[6] David D. Cramer. *Stimulating Unconventional Reservoirs: Lessons Learned, Successful Practices, Areas for Improvement.* SPE 114172.
[7] Schlumberger 2005. *Shale Gas White Paper*. 05-OF299. October 2005, Schlumberger Marketing Communications.
[8] John A. Harper. *The Marcellus Shale – An Old "New" Gas Reservoir in Pennsylvania*. In Pennsylvania Geology, Volume 28 Number 1. Published by the Bureau of Topographic and Geologic Survey, Pennsylvania Department of Conservation and Natural Resources. 2008.

Illinois Basin; Pearsall Shale in the Maverick Basin; Chattanooga Shale in Tennessee; Hovenweep Shale in the Paradox Basin; Bend Shale in the Palo Duro Basin; and Barnett/Woodford Shale plays in the Delaware and Marfa Basins[9]. Total natural gas resource potential for gas shales has been estimated between 500 and 1,000 Trillion cubic feet (Tcf)[10], with estimates increasing as additional wells are brought online and information is gathered.

Exhibit 2: Gas Shale Basins of the United States with Estimated Gas Reserves



Modified from Schlumberger, 2005

Each gas shale basin is different and 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 faces potential challenges to the surrounding communities and ecosystems   For example, the Antrim and New Albany Shales are shallower shales which produce greater volumes of formation water unlike other gas shales in the United States. While development of the Fayetteville Shale is occurring in rural areas of north central Arkansas, development of the Barnett Shale is focused in the area of Forth Worth, Texas, which is largely an urban and suburban environment. Barnett Shale development technologies continue to mature and petroleum industry innovators continue to export lessons learned at one shale play to other shale plays. This has led to more development activity in increasingly more shale basins[11].

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[9] David Brown. 2007. *From Sea to Shining Sea: If It's Shale, It's Probably in Play*. AAPG Explorer April 04 2007.
[10] Hayden, J., and Pursell, D. *The Barnett Shale. Visitor's Guide to the Hottest Gas Play in the US*. October 2005.
[11] D.W. Walser and D.A. Pursell. *Making Mature Shale Gas Plays Commercial: Process vs. Natural Parameters*. SPE 110127 2007.

Exhibit 3 is a summary of the characteristics for select U.S. gas shale plays and provides several characteristics for comparison including; estimated reserves, play size, production volumes, depth to production zone, characteristics of the shales and estimated or known well spacing. Exhibit 3 shows the variations in depth of target formation across the different plays with Haynesville Shale development representing some of the deepest at more than 10,000 feet below land surface (ft bls). Exhibit 3 also highlights those formations with largest estimated maximum recoverable gas volumes (Haynesville and Marcellus Shales) having six to eight times greater volumes than the Barnett Shale.

Exhibit 3. Comparison of Data for the Active Gas Shales in the United States

Gas Shale Basin	Fayetteville	Barnett	Marcellus	Haynesville	Woodford	Lewis
Estimated Basin Area, square miles	9,000	5,000	95,000	9,000	11,000	10,000
Depth, ft	1,000-7,000[12]	6, 500 - 8,500[12]	4,000-8,500[13]	10,500-13,500[13]	6,000-11,000[3]	3,000-6000[12]
Net Thickness, ft	20-200[12]	100-600[12]	50-200[6]	200-300[7,14]	120-220[12]	200-300[12]
Depth to Base of Treatable Water, ft#	~500[15]	~1200	~850	~400	~400	~2000
Total Organic Carbon, %	4.0-9.8[12]	4.5[12]	3-12	0.5 – 4.0[14]	1-14	0.45-2.5[12]
Total Porosity, %	2-8[12]	4-5[12]	10	8-9	3-9	3.0-5.5[12]
Gas Content, scf/ton	60-220[12]	300-350[12]	60-100	100-330	200-300	15-45[12]
Water Production, Barrels water/day[12]	0	0	0	0		0
Well spacing, Acres	40-160	40-160[6]	40-160[6]	40-560[6]	640[6]	80-320[12]
Gas-In-Place, Tcf	52 [3]	1,500 [3]	1,500 [3]	717 [3]	52 [3]	61.4 [3]
Reserves, Tcf	41.6 [3]	262[3], 500	262[3], 500	251 [3]	11.4 [3]	20 [3]
Est. Gas Production, mcf/day/well	530	3,100	3,100	625-1800[13]	415	100-200[12]

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 of casing information if the state's oil and gas agency did not specifically report BTW values in their data base.

Estimated depth to target zone data and base of treatable water data demonstrates that most gas shale development is projected to occur thousands of feet below treatable water zones. In analyzing Fayetteville data, it is important to understand that the Arkansas Oil and Gas Commission (AOGC) regulates the depth of protective casings (as do other state oil & gas regulatory agencies) based on field rules in order to protect groundwater resources[15]. These rules and regulations are not exclusive to Arkansas. Oil and Gas agency rules regarding depth of casings in order to protect groundwater resources are common to state oil and gas programs throughout the United States.

[12] Hayden, J., and Pursell, D. *The Barnett Shale. Visitor's Guide to the Hottest Gas Play in the US*. Oct. 2005.
[13] Halliburton Energy Services. *U.S. Shale Gas: An Unconventional Resource, Unconventional Challenges.* 2008
[14] Berman, A. 2008. *The Haynesville Shale Sizzles with the Barnett Cools*. World Oil Magazine. Vol. 229 No.9. Sept.2008.
[15] Arkansas Oil and Gas Commission. 2008. *Field Rules and Rule B-15*.

The Fayetteville Shale

Western and central portions of the Fayetteville Shale play are a part of the Ozark Plateaus Region of northern Arkansas (Exhibit 1). This region is made up of generally flat-lying Paleozoic age strata divided into three plateau surfaces[16]. The plateaus are dissected by numerous streams throughout the area, and gentle folds are noted but are generally of very low amplitude. The depositional environment of the rocks found in the Arkansas Ozarks is one of a relatively shallow continental shelf, sloping toward deeper water generally toward the south. This shelf emerged many times during the Paleozoic period resulting in numerous unconformities throughout the sequence[16].

EXHIBIT 4: STRATIGRAPHY OF THE FAYETTEVILLE SHALE

Period		Group/Unit		Geology
Carboniferous	Pennsylvanian	Atoka		Sequence of marine, mostly tank to gray, silty sandstones and grayish-black shales.
		Bloyd		Consists of Brentwood Limestone Member, the Woolsey Member, Dye Shale Member, Kessler Limestone Member, and the Trace Creek Shale Member.
		Hale	Prairie Grove	Light-gray to dark-brown, limy sandstone or variously sandy limestone with lenses of relatively pure, crinoidal, highly fossiliferous limestone and oolitic limestone.
			Cane Hill	Dark gray silty shale interbedded with siltstone and thin-bedded fine-grained sandstone.
	Mississippian	(IMO)		
		Pitkin		Fine- to coarse-grained, oolitic, bioclastic limestone.
		Fayetteville		Black, fissile, concretionary, clay shale. Dark-gray, fine-grained limestones commonly are interbedded with the shales in north-central Arkansas
		Batesville		Flaggy, fine- to coarse-grained, cream-colored to brown sandstone with thin shales.
		Moorefield		Consist of a lower member black, calcareous shale and siliceous limestone and an upper member of dark, fissile clay shale.
		Boone		Gray, fine- to coarse grained fossiliferous limestone interbedded with chert.
Source: AGC, 2008				*Source: McFarland, 2004*

The Fayetteville Shale play is situated in the Arkoma Basin of northern Arkansas and eastern Oklahoma. The Fayetteville Shale play ranges over a depth from outcropping at the surface to depths of 7,000 ft bls[17]. The Fayetteville Shale is Mississippian aged shale bound by the Pitkin Limestone above and Batesville Sandstone below (Exhibit 4). The Fayetteville Shale is the geological equivalent to the Caney Shale in Oklahoma and the Barnett Shale in North Texas[18]. Stratigraphically and structurally, the geology of the Arkoma Basin is more complex than in the Fort Worth Basin. These complexities have made exploration and exploitation of the Fayetteville Shale more difficult than the Barnett[19]. Most importantly, the Fayetteville was deposited in a different environment than the Barnett; with the Barnett Shale gas play being restricted to a smaller area[19]. The Fayetteville Shale thickens towards the north and northeast near the outcrop belt (Exhibit 5). This is in direct contrast to the Barnett, where the thickest section is in the deepest portion of the Fort Worth Basin, which is in front of the Muenster Arch in Montague County[19].

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[16] McFarland, John D. *Stratigraphic Summary of Arkansas*, Information Circular 36, Arkansas Geological Commission. 2004.
[17] Halliburton Energy Services. *U.S. Shale Gas: An Unconventional Resource, Unconventional Challenges*. 2008
[18] Shelby, Phillip R. *The Fayetteville Shale Play – A Bonanza for Arkansas?, Norman Lecture Series, Arkansas Tech University. October 2006.*
[19] Bowker, Kent A, Moretti Jr., George, and Utley, Lee. *Fayetteville Maturing*. Oil and Gas Investor, January 2007

Reviewing the Stratigraphic Column in Exhibit 4, limestone and sandstone are the most prevalent strata above and below the Fayetteville Shale. Shale formations are present however, to prevent the interaction of fluids from Fayetteville Shale production with sources of groundwater in northern Arkansas. These confining layers consist of the Pennsylvanian age Cane Hill and Atoka Shales above and the Mississippian age Moorefield Shale below.

Exhibit 5: Northern Arkansas Fayetteville Shale Outcrop

Source: ALL Consulting, 2008

Progression of Fayetteville Shale Gas Development

Fayetteville Shale gas development is in its very early stages with the first modern well with Fayetteville Shale as the target formation in Johnson County, Arkansas[2]. First reported production to the AOGC was received in April of 2001[20]. After the first two wells were drilled in 2001, it was not until 2004 when an additional 24 wells were drilled in the Fayetteville Shale. Forty-five seismic permits were issued for the Fayetteville Shale play from 2005 to 2007[5]. Growth of the Fayetteville Shale can be seen in the news, with wells and annual gas production rapidly increasing since 2004. Recent well reports for the Fayetteville have noted increases from 24 active wells in 2004 to 33 in 2005, 129 in 2006, 428 in 2007, and 481 through October 7, 2008[2]. Annual cumulative production has increased from 101 MMcf in 2004 to 89,168 MMcf in 2007[2].

During the early stages of exploration, multiple field rules were established throughout the area to facilitate compliance with regulations of the AOGC. As production in the Fayetteville has been established, a greater knowledge of the reservoir has been obtained and the AOGC has identified the need to develop uniform field rules for all areas of the Fayetteville Shale play. Early Fayetteville development occurred in multiple fields with different field spacing rules and setbacks. However, as more information became available, the AOGC determined there was a need for uniform field rules for unconventional reservoirs [15]. As a result, General Rule B-43 was created. It is too early in the development of Fayetteville to determine if B-43 will be the final spacing rule, but assumptions can be made based on information gathered from other gas shale basins that less surface disturbance can be expected from horizontal well technology than conventional vertical wells. According to the AOGC, there has been a 100% success rate for modern Fayetteville Shale wells (i.e., No dry holes have been drilled)[2].

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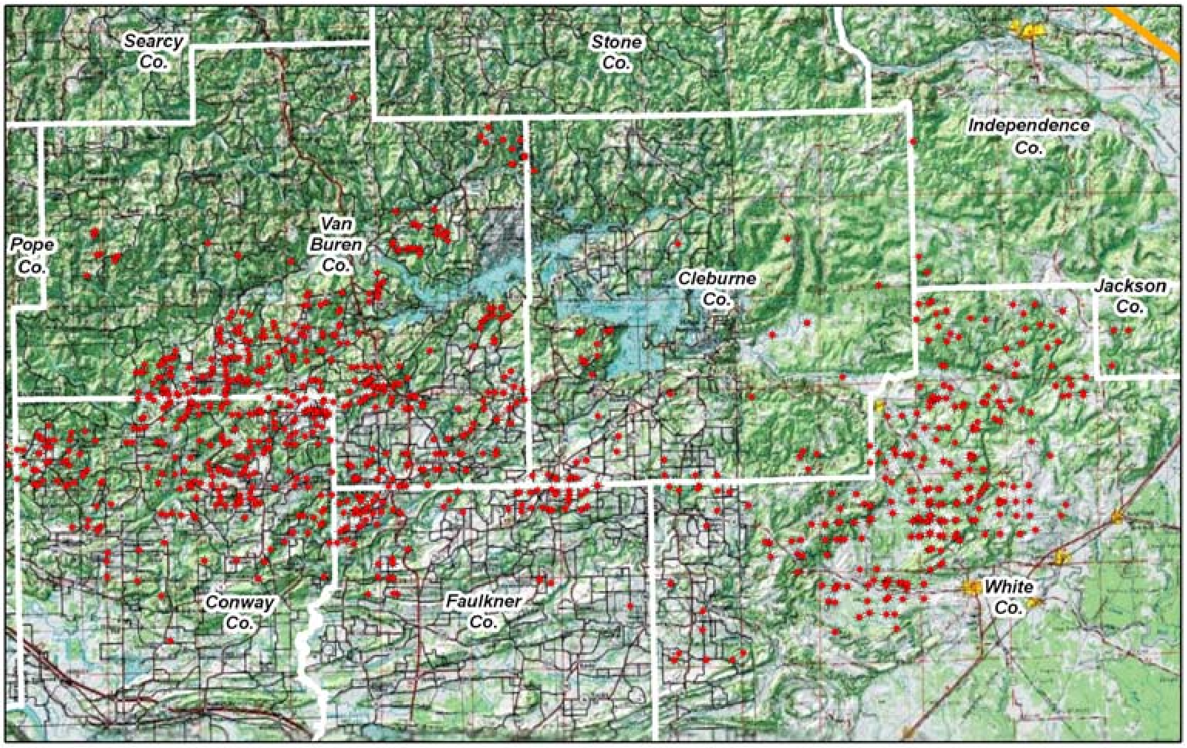
[20] Arkansas Oil and Gas Conservation Commission, *Online Oil and Gas Database*, October 2008.

Fayetteville Shale is listed as the target pool for a total of 1,100 wells in the AOGC database (October 2008[2]). A well location map for the Arkansas portion of the Fayetteville Shale is shown in Exhibit 6. Arkansas development has primarily focused in a 5 county area with a few scattered wells in an additional 5 counties in north-central Arkansas.

Exhibit 6: Well Locations in the Fayetteville Shale of Arkansas



Source: ALL Consulting, 2008

Fayetteville Shale Development and the Environment

Horizontal Well Completions

Operators developing the Fayetteville Shale have been using both horizontal and vertical wells to extract the natural gas present in the shale. Shale gas operators who are able to incorporate horizontal wells into the development of the Fayetteville can reduce the number of wells needed to develop the resource. Horizontal wells can also reduce the number of well pads, access roads, pipeline routes, and production facilities required, thus minimizing forest fragmentation, impacts to public environment and the overall environmental footprint of development of this resource.

Advantages of horizontal wells include reduced surface disturbances resulting from a reduced number of well pads, roads, and pipelines. Several horizontal wells can be placed on multi-well pads for a less intrusive impact to the surrounding area. Decreasing surface disturbance can lessen impacts from noise or traffic and result in fewer visual changes to the landscape. Horizontal wells are used in many areas of the country to access natural gas resources where it is not possible to drill a vertical well due to existing infrastructure, buildings, environmentally sensitive areas, or other conflicts at the surface. Development of the Barnett Shale near Dallas-Fort Worth

International Airport has been a prime example of development of an urban area using horizontal wellbores[21].

Hydraulic Fracturing

In addition to horizontal drilling, hydraulic fracturing has proven to be a technology key to facilitating economic recovery of natural gas from shale. Hydraulic fracturing is a formation stimulation practice used to create additional permeability in a producing formation to allow natural gas to flow more easily toward the wellbore for purposes of production[22]. Hydraulic fracturing can be used to overcome natural barriers to the flow of fluids. Barriers may include naturally low permeability common in shale formations or reduced permeability resulting from near wellbore damage during drilling activities[22]. While methods of hydraulic fracturing continually change (mostly changes in the design process and updates to additives and propping agents), this technology is utilized by the natural gas industry to increase production and to support an ever increasing demand for energy.

Modern formation stimulation practices have become more complex. The process has developed into a sophisticated, engineered process in which production companies work to design a hydraulic fracturing treatment to emplace fracture networks in specific areas[23]. Hydraulic fracture treatments are not a haphazard process but are designed to specific character of target formations (e.g., thickness of shale, lithology, rock stress characteristics, etc.) to optimize development of a complex network of fractures. Understanding in-situ conditions present in the reservoir and their dynamics is critical to successful stimulations. Hydraulic fracturing designs are refined at the field or well level to optimize fracture networking and to maximize gas production while ensuring that fracture development is confined to the target formation[23].

Design and Operations of a Staged Hydraulic Fracture Treatment

Fracture design incorporates many state-of-the-art and sophisticated procedures to accomplish an effective, economic and highly successful fracture job. The purpose of the design procedure is to develop an understanding of how to efficiently achieve optimal fracture patterns. Design procedures include pre- and post-treatment computer simulations, geologic studies including using microseismic fracture mapping, and additional data collection used to refine future stimulations. In designing a fracture stimulation, three primary considerations are utilized. These include reservoir characteristics, mechanical properties and natural stress profiles, and the method utilized for the 3-D Fracture Simulation. Simulations are performed to maximize the effectiveness of a hydraulic fracturing event[24].

In evaluating reservoir characteristics, key aspects include the lithology, porosity and permeability and degree of water saturation. Hydraulic fracturing modeling programs allow geologists and engineers to modify the design of a hydraulic fracture treatment and evaluate the height, length and

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21 Joel Parshall. *Barnett Shale Showcases Tight-gas Development.* Journal of Petroleum Technology

22 Veatch, Ralph W. Jr.; Zissis A. Moschovidis; and C. Robert Fast, *An Overview of Hydraulic Fracturing.* in Recent Advances in Hydraulic Fracturing, Edited by John L Gidley, Stephen A. Holditch, Dale E. Nierode, and Ralph W, Veatch Jr. Society of Petroleum Engineers, Henry L Doherty Series Monograph Volume 12.

23 C. Boyer, J. Kieshchnick, and R Lewis. 2006. Producing Gas from Its Source. In Oilfield Review Autumn 2006. pgs 36-49.

24 Chesapeake Energy, *Components of Hydraulic Fracturing,* presented to the NY DEC in October 2008.

orientation of potential fracture development prior to initiation of the actual fracture treatment[25]. The cost of a hydraulic fracture treatment can a significant expenses and as such, it is important to utilize modeling methods to optimize the treatment program such that the quantity of fracturing fluids and additives added are minimized[24]. Minimization of fluid volumes also has the potential for additional cost savings by minimizing the volume of flow-back water that will need to be managed in later operations.

Hydraulic fracturing of a horizontal well, like those being utilized for the Fayetteville Shale, is performed in stages. It is not possible to stimulate the entire length of a lateral in a single event. As such, each stage of a hydraulic fracture treatment is performed by isolating sections of the lateral portion of the well[24].

A Ball and Ball Packer (Pennsylvania Marcellus Shale)
Source: ALL Consulting 2008

A hydraulic fracturing treatment starts with bringing necessary volumes of fluids and equipment onto the well pad site. Equipment includes frac tanks, frac pumps, blender pumps, proppant storage tanks, monitoring equipment and additive storage containers. Once all the equipment is on site, the rig up process begins with the placement of a fracture treatment head or "goat head". Rig-up continues by making all of the iron connections necessary between the goat head, frac pumps and equipment which feed fluids and additives into the frac pumps. Iron connections are typically secured with restraints to ensure safety in case of iron failure.

Each fracture stage is performed within an isolated interval (typically 500 ft in length) within which a cluster of perforations is created through the casing using a perforating tool. Perforations allow fluids to flow through the casing to the formation during the fracture treatment and also allow gas to flow into the wellbore during the production phase of operatons[24]. In order to isolate each fracture stage of a fracture treatment, a packer is used to isolate each fracturing interval. One type of packer used for creating zonal isolation is a ball packer. A ball packer works by having a steel ball pumped into a seat point typically located where the last fracture stage was completed. The ball acts as a sealing agent to the previously treated zone isolating the next treatment interval.

In the Fayetteville Shale, an individual fracture treatment stage may include as many as 20 sub-stages, where different blends of fluids are pumped into the well. Initial sub-stages are typically performed as a flush and often may simply include pumping fresh water into the wellbore. This is typically followed by an acid flush to clean perforations and the formation near the wellbore to

[25] Schlumberger Fracturing Services PowerSTIM webpage. www.slb.com September 2, 2008.

facilitate the fracturing process. Following the acid flush is typically a spacer which pushes the acid into the formation and begins the propagation of fracturing. After the spacer is pumped, the fourth sub-stage is typically a well shut-in so that a fracture gradient can be calculated in the field. When the well is opened back up, a clean fracture fluid pad is injected to lubricate well tubing and fractures in the formation and to aid the proppant sub-stages. The next sub-stages are a series in which proppant is used to create and maintain fractures.

Monitoring Fracturing Activities (Fayetteville Shale)
Source: ALL Consulting, 2008

In some fracture treatments, two or three different proppants may be used to ensure propping of fractures at various distances away from the wellbore[22]. During a fracture treatment in the Fayetteville Shale, three different proppants (or more) are commonly used and include 100 mesh sand, 40/70 mesh sand to a resin coated 40/70 mesh sand proppant. Initial proppant placement sub-stages start with low concentrations typically around 0.1 pounds of the finest sand per gallon (ppg) of fluid[26]. At each subsequent sub-stage, an increase in proppant concentration is performed at a regular volume, perhaps increments of 0.2 ppg per sub-stage. The number of sub-stages is determined by volumes of proppant and fracture fluid that were designed for the fracture treatment. For a multiple proppant treatment schedule, the proppant concentration is typically maintained when a transition from one proppant to another occurs such that the final slurry density would be the same as the initial slurry density of the next stage. Once the prescribed volume of fluids and proppant has been pumped, a final flush is performed to clean the wellbore and tubing of proppant.

Hydraulic fracturing stimulations are monitored continuously by operators and service companies to evaluate and document the events of the hydraulic fracturing treatments (see photo). Monitoring of fracture treatments includes tracking the process with wellhead and downhole pressures, pumping rates, fracturing fluid slurry density measurements, tracking volumes for additives, tracking volumes of water, and ensuring that equipment is functioning properly. During a typical hydraulic fracturing event for a horizontal Fayetteville Shale well in Arkansas, there may be more than 30 service company representatives on site performing and monitoring the stimulation as well as additional staff from the operator and perhaps the state oil & gas agency. This level of manpower also serves as an emergency response team should an unforeseen incident occur.

[26] Data collected by ALL Consulting from Weatherford Fracturing Technologies on a treatment schedule of a Fayetteville Shale gas well, September 2008.

Refinement of the hydraulic fracturing process occurs as operators collect more resource specific data. This process generally helps to create a more optimized fracture patterns within the target formation for purposes of increasing gas production as well as further ensuring that fractures do not grow out of the target formation[25]. The refinement of the hydraulic fracturing process was a necessary step in the success of the Barnett Shale as development moved away from the core area of the Barnett[21]. Hydraulic fracturing in some areas of the Barnett resulted in fractures extending into the underlying Ellenberger Formation. Wells in which fractures extended into the Ellenberger Formation had increased water production as water from the more water laden Ellenberger flowed into these wellbores[21]. This resulted in higher costs and undesired water handling issues. As a result, fracturing processes have been refined and unintentional fracturing of adjacent zones has become a lesser issues as the technology has evolved.

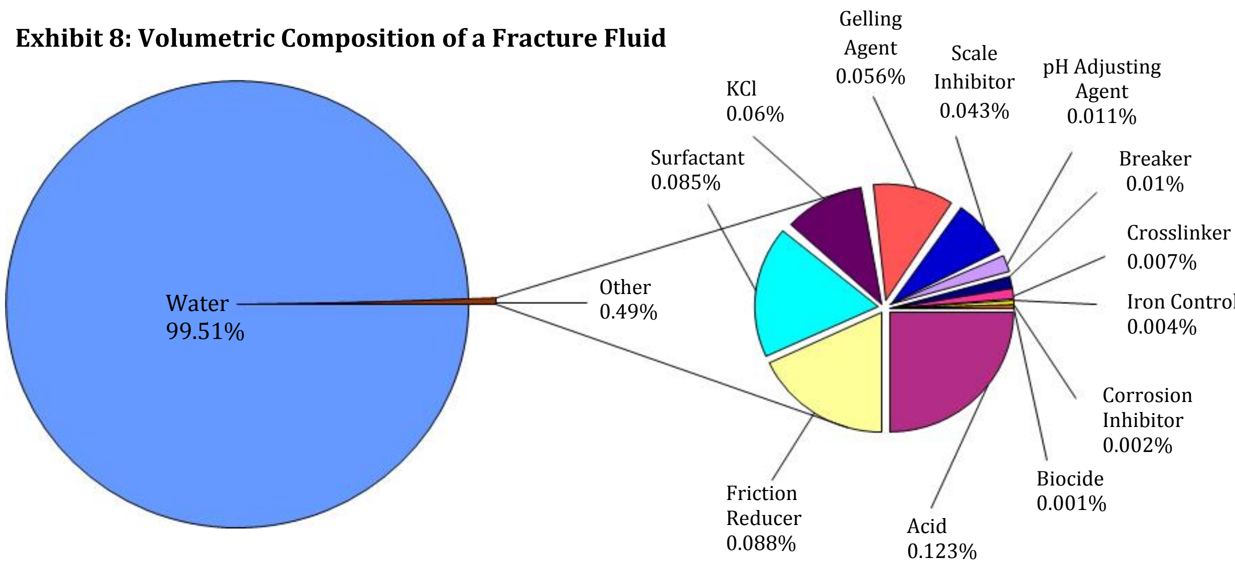
Fracturing Fluids and Additives

Current practices for hydraulic fracturing of gas shale reservoirs are commonly sequenced events requiring thousands of barrels of water-based fracturing fluids mixed with proppant materials pumped in a controlled and monitored manner into target shale formations above fracture pressure[27].

Fracturing fluids used for fracturing gas shales include a variety of additive components, each with an engineered purpose to facilitate fractures and the production of gas[27]. Fluids currently being used for fracture treatments in Fayetteville Shale wells are water based or mixed slickwater fracturing fluids. Slickwater fracturing fluids are water-based fluids mixed with friction reducing additives, primarily potassium chloride[8], which allows a fracturing fluid and proppant to be pumped to the target zone at a higher rate and reduced pressure than by using water alone. In addition to friction reducers, other additives including biocides are utilized to prevent micro-organism growth and to reduce bio-fouling of fractures. Oxygen scavengers and other stabilizers which prevent corrosion of metal pipes and acids which are used to remove drilling mud damage near the wellbore area are also common either in fracturing fluids or as part of fracture treatments[25].

[27] Schlumberger Fracturing Services Page of Schlumberger website, www.slb.com September 2, 2008.

Exhibit 8: Volumetric Composition of a Fracture Fluid



Source: Compiled from Data collected at a Fayetteville Shale Fracture Stimulations by ALL Consulting 2008.

EXHIBIT 9: FRACTURING FLUID ADDITIVES, MAIN COMPOUNDS AND COMMON USES.

Additive Type	Main Compound	Use in Hydraulic Fracturing Fluids	Common Use of Main Compound
Acid	Hydrochloric acid or muriatic acid	For the fracturing of shale formations, acids are used to clean cement from casing perforations and drilling mud clogging natural formation porosity, if any prior to fracturing fluid injection (dilute acids concentrations are typically about 15% acid)	Swimming pool chemical and cleaner
Biocide	Glutaralde-hyde	Fracture fluids typically contain gels which are organic and can therefore provide a medium for bacterial growth. Bacteria can break down the gelling agent reducing its viscosity and ability to carry proppant. Biocides are added to the mixing tanks with the gelling agents to kill these bacteria.	Cold sterilant in health care industry
Breaker	Sodium Chloride	Chemicals that are typically introduced toward the later sequences of a frac job to "break down" the viscosity of the gelling agent to better release the proppant from the fluid as well as enhance the recovery or "flowback" of the fracturing fluid,	Sodium chloride is also used as a food preservative.
Corrosion inhibitor	N,n-dimethyl formamide	Used in fracture fluids that contain acids; inhibits the corrosion of steel tubing, well casings, tools, and tanks.	Used as a crystallization medium in Pharmaceutical Industry
Crosslinker	Borate Salts	There are two basic types of gels that are used in fracturing fluids; linear and cross-linked gels. Cross-linked gels have the advantage of higher viscosities that do not break down quickly.	Non-CCA wood preservatives and fungicides
Friction Reducer	Petroleum distillate or Mineral oil	Minimizes friction allowing fracture fluids to be injected at optimum rates and pressures	Cosmetics including hair, make-up, nail and skin products
Gel	Guar gum or hydroxyethyl cellulose	Gels are used in fracturing fluids to increase fluid viscosity allowing it to carry more proppant than a straight water solution. In general, gelling agents are biodegradable.	Guar gum is a food-grade product used to increase the viscosity and elasticity of foods such as ice cream, and

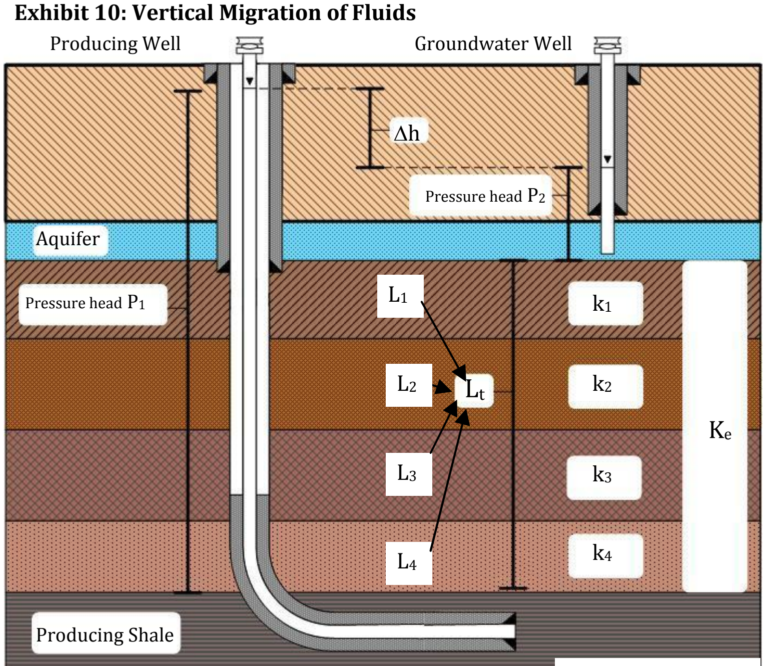
			salad dressings
Iron Control	Citric acid	Sequestering agent that prevents precipitation of metal oxides.	Citric Acid it is used to remove lime deposits. Lemon Juice is approximately 7% Citric Acid
KCl	Potassium Chloride	Added to water to create a brine carrier fluid.	Low sodium table salt substitute
Oxygen scavenger	Ammonium bisulfite	Oxygen present in fracturing fluids through dissolution of air causes the premature degradation of the fracturing fluid, oxygen scavengers are commonly used bind the oxygen.	Used in cosmetics
Proppant	Silica, quartz sand	Proppants consist of granular material, such as sand, which is mixed with the fracture fluid and is used to hold open the hydraulic fractures allowing the gas or oil to flow to the production well.	Play box sand, concrete or mortar sand
Scale inhibitor	Ethylene glycol	Additive to prevent precipitation of scale (calcium carbonate precipitate).	Automotive antifreeze and de-icing agent
Surfactant	Naphthalene	Used to increase the viscosity of the fracture fluid.	Household fumigant (found in mothballs)

Exhibit 8 is a pie chart showing a relational breakdown of the volumes used for additives in a 50,000 barrel fracture treatment which would be a similar size to a Fayetteville Shale horizontal well treatment. Exhibit 8 shows water as the primary component of a fracturing fluid and represents the greatest percentage in comparison to other additives in a fracturing fluid. Exhibit 9 provides a summary of additives, their main compounds and some other common uses for frac additives in day-to-day life. While a variety of different additives can be used in fracturing fluids, many are items that people encounter in their daily lives. Because the make-up of fracturing fluids vary to meet specific needs for a well, it is impossible to provide a single amount or volume present in each additive. However, based on the volume of water used in making a fracturing fluid as seen in Exhibit 8, concentrations of these additives are diluted considerably when considered on an overall volumetric basis. Service companies are also working to develop even more environmentally friendly fluids, including the use of hydrochloric acids which more easily break down into simple salts[21].

Vertical Migration of Fluids

Formations overlying the Fayetteville Shale act as confining layers for migration of fluids upward towards groundwater in shallow subsurface formations. Exhibit 10 presents a theoretical example of a Fayetteville gas shale well completed at a depth of 4,000 ft bls and a shallow groundwater well completed at a depth of 705 ft bls. Using known stratigraphy shown in Exhibit 4 and assuming approximate thicknesses for the Pitkin, Hale, Bloyd, and Atoka Formations which lie between the Fayetteville shale and shallow groundwater zones, it is possible to develop an estimated time for a fluid to migrate vertically upward from the Fayetteville to the freshwater zone. By applying Darcy's Law, it is possible to determine a linear velocity for the migration of fluids across the thickness of intervening formations between the Fayetteville Shale and the groundwater zone. The first step is to calculate an effective permeability for a combined unit thickness of the intervening formations such that:

Exhibit 10: Vertical Migration of Fluids



Source: ALL Consulting

Not to Scale

$$Ke = \frac{L_t}{\sum (L/k)}$$

Ke = Effective permeability
L_t = Total thickness of Formations between the Fayetteville Shale and groundwater
L = Formation thickness
k = Formation permeability

Once an effective permeability is calculated, a linear velocity equal to a flow rate per unit area can be calculated using a derivative of Darcy's Law:

$$\frac{Q}{A} = v = \frac{K_e \rho g \Delta h}{\mu L}$$

Q = Flow Rate
K_e = effective permeability
ρ = density of fluid
A = Area
g = gravity
μ = viscosity
Δh = height of the pressure head above the groundwater head
L = combined thickness of formations between the Fayetteville and groundwater.

Average horizontal permeabilities were obtained from groundwater references[28] and converted to vertical permeability using a factor of 0.1. These permeability values were used to calculate an average linear velocity of 1.2 X 10^{-10} ft/sec, assuming a fluid with a density and viscosity similar to water. Based on an estimated thickness (length) between the Fayetteville shale producing formation and the groundwater aquifer of approximately 3,145 ft, it would take approximately 830,000 years for fluid to migrate from the Fayetteville to a groundwater aquifer. With this in mind, once fracturing fluids were pumped into the formation, it would take approximately 830,000

[28] R.A. Freeze and J.A. Cherry. 1979. *Groundwater*. Prentice Hall. 604pgs.

years for those fluids to migrate vertically upward into a potentially useable quality aquifer assuming that initial natural formation pressure was maintained.

Water Availability, Fluid Handling, and Disposal

Availability of water for fracturing operations has received considerable attention over recent months. Fracture treatments in Fayetteville Shale gas wells involve in the rage of 50,000 bbls of fracture water in what might typically be applied through 4 to 8 stages[5]. Multiple options are available for obtaining water for fracture use, such as water supply wells, private water sources including private lakes, ponds and stock tanks, surface water, and recycled flow-back water from previous fracturing operations[29].

To support its Fayetteville Shale play in Arkansas, Chesapeake Energy is constructing a 500 acre-ft impoundment to store water withdrawals. The objective would be to withdrawal water from the Little Red River during periods of high flow (storm events or power generation releases from Greer's Ferry Dam upstream of the intake) when excess water is available. Current permits allow for up to a maximum of 1550 acre-ft annually to be collected[30]. And as an ancillary safety precaution, Chesapeake has or is in the process of adding pipelines and hydrants to provide portions of this rural area with water for fire protection.

Little Red River Reservoir near Searcy, AR during Construction
Source: ALL Consulting, 2008

Monitoring of in-stream water quality, game and non-game fish species within the reach of river surrounding the intake is part of the conditions of the permit. The design provides a water storage and recovery system similar in concept to municipal water facilities. Because surface water withdrawals are limited to times of excess flow in the Little Red River, impacts on local water supplies are anticipated to be minimal. This project was developed with input from a local chapter of Trout Unlimited, a conservation organization in the area of the Little Red River project. This project represents an innovative environmental solution that serves both the community and gas

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[29] Chesapeake Energy. *Managing Water Resource Challenges in Select Natural Gas Shale Plays.* Presented at GWPC Annual Forum, September 20-24, 2008.
[30] Chesapeake Energy Corporation, *Little Red River Project*. Presentation to Trout Unlimited, May 6, 2008.

developers. It is also an example of low impact gas development and what might be considered "Green" development.

Because development of gas shale is new in some areas, water needs may challenge supplies and infrastructure. As operators look to development new shale gas plays, communication with local water planning agencies can help operators and communities to coexist and effectively manage local water resources. Understanding local water needs can help operators develop a water storage or management plan that will be meet with acceptance in neighboring communities. Although water needed for drilling individual wells may represent a small volume over a large area, withdrawals may have a cumulative impact to watersheds over the short term. Potential impacts can be mitigated through effective coordination with local water resource managers (i.e. avoiding headwaters tributaries, small surface water bodies, or other sensitive sources).

Flow-back water from fracturing applications is primarily disposed of under general land application permits, which are regulated and issued by the Arkansas Department of Environmental Quality (ADEQ)[31]. Twelve commercial land farm facilities are in operation in Arkansas and 3 additional applications are being drafted. Over 100 single time use permits have been issued for land farming operations. In order for operators to obtain land application permits, Notice of Intents (NOI) and Site Management Plans (SMP) must be completed by a Professional Engineer and submitted for review and approval by the Arkansas Department of Health. At a minimum, a soil analysis, fluid analysis, maps of proposed application areas, and topographic maps for reference must accompany an application. In addition, proof of surface ownership or a copy of a land use license or lease agreement must be included.

For example, the Central Arkansas Disposal Facility (CAD) operates two lined storage pits to contain water from Fayetteville shale operations prior to land application. Each pit can hold approximately 5,855,045 gallons or 139,406 barrels of water[32]. Water is accepted from trucking companies and pumped into one pit for settling. Water is transferred to the second pit for storage until it can be land applied. Prior to land application, a water analysis, soil analysis, and total pit volumes are submitted to the ADEQ so that they can determine an appropriate application rate based on provided data. For the CAD site, soil grab samples for every ten acres within the 364 acre facility are required. Soil analyses must meet permit limitations for arsenic, cadmium, copper, lead, mercury, nickel, selenium and zinc[32]. In addition, limitations for chloride concentration, pH, conductivity, and Exchangeable Sodium Percentage (ESP) of the soil must be met. If either water or soil conditions do not meet criteria established in the permit, operations must cease until levels are within approved limitations. Waters cannot be land applied when the ground is saturated, frozen, or if precipitation is imminent.

In order for water to be applied to the surface under land application permits, it must have a chloride concentration of less than 5,000 parts per million (ppm)[33]. However, some permits,

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[31] Hill, Cara. Personal Communication between Brian Bohm, ALL Consulting and Cara Hill, Arkansas Department of Environmental Quality, October 21, 2008.
[32] ADEQ Permit No. 4929-WR-1, Central Arkansas Disposal Facility permit dated June 30th, 2007.
[33] ANL Trip Report Located at http://www.ead.anl.gov/pub/doc/ANL-EVS_R07-4TripReport.pdf accessed on October 24, 2008.

including the permit for the CAD facility, have more stringent criteria for acceptable chloride concentrations. If chloride content is less than 1,500 ppm, water can also be utilized on roads for dust suppression. If chloride concentrations exceed 5,000 ppm, disposal in approved disposal wells is required. Three commercial disposal facilities are permitted in Arkansas.[40] Transportation to a disposal well is an expensive process. It can costs upwards of $6 per barrel to transport and dispose of water in an independently owned disposal well. Some companies have begun drilling their own wells for disposal purposes to alleviate costs associated with water management.

Naturally Occurring Radioactive Material

NORM is the common acronym for naturally occurring radioactive material. It can originate naturally in subsurface formations and may be transported to the surface through production of formation water in association with oil or gas development[34]. Because of the potential presence of NORM in fracturing fluids, it is also an issue that is closely evaluated relative to worker and public safety as well as protection of the environment.

NORM concentrations associated with natural gas development are primarily noticeable in scale accumulations in pipes, storage tanks, and other surface equipment or in sediment accumulations inside tanks and process vessels. It generally takes several years before accumulations reach regulatory thresholds. For comparison, most natural rocks and soils contain approximately 0.5-5 pCi/g of total radium[35]. A uranium ore sample that contains 1 percent uranium by weight has approximately 3300 pCi/g of ^{226}Ra.

While everyone is exposed to levels of radiation in everyday elements such as sun exposure, x-rays, porcelain dental work, or even books and wristwatches, it is unlikely that an individual would be exposed to a dosage exceeding one rem per year. It is important to note that exposure from oil and gas operations can only occur when repair work is performed due to the dense steel used in equipment that blocks alpha and beta radiation and significantly reduces gamma radiation. Only when equipment is opened and exposed to the atmosphere can human exposure occur.

Although methods for managing NORM in oilfield operations varies, a number of states have enacted regulations specific to NORM while others handle this issue through standard oilfield waste rules as well as permit stipulations in some cases. Standards for cleanup typically require average concentrations of less than 5 pCi/g in the upper 15cm of soil and an average of less than 15 pCi/g in deeper soils. However, management and cleanup practices vary based on very low perceived risks to human health and the environment.

Economic Impact

Economic impacts of the Fayetteville shale play are much more far reaching than company profits and landowner royalties. According to a 2007 study of Barnett shale development in the Fort Worth basin of Texas by the Perryman Group, "Exploration, drilling, and production in the field have transformed the economy with thousands of jobs and millions of dollars in investment; led to

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[34] Chesapeake Energy White Paper "Norm Fact Sheet", 2008

[35] United States Geological Survey. *"Naturally Occurring Radioactive Materials (NORM) in Produced Water and Oil-Field Equipment – An Issue for the Energy Industry."* Fact Sheet FS-142-99. September 1999.

royalty and bonus payments to local residents, cities, school districts, and others totaling millions of dollars each year; increased property tax revenues to counties, schools, and other entities; and contributed to the opportunities and prosperity for the entire region." Fayetteville shale gas development in Arkansas is no exception. According to a study by the Center of Business for Economic Research, in 2007, more than $54.6 million in tax revenues were generated at the state level and an additional $8.3 million in local taxes, including local sales tax generated for cities and counties and property taxes from production. A total of $1.8 billion in direct expenditures resulted in a net economic output of over $2.6 billion and provided employment for 9533 people. Estimates for the years 2008 to 2012 indicated a total annual state employment of over 11,000 people and a total economic activity of about $17.9 billion. Additionally, significant revenue is expected to be generated from income, sale, property, and several tax revenues which will benefit the economy of Arkansas.

Summary

Horizontal drilling in conjunction with hydraulic fracturing has made development of the Fayetteville shale gas resource an economic venture. Early estimates have indicated that there are over 40 Tcf of gas reserves in the Fayetteville shale. As additional wells are drilled and more information is gathered on reservoir characteristics, additional reserves could be realized. Development of the Fayetteville shale, as well as other unconventional gas resources should help to decrease the dependence of foreign imports.

Development of the Fayetteville shale includes many unique challenges, including water availability and water disposal. For developers to be successful, they must create innovate solutions to the many developmental challenges. For example, Chesapeake Energy is constructing a 500 acre-foot reservoir to hold water from the Little Red River. Chesapeake estimates that volumes will be enough to service the drilling and completion of 200 to 2,000 new wells. Once hydraulic fracturing of a well is complete, flow-back water is generally transported to a permitted land disposal facility, a disposal well or recycled for other hydraulic fracturing treatments. As more wells are drilled and development increases, it is anticipated that companies will continue designing leading edge technological solutions to water availability and disposal.

Some concerns have been expressed relative to vertical migration of fracturing fluids and groundwater contamination. However, regulatory requirements and stratigraphic barriers minimize the possible interaction of fracturing fluids with potential usable quality aquifers. The AOGC has regulatory requirements for casing depth and properties, as well as cementing requirements to minimize the potential for impacts to groundwater aquifers that are or may be of use in the future.