TOPIC PAPER #29

UNCONVENTIONAL GAS

On July 18, 2007, The National Petroleum Council (NPC) in approving its report, *Facing the Hard Truths about Energy,* also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the Task Groups and their Subgroups. These Topic Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

The attached Topic Paper is one of 38 such working document used in the study analyses. Also included is a roster of the Subgroup that developed or submitted this paper. Appendix E of the final NPC report provides a complete list of the 38 Topic Papers and an abstract for each. The printed final report volume contains a CD that includes pdf files of all papers. These papers also can be viewed and downloaded from the report section of the NPC website (www.npc.org).

NATIONAL PETROLEUM COUNCIL

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Unconventional Gas Reservoirs—Tight Gas, Coal Seams, and Shales

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Date: February 21, 2007

I. Executive Summary

A study was undertaken on behalf of the National Petroleum Council to assess the impact of technology on unconventional gas development and estimate the potential impact of technology on a worldwide basis over the next 25 years. The methodology used was to conduct a literature search of relevant material, assess that material, prepare a draft report on the topic, and vet it through an unconventional gas subgroup (See Table I.1).

Outside of the United States, with a few exceptions, unconventional gas resources have largely been overlooked and understudied. In most of the world, the natural gas industry is focusing on producing gas from conventional reservoirs and has yet to turn its attention to unconventional gas reservoirs. These unconventional gas reservoirs represent a vast, long-term, global source of natural gas and have not been appraised in any systematic way. Unconventional gas resources—including tight sands, coalbed methane, and gas shales—constitute some of the largest components of remaining natural gas resources in the United States. Research and development concerning the geologic controls and production technologies required to evaluate and produce these unconventional gas resources has provided many new technologies during the past several decades. These new technologies have enabled operators in the United States to unlock the vast potential of these challenging resources, boosting production levels to an estimated 30% of the natural gas production in the United

States. Around the world, unconventional gas resources are widespread, but with several exceptions, they have not received close attention from natural gas operators. This is due in part because geologic and engineering information on unconventional resources is scarce, and natural gas policies and market conditions have been unfavorable for development in many countries. In addition, there is a chronic shortage of expertise in the specific technologies needed to develop these resources successfully. As a result, only limited development has taken place to date outside of North America. Interest is growing, however, and during the last decade development of unconventional gas reservoirs has occurred in Canada, Australia, Mexico, Venezuela, Argentina, Indonesia, China, Russia, Egypt, and Saudi Arabia.

Many of those who have estimated the volumes of gas in place within unconventional gas reservoirs agree on one aspect: that it is a large resource. In Table I.1 below, Kawata and Fujita summarized the work of Rogner, who estimated the worldwide unconventional gas resource.[1] Using the United States as an analogy, there is good reason to expect that unconventional gas production will increase significantly around the world in the coming decades for the following reasons:

- A significant number of geologic basins around the world contain unconventional gas reservoirs.
- Rogner estimates that in the world there are around
  - 9,000 Tcf of gas in place in coalbed methane,
  - 16,000 Tcf of gas in place in shale gas, and
  - 7,400 Tcf of gas in place in tight gas sands.
- Any reasonable recovery efficiency leads one to the conclusion that there is an ample opportunity in the future to develop unconventional gas worldwide.
- Tight gas sand development in the United States, critical to future U.S. gas supply, has to over 4 Tcf/year and is supported by ongoing technological development.

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[1] Kawata Y and Fujita K: "Some Predictions of Possible Unconventional Hydrocarbon Availability Until 2100," SPE 68755 presented at the SPE Asia Pacific Oil and Gas Conference, Jakarta, Indonesia, (April 17–19, 2001).

- The technology developed in the United States over the past 3 to 4 decades will be available for application around the world.
- New technology is rapidly becoming a worldwide commodity through efforts of major service companies.
- The global need for energy, particularly natural gas, will continue to be an incentive for worldwide unconventional gas resource development.
- Tight gas sands, gas shales, and coalbed methane are already critical to North America today and will be an important energy source worldwide during the 21st Century.

Region	Coalbed Methane (Tcf)	Shale Gas (Tcf)	Tight-Sand Gas (Tcf)	Total (Tcf)
North America	3,017	3,842	1,371	8,228
Latin America	39	2,117	1,293	3,448
Western Europe	157	510	353	1,019
Central and Eastern Europe	118	39	78	235
Former Soviet Union	3,957	627	901	5,485
Middle East and North Africa	0	2,548	823	3,370
Sub-Saharan Africa	39	274	784	1,097
Centrally planned Asia and China	1,215	3,528	353	5,094
Pacific (Organization for Economic Cooperation and Development)	470	2,313	705	3,487
Other Asia Pacific	0	314	549	862
South Asia	39	0	196	235
World	9,051	16,112	7,406	32,560

Table I.1. Distribution of worldwide unconventional gas reservoirs.[2]

[2] Holditch SA: "Tight Gas Sands," SPE Paper 103356, Distinguished Author Series (2006). Data after Rogner H: "An Assessment of World Hydrocarbon Resources," Institute for Integrated Energy System, University Of Victoria (1997).

II. Introduction

Unconventional gas reservoir is a term commonly used to refer to a low-permeability reservoir that produces mainly dry natural gas. Many of the low-permeability reservoirs that have been developed in the past are sandstone, but significant quantities of gas are also produced from low-permeability carbonates, shales, and coalbed methane.

In general, a vertical well that has been drilled and completed in an unconventional gas reservoir must be successfully stimulated to produce at commercial gas flow rates and recover commercial gas volumes. Normally, a large hydraulic fracture treatment is used to achieve successful stimulation. In some naturally fractured unconventional gas reservoirs, horizontal wells can be drilled, but many of these wells also need to be stimulated with hydraulic fracturing methods. To optimize the development of an unconventional gas reservoir, a team of geoscientists and engineers must determine the optimum number and locations of wells to be drilled, as well as the drilling and completion procedures for each well. Often, more data and more engineering manpower are required to understand and develop unconventional gas reservoirs than are required for higher-permeability, conventional reservoirs. On an individual well basis, an unconventional gas reservoir will produce less gas over a longer period of time than will a well completed in a higher-permeability, conventional reservoir. As such, many more wells with smaller well spacing must be drilled in an unconventional gas reservoir to recover a large percentage of the original gas in place, when compared to a conventional reservoir.

A. Definition of an Unconventional Gas Reservoir

In the 1970s, the United States government defined a tight gas reservoir as one in which the expected value of permeability to gas flow would be less than 0.1 md. This definition was a political definition that has been used to determine which wells would receive federal or state tax credits for producing gas from tight reservoirs. Actually, the definition of a tight gas reservoir is a function of many physical and economic factors. The following equation, known as Darcy's Law, relates these physical factors.'

$$q = \frac{kh\left(\bar{p} - p_{wf}\right)}{141.2\ \bar{\hat{a}}\ \bar{\imath}\left[\ln\left(\frac{r_e}{r_w}\right) - 0.75 + s\right]}$$

The above equation clearly shows that the flow rate, q, is a function of permeability k; net pay thickness h; reservoir pressure $\bar{p}$; flowing pressure p_{wf}; formation volume factor and gas viscosity evaluated at the average pressure, $\bar{\beta}\bar{\mu}$; drainage area r_e; wellbore radius r_w; and skin factor s. Thus, to choose a single value of permeability to define "tight gas or unconventional gas" is of limited significance. In deep, high-pressure, thick reservoirs, commercial completions can be achieved when the formation permeability to gas is in the microdarcy range (0.001 md). In shallow, low-pressure, thin reservoirs, permeabilities of several millidarcies might be required to produce the gas at economic flow rates, even after a successful fracture treatment.

One way to define unconventional gas is as *"natural gas that cannot be produced at economic flow rates nor in economic volumes of natural gas unless the well is stimulated by a large hydraulic fracture treatment, a horizontal wellbore, or by using multilateral wellbores or some other technique to expose more of the reservoir to the wellbore."*

So what is a typical unconventional gas reservoir? The answer is that there are no "typical" unconventional gas reservoirs. An unconventional gas reservoir can be deep or shallow; high pressure or low pressure; high temperature or low temperature; blanket or lenticular; homogeneous or naturally fractured; and containing a single layer or multiple layers.

The optimum drilling, completion, and stimulation methods for each well are a function of the reservoir characteristics and the economic situation. Unconventional gas reservoirs in south Texas may have reservoir properties that are significantly different from those in South America or the Middle East. The costs to drill, complete, and stimulate these wells, as well as the gas price and the gas market affect how tight-gas reservoirs are developed.

B. The Resource Triangle

The concept of the resource triangle was used by Masters and Grey to find a large gas field and build a company in the 1970s.[3] The concept is that all natural resources are distributed log-normally in nature. If you are prospecting for gold, silver, iron, zinc, oil, natural gas, or any resource, you will find that the best or highest-grade deposits are small and, once found, are easy to extract. The hard part is finding thes pure veins of gold or high-permeability gas fields. Once you find the high-grade deposit, producing the resource is rather easy and straightforward. Figure IIC.1 illustrates the principle of the resource triangle.

As you go deeper into the resource triangle, the reservoirs are lower grade, which usually means the reservoir permeability is decreasing. These low permeability reservoirs, however, are usually much larger than the higher quality reservoirs. As with other natural resources, low quality deposits of natural gas require improved technology and adequate gas prices before they can be developed and produced economically. However, the size of the deposits can be very large, when compared to conventional or high-quality reservoirs. The concept of the resource triangle applies to every hydrocarbon-producing basin in the world. One can estimate the volumes of oil and gas trapped in low quality reservoirs in a specific basin by knowing the volumes of oil and gas that exist in the higher-quality reservoirs.

[3] Masters JA: "Deep Basin Gas Trap, Western Canada," AAPG Bulletin (1979) 63, No. 2: 152. Rogner H-H: "An Assessment of World Hydrocarbon Resources," IIASA, WP–96–26, May 1996.

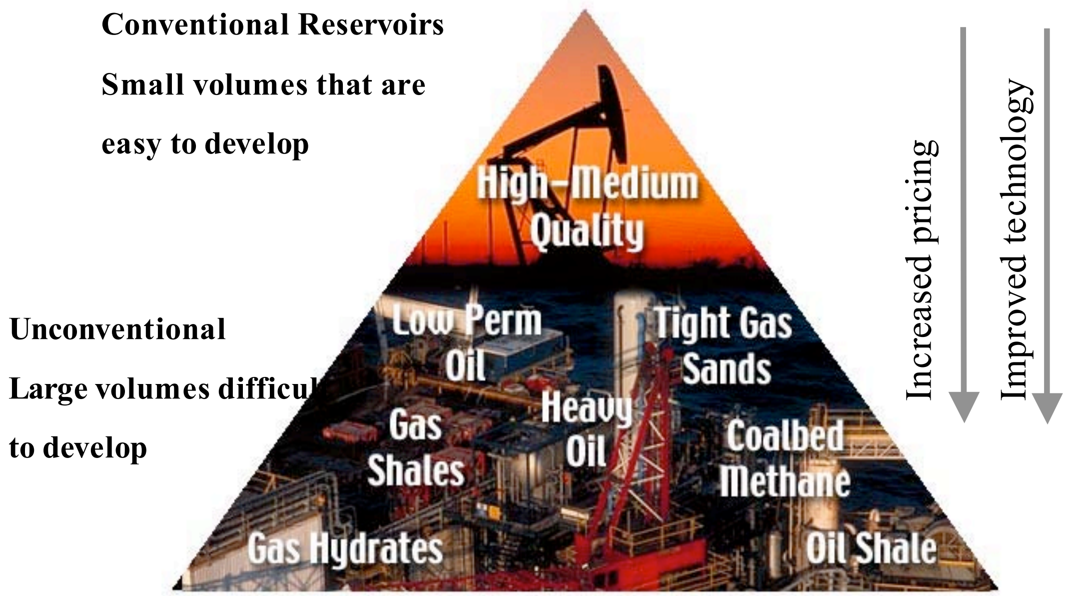

Figure IIC.1. The resource triangle for oil and gas reservoirs.

III. Overview of Methodology

A significant volume of information and data has been accumulated over the past 20 years regarding unconventional gas reservoirs and the technology that enabled their development. The primary methodology utilized for this study was to identify and assess relevant material from this accumulated record. This study included the following specific steps:

1) Review of literature worldwide on the topics of unconventional gas including coalbed methane, gas shales, and tight gas sands
2) Posting of relevant literature to a website available to all technology subgroup team members for review
3) Assessment of all the information posted, writing draft documents for each of the unconventional resource areas (coalbed methane, gas shales, and tight

gas sands) including a discussion and final review of the draft report by team members

4) Discussion and review with other NPC study task groups
5) Second revision and review of report by team members
6) Final revision of report.

The team members for the Unconventional Gas Technology Subgroup included those identified in Table III.1.

Team Member	Affiliation
Stephen A. Holditch	Texas A& M University
John Lee	Texas A&M University
Kent Perry	Gas Technology Institute
Tom Blasingame	Texas A&M University
Mark Hoefner	ExxonMobil
John Bickley	Shell
Duane McVay	Texas A& M University
Walt Ayers	Texas A& M University
Catalin Teodoriu	Texas A& M University
Valerie Jochen	Schlumberger
Mukul Sharma	University of Texas at Austin
Carlos Torres-Verdes	University of Texas at Austin

Table III.1. NPC Technology subgroup on unconventional-gas team members.

As mentioned, a worldwide literature search was conducted on each of the unconventional resources with emphasis on technology important for its development. For tight gas sands, the largest and most extensively developed of the three resources, there is a considerable amount of information available, particularly in the United States, where tight gas sands are a very significant contributor to gas production. For coalbed methane and gas shales, a significant amount of information is available in North America, particularly the United States where these two resources have been widely developed. The primary documents that were used for the tight gas sands, coalbed methane, and gas shales are given in Tables III.2, III.3, and III.4. respectively.

Primary Reports Used for Tight Gas Sands
Holditch SA: “Tight Gas Sands,” SPE Paper 103356, Distinguished Author Series (2006).
Feugueur K, and Schenckery M: “Unconventional Gas in North America.” Mission

Economique de HOUSTON (2006): 1–52.
Xiong H and Holditch SA: "Will the Blossom of Unconventional Natural Gas Development in North America Be Repeated in China?" paper SPE 103775 presented at the 2006 SPE International Oil & Gas Conference and Exhibition in China, Beijing, (December 5–7, 2006).
Stark P and Chew K: *Global Gas Resources: Implications for North America*, IHS Energy (August 2004).
Ammer J: "Tight Gas Technologies for the Rocky Mountains", *GasTIPS* 8, number 2 (Spring 2002): 18–23.
"Technology Impact on Natural Gas Supply" Chapter 5 in *Supply Task Group Report*, Volume 4 of *Balancing Natural Gas Policy, Fueling the Demands of a Growing Economy*, National Petroleum Council (September 2003). Available at http://www.npc.org/.
Filling the Gap, Unconventional Gas Technology Roadmap, Petroleum Technology Alliance Canada (June 2006).
Technology Needs for Unconventional Gas Development, Research Partnership to Secure Energy for America, Final DOE Report, Contract DE-RP26-04NT41817 TSK41817.211.01.05 (November 2005).
Global Emerging Resource Consortia, Gas Research Institute (October, 1998).

Table III.2. Primary reports used for the tight gas sands study.

Primary Reports Used for Coalbed Methane
"Technology Impact on Natural Gas Supply" Chapter 5 in *Supply Task Group Report*, Volume 4 of *Balancing Natural Gas Policy, Fueling the Demands of a Growing Economy*, National Petroleum Council (September 2003). Available at http://www.npc.org/.
Filling the Gap, Unconventional Gas Technology Roadmap, Petroleum Technology Alliance Canada (June 2006).
Technology Needs for Unconventional Gas Development, Research Partnership to Secure Energy for America, Final DOE Report, Contract DE-RP26-04NT41817 TSK41817.211.01.05 (November 2005).
"Technology Needs for Unconventional Gas in the United States," New Mexico Tech, Socorro NM (2002).
Stevens SH, Kuuskraa J, and Kuuskraa V: "Unconventional Natural Gas in the United States: Production, Reserves, and Resources Potential (1991-1997)," Advanced Resources International, Inc. (1998).
"Global methane and the coal industry," Coal Industry Advisory Board, International Energy Agency (1994): 1–66.
McCallister T: "Impact of Unconventional Gas Technology in the Annual Energy Outlook 2000," *Issues in Midterm Analysis and Forecasting*, Energy Information Administration (2000): 1–21.

Table III.3. Primary reports used for the coalbed methane study.

Primary Reports Used for Gas Shales Study
Rogner H: "An Assessment of World Hydrocarbon Resources," Institute for Integrated Energy System, University Of Victoria (1997).
IFP: "Gas Reserves, Discoveries, and Production", *Panorama* (2006).
Energy Information Agency: *Annual Energy Outlook*, 2006.
Johnston D: "Technological Advances Expand Potential Pay", *Oil & Gas Journal* 102, number 3 (January 19, 2004).
Fisher MK, Heinze JR, Harris CD, Davidson BM, Wright CA, and Dunn KP: "Optimizing Horizontal Completion Techniques in the Barnett Shale Using Microseismic Fracture Mapping," paper SPE 90051presented at the SPE Annual Technical Conference and Exhibition, Houston, Texas (September 26-29, 2004).
Campbell SM, Fairchild Jr. NR, and Arnold DL: "Liquid CO_2 and Sand Stimulations in the Lewis Shale, San Juan Basin, New Mexico: A Case Study," paper SPE 60317 presented at the SPE Rocky Mountain Regional/Low-Permeability Reservoirs Symposium and Exhibition, Denver, Colorado (March 12–15, 2000).
Faraj B, Williams H, Addison G, McKinstry B, et al: "Gas Potential of Selected Shale Formations in the Western Canadian Sedimentary Basin," *GasTIPS* 10, number 1 (Winter 2004): 21–25.

Table III.4. Primary reports used for the gas shales study.

The publications and papers we selected for this report cover general hydrocarbon resource estimates, unconventional gas reserves and production, and technology practices in developing shale gas.

IV. Background

Outside the United States, with a few exceptions, unconventional gas resources have largely been overlooked and understudied. They represent a potential long-term global resource of natural gas and have not been appraised in any systematic way. Unconventional gas resources—including tight sands, coalbed methane, and gas shales—constitute some of the largest components of remaining natural gas resources in the United States. Research and development into the geologic controls and production technologies for these resources during the past several decades has enabled operators in the United States to begin to unlock the vast potential of these challenging resources. These resources are particularly attractive to natural gas producers due to their long-lived reserves and stabilizing influence on reserve portfolios.

Worldwide, unconventional gas resources are widespread but, with several exceptions, they have not received close attention from natural gas operators. This is due in part because information on unconventional resources is scarce, and natural gas policies and market conditions have been unfavorable for development in many countries. In addition, there is a chronic shortage of expertise in the specific technologies needed to develop these resources successfully. As a result, only limited development has taken place to date. Interest is growing, however, and during the last decade development of tight gas reservoirs has occurred in Canada, Australia, Mexico, Venezuela, Argentina, Indonesia, China, Russia, Egypt, and Saudi Arabia.

A. Tight Gas Sands

From a global perspective, tight gas sand resources are vast, but undefined. No systematic evaluation has been carried out on global emerging resources. The magnitude and distribution of worldwide gas resources in gas shales, tight sands, and coalbed methane formations has yet to be understood. Worldwide estimates, however, are enormous, with some estimates higher than 32,000 Tcf (see Table IVA.1). The probability of this gas resource being in place is supported by information and experience with similar resources in North America. This is likely to be a conservative estimate of the volume of gas in unconventional reservoirs worldwide, because there are fewer data to evaluate outside of North America. As more worldwide development occurs, more data will be available, and the estimates of worldwide unconventional gas volumes will undoubtedly increase.

Unconventional resources, defined as those that have low permeability and require advanced drilling or stimulation technologies to be produced at commercial flow rates, have been an important component of the U.S. domestic natural gas supply base for many years. From almost nonexistent production levels in the early 1970s, today unconventional resources, particularly tight sands, provide almost 30% of domestic gas supply in the United States. The volumes of gas produced from unconventional resources in the United States are projected to increase in importance over the next 25 years, exceeding production levels of 9.0 Tcf per year (Figure IVA.1).

Region	**Coalbed Methane (Tcf)**	**Shale Gas (Tcf)**	**Tight-Sand Gas (Tcf)**	**Total (Tcf)**
North America	3,017	3,842	1,371	8,228
Latin America	39	2,117	1,293	3,448
Western Europe	157	510	353	1,019
Central and Eastern Europe	118	39	78	235
Former Soviet Union	3,957	627	901	5,485
Middle East and North Africa	0	2,548	823	3,370
Sub-Saharan Africa	39	274	784	1,097
Centrally planned Asia and China	1,215	3,528	353	5,094
Pacific (Organization for Economic Cooperation and Development)	470	2,313	705	3,487
Other Asia Pacific	0	314	549	862
South Asia	39	0	196	235
World	9,051	16,112	7,406	32,560

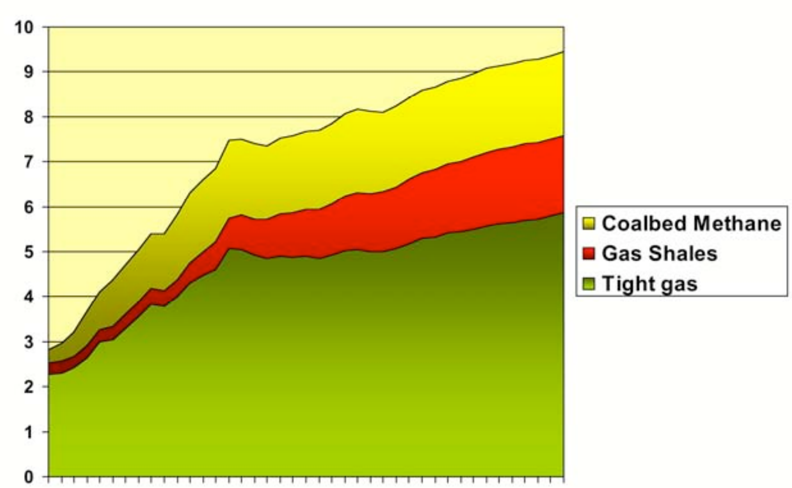

Table IVA.1. Distribution of worldwide unconventional gas resources.[4]

Figure IVA.1. United States unconventional gas production and future projection.[5]

[4] Holditch, reference 1.

Once the technical challenges have been overcome for a particular emerging-resources play, they tend to provide a long-term, economic base-load gas supply. In the United States, development of these resources now composes a significant percentage of the onshore exploration activity in the lower 48 states. During the 1990s, unconventional resources comprised 80% of the large gas field discoveries. Of those discoveries, tight gas sands were the most prominent of the resources being developed (Table IVA.2).

There is an ongoing technical need to delineate the size and distribution of global unconventional gas resources, provide preliminary insights into commercial potential, and begin transferring the technologies needed for development, such that these resources can be developed in the international arena as they have in the USA.

[5] EIA: *Annual Energy Outlook 2005 with Projections to 2025*, DOE Report #: DOE/EIA-0383(2005).

U.S. Onshore Gas Giants of the 1990s			
	Name	**Expected Ultimate Recovery (Tcf)**	**Play Type**
1	Newark East—Barnett Shale	26.2	Continuous shale gas
2	Powder River CBM	24.0	Coalbed methane
3	Jonah	3.3	Basin-centered gas
4	Pinedale	2.0	Tight sands
5	Madden Deep (mostly conventional)	2.0	Structural
6	Vernon	1.8	Tight sands
7	Ferron coal play Utah	1.5	Coalbed methane
8	Freshwater Bayou (conventional)	1.5	Structural
9	Dew—Mimms	1.2	Tight sands
10	Bob West	1.1	Structural/tight sands

Table IVA.2. Top onshore gas discoveries in the United States during the 1990s (eight of the top ten U.S. onshore giant gas discoveries are unconventional).[6]

B. Coal Seams

Coalbed methane is one of the best examples of how technology can have an impact on the understanding and eventual development of a natural gas resource. While gas has been known to exist in coal seams since the beginning of the coal mining industry, only since 1989 has significant gas production been realized (Figure IVB.1).

Coalbed methane (CBM) was drilled through and observed for many years, yet never produced and sold as a resource. New technology and focused CBM research ultimately solved the resource complexity riddle and unlocked its production potential. Coalbed methane now provides over 1.6 Tcf of gas production per year in the United States and is under development worldwide including the countries of Canada, Australia, India, China, and others.

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[6] Anadarko: "Natural Gas Supply Issues," Howard Weil 33rd Annual Energy Conference (April 2005).

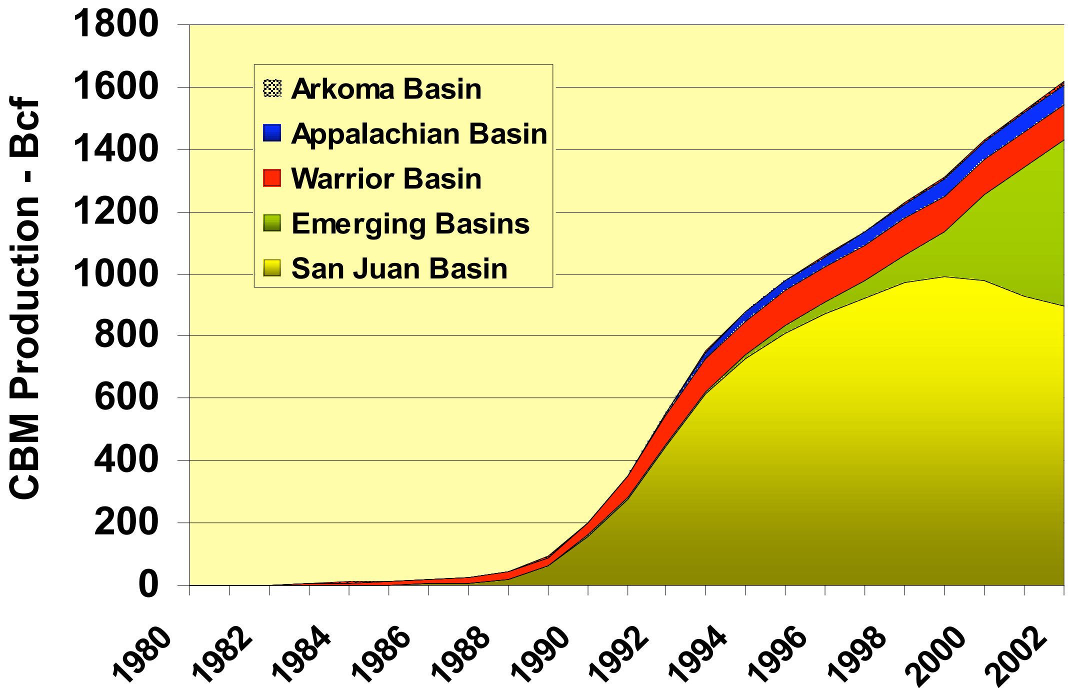

Figure IVB.1. Gas production from coal seams in the United States.[7]

Factors controlling coalbed-methane production behavior are similar to those for conventional gas resources in many respects; yet, they differ considerably in other important areas. One prominent difference is in the understanding of the resource, especially with regard to values of gas-in-place. Natural gas in coal seams adsorbs to the coal surface, allowing for significantly more gas to be stored than conventional rocks in shallow, low-pressure formations. To release the adsorbed gas for production, we have to reduce the pressure in the reservoir substantially. Adsorbed gas volumes are not important for conventional gas resources but are very important for CBM reservoirs. Significant research was required in the 1990s to fully understand how to produce the adsorbed gas in coal seams and to develop the technology required to explore and produce CBM reservoirs.

A major difference between CBM reservoirs and sandstone gas reservoirs is that many of the coal seams are initially saturated with water. Thus, large volumes of

[7] Data provided by and courtesy of IHS Energy, 533 Westheimer, Houston, TX 77056.

water must be pumped out of the coal seams to reduce the pressure so that desorption will occur prior to seeing any significant gas production. The technology developed in the 1990s for understanding and dewatering coal seams paved the way for significant CBM development in several U.S. geologic basins.

C. Potential for Coalbed Methane Worldwide

Deposits of coal reserves are available in almost every country worldwide. Over 70 countries have coal reserves that can be mined and have potential CBM recovery. In 2005, over 5 billion tons of coal were produced worldwide. The top ten countries, (China, United States, India, Australia, South Africa, Russia, Indonesia, Poland, Kazakhstan, and Columbia) produced nearly 90% of the total. Estimates of gas in place around the world in coal seams range from 2,400 to 8,400 Tcf. Using the United States as an analog, it is reasonable to expect that coal seams around the world hold potential for coalbed methane production. It should be noted that coal mining by economic and technical necessity takes place in relatively shallow coal seams. Much of the CBM production in the United States is from coal seams too deep to be mined, and this situation is expected to occur around the world. Worldwide coal resources are found in over 100 geologic basins. Figure IVC.1 is a global coal distribution map showing major geologic basins that contain coal resources. Again, CBM production potential from existing coal basins in the United States serve as a qualitative analogy that can be drawn around the world.

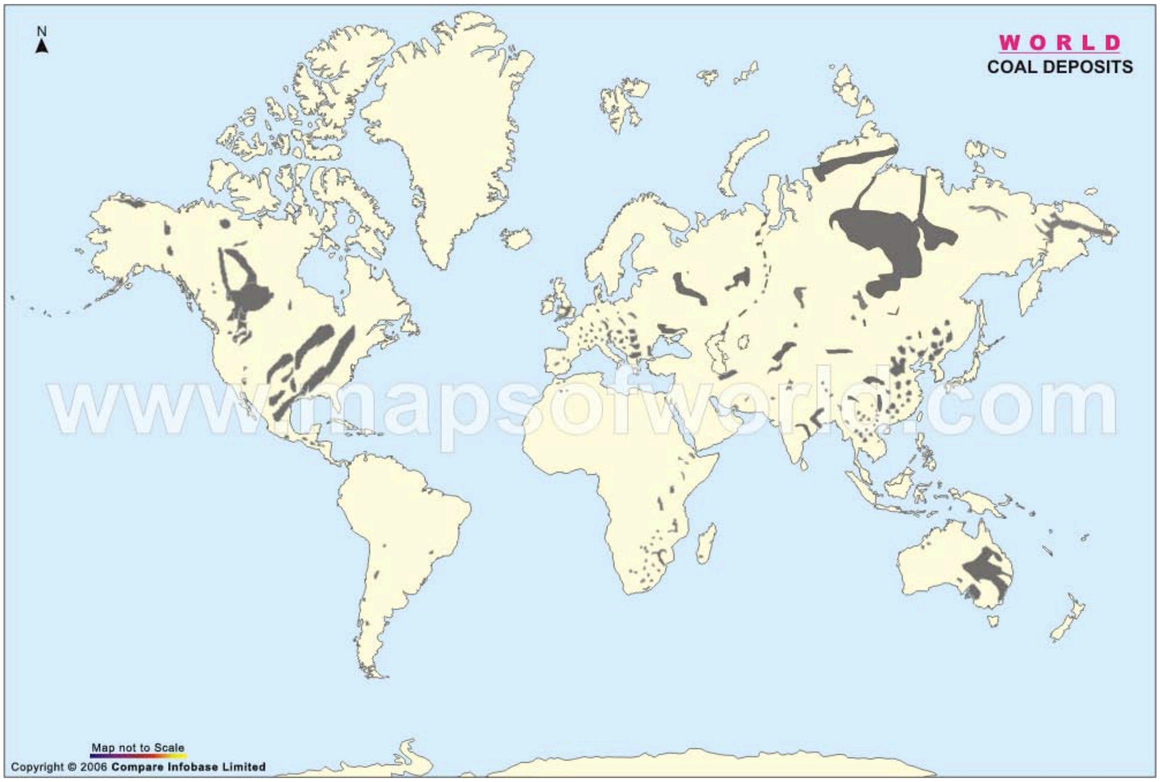

Figure IVC.1. World coal deposits.[8]

D. Shale Gas

Shale formations act as both a source of gas and as its reservoir. Natural gas is stored in shale in three forms: free gas in rock pores, free gas in natural fractures, and adsorbed gas on organic matter and mineral surfaces. These different storage mechanisms affect the speed and efficiency of gas production.

A global energy study in 1997 estimated that abundant shale gas resources are distributed mostly in North America, Latin America, and Asia Pacific (Table IVD.1).[9] Recent estimates suggest the resource ranges from 1,483 to 1,859 Tcf in the U.S., and 500 to 600 Tcf in Canada.[10] In other regions of the world, this resource has been studied to only a limited extent.

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[8] See http://www.mapsofworld.com/business/industries/coal-energy/world-coal-deposits.html.
[9] Rogner H: "An Assessment of World Hydrocarbon Resources," Institute for Integrated Energy System, University Of Victoria (1997).
[10] IFP: "Gas Reserves, Discoveries, and Production", *Panorama* (2006).

Region	Gas Resource in Fractured Shales (Tcf)
NAM–North America	3,842
LAM–Latin America	2,117
WEU–Western Europe	510
EEU–Eastern Europe	39
FSU–Former Soviet Union	627
MEA–Middle East Asia	2,548
AFR–Africa	274
CPA–Central Pacific	3,528
PAO–Asia and China	2,313
PAS–Other Asia Pacific	314
World	**16,112**

Table IVD.1. Estimated worldwide shale gas resources.[11]

E. Shale Gas Production in the United States

Commercial shale gas production occurs primarily in the USA, distributed in the Appalachian basin, Michigan basin, Illinois basin, Fort Worth basin, and San Juan basin (Figure IVE.1). Production increased rapidly in the 1990s (Figure IVE.2). In 2004, shale gas production in the USA reached about 700 Bcf/yr, a huge increase compared to 350 Bcf/yr in 2000. Since the late 1990s, the largest producer of shale gas has been the Barnett shale in the Forth Worth basin. While technological innovations have increased per-well with gas recovery efficiency up to 20%, considerable increases in reserves have come from the increase in well density.

[11] Rogner, reference 9.

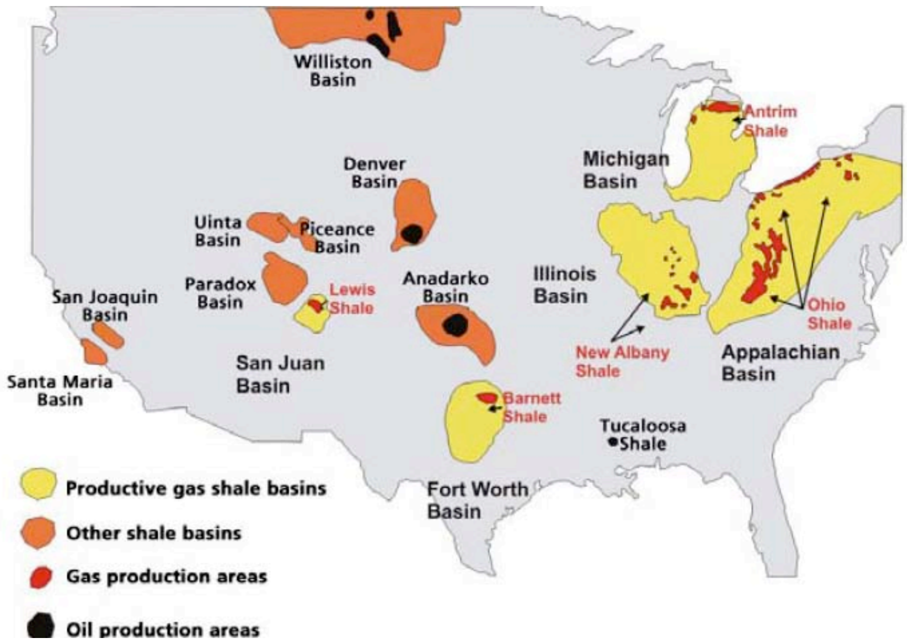

Figure IVE.1. Commercial shale gas production in the USA.[12]

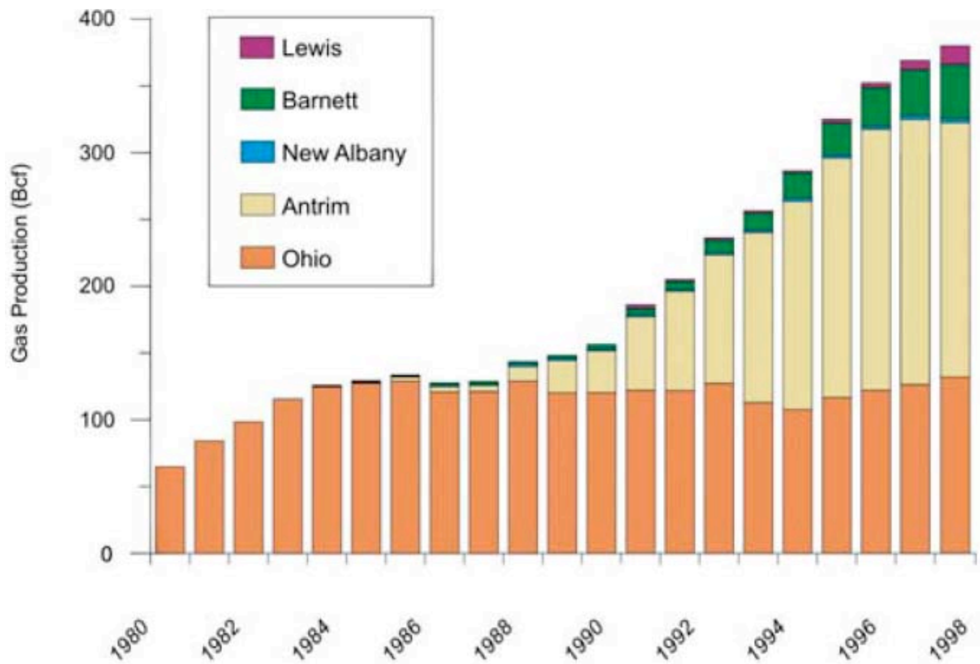

Figure IVE.2. Increasing shale gas production in the 1990s.[13]

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[12] Faraj B, Williams H, Addison G, McKinstry B, et al: (GTI Canada), "Gas Potential of Selected Shale Formations in the Western Canadian Sedimentary Basin," *GasTIPS* 10, number 1 (Winter 2004): 21–25.
[13] Faraj et al, reference 12.

F. Discussion of Current Technology for Shale Gas in the United States

Gas-shale production experience in the USA shows that stimulation techniques, especially hydraulic fracturing, are almost always necessary for shale-gas production. Other important technology advances include application of horizontal and directional drilling and reservoir characterization. For Barnett shale wells, using currently available technology, the per-well recovery factor averages 7% of the gas in place. This is far below a potentially achievable 20% recovery factor.

The Barnett shale has had the highest level of recent activity among shale-gas resources. Prior to 1998, most Barnett Shale wells were completed with massive hydraulic fracture treatments using 100,000–1,000,000 pounds of propping agent, usually sand. This method was expensive and was often not effective due to fracture fluid clean-up problems. In 1998, light sand fracturing (water fracture treatment) was introduced and has been successful in many areas of the Barnett Shale. Water fracture treatments cost less than gel fracture treatments, and appear to improve productivity. Many operators consider water fracture treatments in vertical wells to be a more important advance in developing the Barnett Shale than any previously developed technology.

In areas with limited surface access and landowner restrictions, horizontal drilling has been applied. Horizontal wells provide greater wellbore contact within the reservoir rocks than do vertical wells. Figure IVF.1 shows the result of a pilot study by Devon Energy. The study proved that hydraulic fracturing in horizontal wells results in production increases of two to three times that in vertical wells for the first 180 days. Microseismic fracture mapping has also been successfully used to improve the evaluation of hydraulic fracturing in horizontal wells.

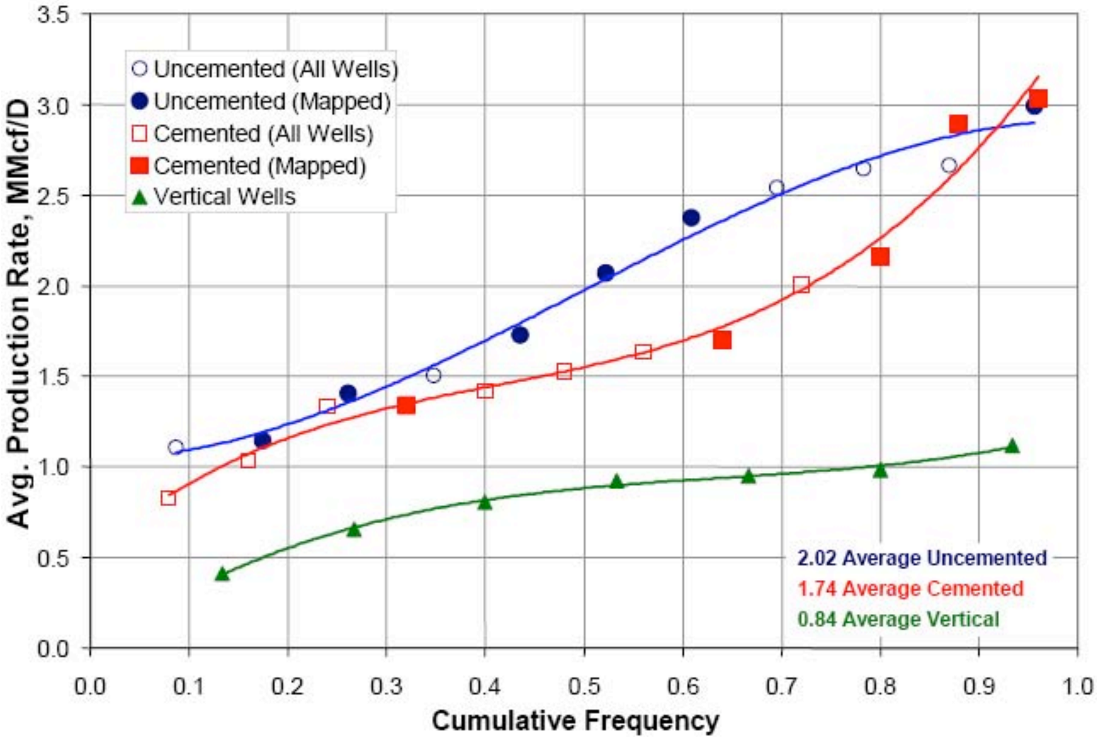

Figure IVF.1. Fractured horizontal well production rate was two to three times the rate in vertical wells.[14]

V. Table of Advances

Three technology tables (Tables V.1, V.2, and V.3) have been prepared describing current technology under development and technology that needs to be developed for use in future years. Specifically, these tables include: advances currently being pursued along with development anticipated by 2010; advances that might be in commercial use by 2020; and advances that might be in commercial use by 2030. The priority for each was determined by estimating the difference in impact

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[14] Fisher MK, Heinze JR, Harris CD, Davidson BM, Wright CA, and Dunn KP: "Optimizing Horizontal Completion Techniques in the Barnett Shale Using Microseismic Fracture Mapping," paper SPE 90051presented at the SPE Annual Technical Conference and Exhibition, Houston, Texas (September 26–29, 2004).

between a "business as usual" case and an accelerated technology case, listed with the greatest impact first. We used the following rules for making these estimations:

- High—Greatest impact on producing more gas or reducing cost
- Moderate—Less impact or more difficult to measure its effectiveness.

We have also included a column to estimate the amount of research and development needed to fully develop the given technology. We used the following rules for making these estimations:

- Incremental—research and development as usual
- Accelerated—research and development as usual but with a major increase in funding (a factor of 3 to 5)
- Breakthrough—substantial increase in funding (a factor of 10 to 100) and more use of consortia.

Summary of Technologies for Unconventional Gas from Now to 2010			
Unconventional Gas Technology Under Development or Anticipated by 2010	**Significance**	**Research and Development Required for Success**	**Discussion**
Fracture modeling and analysis, full 3D models for new types of treatments	High	Accelerated	Incorporating new physics for fracture propagation, in naturally fractured reservoirs, for proppant transport, and to make better models for horizontal and multilateral wells
New fracturing fluids and proppants	High	Incremental	Strong, light-weight proppants are needed. Better fluids that do not damage the reservoir and fracture must be developed
Hydraulic fracturing methods used in horizontal wells	High	Incremental	Fort Worth basin (Barnett Shale): increased production rate by 2–3 times rate of vertical well
Stimulation methods used in naturally fractured formations	High	Incremental	Gas shales and coal seam reservoirs are normally naturally fractured. We need a better understanding and better

Summary of Technologies for Unconventional Gas from Now to 2010			
Unconventional Gas Technology Under Development or Anticipated by 2010	**Significance**	**Research and Development Required for Success**	**Discussion**
			technologies for such reservoirs to include better models to determine gas storage and gas production using multiple gas systems, such as CO_2, wet gas, and N_2
Micro-seismic fracture mapping and post fracture diagnostics	High	Accelerated	Fort Worth basin (Barnett Shale): improved understanding of hydraulic fracturing in horizontal wells so that designs can be improved
Data collection and availability during drilling, completions, stimulations, and production	High	Incremental	Significant data are being generated by increased drilling and new tools and techniques. The ability to handle and use data is being challenged. The data need to be evaluated in detail to learn more about formation evaluation, fracture treatments, and production
Integrated reservoir characterization of geologic, seismic, petrophysical, and engineering data	High	Accelerated	More complex reservoirs, lower permeability, greater depth, and more cost require a more in-depth understanding of reservoir petrophysics. Better models will be required to properly integrate all the data and optimize drilling and completion methods
Horizontal drilling and multilateral wellbore capability	High	Accelerated	Enables development of stacked, thin-bed coal seams and reduces environmental impact. Also, need to develop multiple wells from a single pad. This technology is very important in shale gas

Summary of Technologies for Unconventional Gas from Now to 2010			
Unconventional Gas Technology Under Development or Anticipated by 2010	**Significance**	**Research and Development Required for Success**	**Discussion**
			reservoirs, and sometimes important in tight gas reservoirs
Reservoir characterization through laboratory measurements	High	Accelerated	We need better core analyses measurements for basic parameters such as permeability, porosity, and water saturation. In coal seams and shales, we need better methods for estimating sorbed gas volumes and gas-in-place values in the reservoir
Reservoir imaging tools	High	Incremental	Understanding the reservoir characteristics is an ongoing challenge and priority for all unconventional reservoirs
Overall environmental technology	High	Accelerated	We need to reduce the impact of operations on the environment by reducing waste, reducing noise, and by using smaller drilling pads and adequate handling of wastewater
Produced-water handling, processing, and disposal	High	Accelerated	Coal seams and shale gas continue to produce significant volumes of water. Efficient handling and environmentally safe and low-impact disposal are needed
Personnel training and development	Moderate	Incremental	Changing and developing technologies, increased activity, and environmental challenges require a highly technical and efficient workforce
Basin scale petroleum systems	Moderate	Accelerated	Understanding of each geologic basin's complete

Summary of Technologies for Unconventional Gas from Now to 2010			
Unconventional Gas Technology Under Development or Anticipated by 2010	**Significance**	**Research and Development Required for Success**	**Discussion**
studies and resource assessment			tectonic and depositional history is needed to establish fundamentals for future exploration and additional recovery of hydrocarbons for both thermogenic and biogenic hydrocarbons
Basic research	Moderate	Incremental	Ongoing development of fundamentals in all technical disciplines will be necessary as challenges continue to increase.
Rapid technology transfer	Moderate	Incremental	Information technology, including use of the internet to rapidly share and disseminate best practices.

Table V.1. Summary of currently developing technologies for unconventional gas from now to 2010.

Summary of Technologies Anticipated for 2020			
2020 Technology for Unconventional Gas Reservoirs	**Significance**	**Research and Development Required for Success**	**Discussion**
Real-time sweet-spot detection while drilling	High	Breakthrough	Will allow the steering of the drill bit to most productive areas of the reservoir
Coiled tubing drilling for wells less than 5,000 ft measured depth	High	Accelerated	Will allow the advantages of continuous tubing drilling to be realized (fast drilling, small footprint, rapid rig moves) for currently difficult drilling areas

Summary of Technologies Anticipated for 2020			
2020 Technology for Unconventional Gas Reservoirs	**Significance**	**Research and Development Required for Success**	**Discussion**
3D seismic applications for imaging layers and natural fractures in shale reservoirs	High	Accelerated	We could improve recovery efficiency from existing wells if we used well testing methods to better understand the reservoirs
Produced-water processing	High	Accelerated	Produced water is processed and utilized such that it no longer is viewed as a waste stream but as a valuable product for agricultural and industrial use and for all well drilling and completion needs
Deep drilling	High	Incremental	We need to determine how deep we can develop coalbed methane, shale gas, and other naturally fractured unconventional reservoirs
Enhanced CBM recovery via CO_2 injection and sequestration	High	Accelerated	We need to determine the technological solutions and screening of suitable deposits and CO_2 pairs
Data handling and databases	High	Incremental	Databases are available and user friendly allowing access to geologic and engineering data for most North American basins and are being developed for geologic basins worldwide
Recompletion and refracturing technologies	Medium	Accelerated	Small diameter tools, refracturing technology, behind-pipe hydrocarbon detection, lateral drilling technology have all been developed and integrated for increasing recovery from all known unconventional gas fields
Technology	Moderate	Incremental	A systematic approach to

Summary of Technologies Anticipated for 2020			
2020 Technology for Unconventional Gas Reservoirs	**Significance**	**Research and Development Required for Success**	**Discussion**
integration and development planning			developing a CBM field integrating all technology needs development, including the ability to evaluate coal seams prior to completing wells. Effective methods to simulate coal bed performance are required
Fractured shale-formation testing techniques	Moderate	Incremental	We could improve recovery efficiency from existing wells if we used well testing methods to better understand the reservoirs
Reservoir simulation methods to incorporate all the layered reservoir description, the horizontal wells, and the effect of hydraulic fractures	Moderate	Incremental	We need to better understand the reservoir to plan infill drilling and completion methods needed to optimize gas recovery
Shale facies identification using geochemical source rock analysis and well logs	Moderate	Accelerated	A better understanding of the fundamentals will lead to an increase in the exploration success rate in shale gas reservoirs

Table V.2. Summary of technologies anticipated for 2020.

Summary of Technologies Anticipated for 2030			
2030 Technology for Unconventional Gas Reservoirs	**Significance**	**Research and Development Required for Success**	**Discussion**
Resource characterization and gas-in-place potential	High	Accelerated	All the basins worldwide need to be assessed for unconventional gas potential. The results should be recorded in databases and made available to the producing community around the world
Well drilling and completion	High	Accelerated	Well drilling technology must be advanced through improvement in downhole drilling systems, better metallurgy, and real-time downhole sensors, allowing drilling to sweet spots, use of underbalanced drilling where needed, advantages of continuous tubing drilling, and efficient utilization of multilaterals
Enhanced recovery	Moderate	Incremental	Well life must be extended through technology integration increasing gas recovery significantly over what is achievable in 2006
Worldwide technology dissemination	Moderate	Incremental	Unconventional gas technology must be disseminated throughout the world. Production will be developed in most of the basins around the world and data will be readily available on the technologies used and the geologic information of each play is also available
Coalbed farming	Moderate	Accelerated	Biogenic gas stimulation and recovery in situ

Table V.3. Summary of technologies anticipated for 2030.

VI. The Impact of Technology on Costs and Gas Recovery

A 2003 NPC study looked at gas supply from the arctic, the deep water portion of the Gulf of Mexico, the lower 48 states in the USA, Mexico, and Canada. Most of the natural-gas activity in the lower 48 states, Mexico, and southwestern Canada is focused on unconventional reservoirs.[15]

The remainder of this chapter quotes directly from the 2003 NPC gas supply study. We have edited out the portion of the report that pertains to deepwater Gulf of Mexico gas reservoirs and arctic gas reservoirs. Italicized comments in square brackets [*like this*] indicate added text or deletions.

> A Technology Subgroup under the Supply Task Group was formed with representation from various segments of the oil and gas industry to assess the role and impact that technology will have on natural gas supply in North America. Several workshops and meetings were organized to provide a forum for industry experts to discuss the role that current and future technology will play in sustaining the supply of natural gas. From this process, a forecast of technology improvement parameters was developed for input into the natural gas supply model used for the study. Also, various sensitivity cases were run to assess the effects of a range of high and low rate of advancement of technology development and application. Besides predicting technology impact for the model, several insights were developed during the course of the study from the Subgroup members and experts which will be highlighted in this report.

[15] "Technology Impact on Natural Gas Supply" Chapter 5 in *Supply Task Group Report*, Volume 4 of *Balancing Natural Gas Policy, Fueling the Demands of a Growing Economy*, National Petroleum Council (September 2003). Available at http://www.npc.org/.

I. Key Findings

Technology improvements play an important role in increasing natural gas supply.

During the last decade, 3-D seismic, horizontal drilling, and improved fracture stimulation have had significant impacts on natural gas production in many basins in North America. *[...]*

In addition to these step-change technologies, continued improvements in core technical areas have been implemented as a result of industry's continuing efforts to search for more cost-effective ways to find, develop, and operate oil and gas fields. This trend is especially evident in the production of unconventional gas reservoirs such as coal bed methane, shale gas, and tight sand formations. New designs in drilling bits, improved well planning, and modern drilling rigs have also lowered drilling costs in many regions. Advances in remote sensing, information technologies, and data integration tools have served to keep operating expenses in check.

As modeled in the Reactive Path scenario and illustrated in Figure S5-1, by the year 2025, advanced technologies contribute 4.0 trillion cubic feet (TCF) per year of the 27.8 TCF per year produced in the United States and Canada. This amounts to 14% of the natural gas produced during that year *[for all gas sources, not just unconventional gas].*

Adding new North American natural gas supplies will require finding, developing, and producing more technologically challenging resources than ever before.

Overall, when assessing the natural gas resources that will be found and developed over the next 25 years, they can be generally described as deeper, hotter, tighter, more remote, in deeper water and smaller, harder-to-find prospects. The combination of more difficult natural gas resources and higher prices should catalyze increased efforts in research, development, and application of new technologies by the industry and governments.

Many of the geologic plays in the Permian, Midcontinent, and Gulf Coast regions where significant resources are anticipated will tend to be deeper and consequently hotter than previously developed plays. This challenge lends itself to developing new drilling, logging, and completion equipment designed to deal with the increased depth and temperature. Also, further improvements in subsurface imaging technologies will help better locate and define the deeper reservoirs.

As more unconventional gas resources are developed, the average permeability of the producing reservoirs will continue to decrease, requiring the industry to find and apply new technologies and best practices that enable low permeable wells to produce at economic flow rates. The industry will be challenged to find methods to locate "sweet spots" in tight basin-centered gas fields, shale gas and coal bed methane reservoirs, thus reducing the number of marginally commercial wells being completed.

[...]

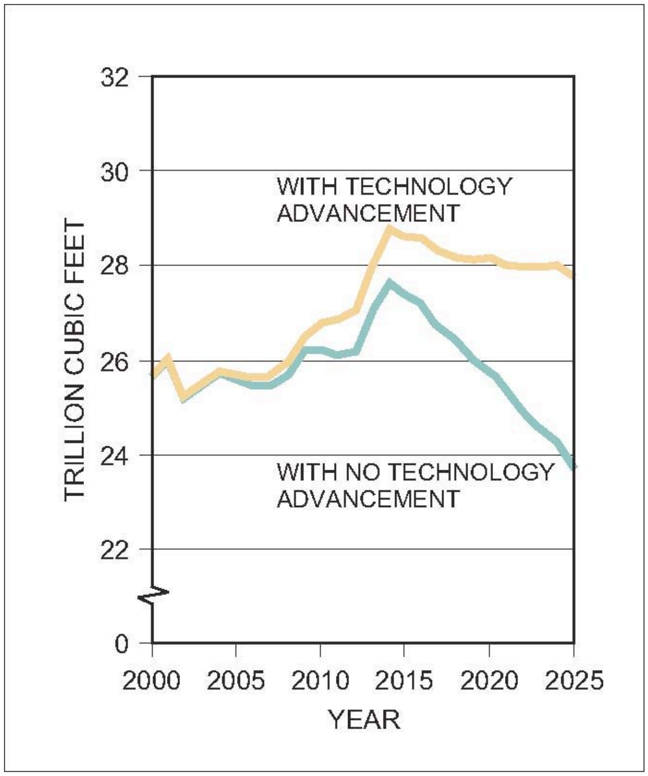

Figure S5-.1. Impact of Technology on U.S. and Canadian Natural Gas Production

Future prospect sizes are projected to continually decrease over time, according to the resources assessment efforts in the study. Advancements in 3-D seismic acquisition and interpretation will be required to locate and appraise these smaller prospects. Improved wellbore designs to drain multiple smaller reservoirs with fewer wells will also be required.

The combination of more difficult natural gas resource and sustained higher prices of natural gas should catalyze increased efforts in research, development, and application of new technologies.

Investments in research, development, and application of new technology have declined over the last 10 years.

Although it is difficult to obtain information concerning how much the total oil and gas industry spends on technology improvements focused on North America natural gas assets, over the last decade the trend in upstream research and development spending has been downward, as reported by the U.S. major energy producers through the EIA (See Figure S5-2).

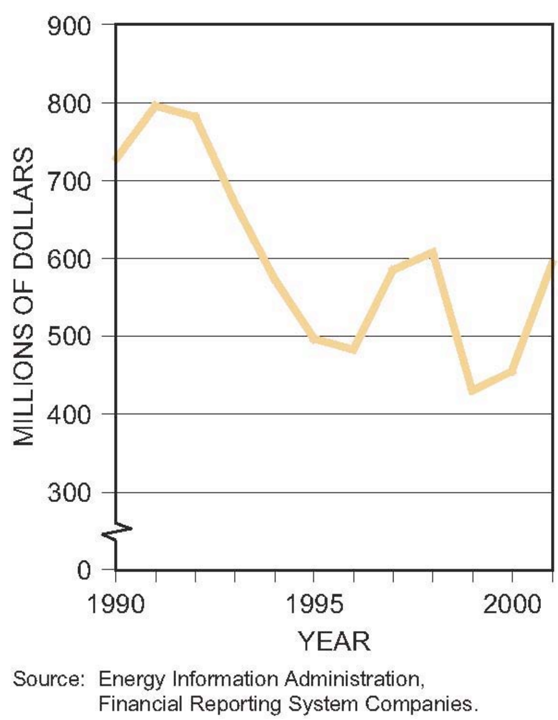

Figure S5-2. Upstream R&D Expenditure History

Forecasting future technology investment is difficult. As a result, the implication of technology improvements on production and prices are cast in terms of a range of outcomes as shown in Figures S5-3 and S5-4. The low advancement sensitivity case reflects a slower pace of technology development and application caused by reduced investment in research. The high advancement case reflects a faster pace of technology development and application. It is envisioned that the rate of which new technologies are developed and applied will fall within this range over the next 25 years.

Service industries and joint-sponsored research programs are playing an increasing role in research and development. This can be viewed as a cost-effective and less redundant method for research. It may also have the effect of slowing down the application of new technologies for the following reasons:

- Collaboration between the users (oil and gas exploration and production companies) and external developers is often not as efficient as when the research was done within the user's own company.
- Users of technologies were more apt to attempt field trials of new technologies when internally developed. Today, the service industry or sponsored research programs are required to prove the effectiveness of new technology before it is adopted by the industry. This has developed into a "Catch 22" since the service sector does not have access to the necessary field assets to conduct the tests.
- New technology is being tested worldwide, particularly where the resource quality and the technology impact are higher. As a result, more new technologies are being field tested overseas as compared to previous years when most new technologies were tried and proven in the United States. One possible exception to this would be in the deepwater regions of North America where the size and scope of these projects compare with overseas projects.

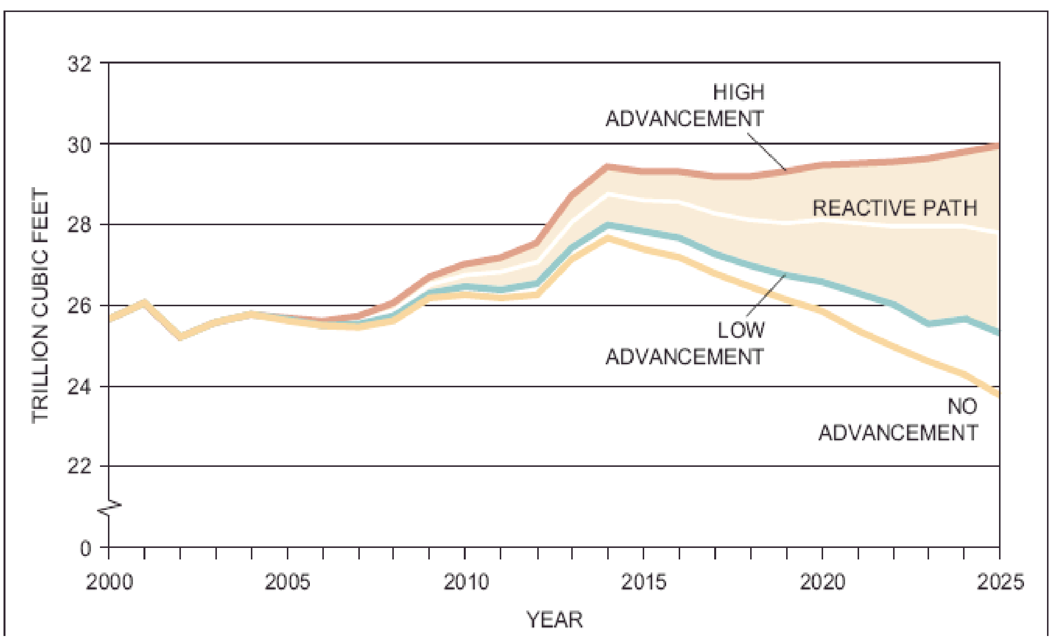

Figure S5-3. Impact of Technology Change on U.S. and Canadian Natural Gas Production

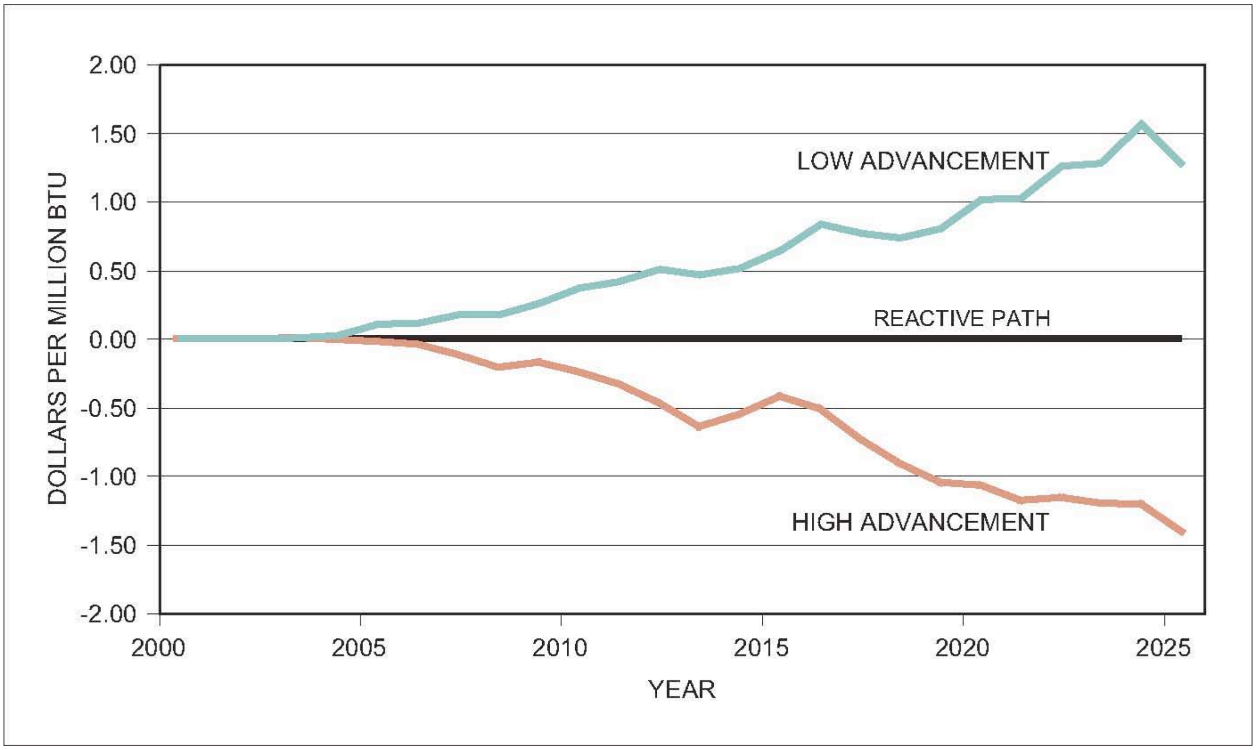

Figure S5-4. Impact of Technology Change on Price at Henry Hub (2002 Dollars)

Adding to the above, independent oil and gas E&P companies have an ever-increasing role in North American conventional and unconventional gas and are less likely to pursue far-reaching research activities than their major company counterparts. This pressures the service companies to fill the technology gap and/or causes research to gravitate toward a short-term focus. This focus impedes long-term or high-risk research, which may have a significant impact and be required for future gas supplies. In many cases, long-term or high-risk research has been relegated to joint industry and/or government-sponsored programs.

[…]

II. Defining Technology for this *[2003 NPC Gas Supply]* Study

To understand how advancements in technology impact the projected natural gas production in North America, it is important to understand how technology is defined. **For the purpose of this study, technology was defined**

broadly as any new or improved product, process, and technique that enhances the overall result compared with the current results observed today. So technology, in this definition, not only includes new "tools" being developed and applied, but also incorporates advancement on the normal learning curve as the industry becomes more experienced in any given basin or methodology.

With regard to natural gas supply, several approaches and "tools" are employed to find, develop, and produce natural gas. It would be impossible to identify every combination of approach and technology currently being applied or attempt to empirically model further advancements in each combination of approach and technology. However, by using this broad definition, the Technology Subgroup, with the aid of several experts' experience and judgment, was able to forecast improvements in various input parameters that are important to the natural gas supply model and describe it as technology improvement.

III. Technology Subgroup Process for the Study

A. Scope

The Technology Subgroup *[for the 2003 NPC Gas Supply Study]* was established to provide insights into the role and impact of upstream technology in delivering natural gas supply during the study period. Composed of thirteen members from a cross-section of industry organizations, the Subgroup established its scope to be:

- To design a methodology for measuring the impact of future technologies in the Hydrocarbon Supply Model
- To estimate the technology improvement parameters for the scenarios developed and a range of sensitivity cases
- To compose an upstream technology commentary for the final report that provides a current-state industry view of research and development, its impact on the outlook, and the role of technology in the future deliverability of North America' natural gas through the year 2025

- To recommend actions that will facilitate the use of new technologies to improve the economics and increase the deliverability of natural gas.

To achieve these goals, the Technology Subgroup scheduled a series of workshops, providing a forum to understand previous studies, provide input into the supply model, and prepare the report. In addition to the workshops, six special technology sessions were held to discuss with industry experts specific issues related to core, high-impact technology areas.

[Details on how the data were collected and analyzed by the Technology Subgroup in the 2003 NPC study, pages 5–6 through 5–7, are not included here.]

V. Projected Technology Improvements

Even with the noted technology advancements, over the last ten years investments in upstream research and development have declined and the industry has been cautious in using high-cost, high-risk technologies regardless of their potential. This reluctance is particularly evident if the technology is perceived to have a longer-term impact. With this observation and the maturity of the exploration and production environment, the Subgroup postulated that technology will play a somewhat lesser role in gas resource enhancement in the near future. Technology will gain slight momentum beyond five years as the industry invests more in technology developments, motivated by the challenges of the resources and higher gas prices. This is not intended to imply that there will not be continued improvements. Indeed, there will be continued improvements in both tools and techniques, but there are no foreseeable major breakthroughs on the horizon.

With this back-drop, the Technology Subgroup developed a series of technology improvement parameters for the Reactive Path scenario in the supply model that reflect the anticipated rate of improvement in each major core technical area of application.

Different improvement parameters were determined for each major geologic region, and in some instances, the type of reservoir, as for example coal bed methane or deep, high-temperature, high-pressure reservoirs. Also, to reflect the anticipated behavior of the industry, different improvement parameters were adopted for each of the different time periods, 2003–2008, 2009–2015, and 2016–2025+. The consensus of the members of the Technology Subgroup was that for most of the technical areas and geologic regions, the later time periods would probably see a faster pace of improvement than the early time period.

The values shown in Table S5-1 were not calculated from any theory or formula. Instead, the values were determined by the Technology Subgroup, using all available information and insights generated during the study. The parameters were based more on collective experience and intuition, than on theory. However, the Technology Subgroup agreed that the parameters seem reasonable given all of the discussions developed at the workshops and special technology sessions.

Technology Area	**% Annual Improvement ***	**% Improvement Extrapolated for 25 Years**
Improvement in Exploration Well Success Rate	0.53	14
Improvement in Development Well Success Rate	0.41	11
Improvement in Estimated Ultimate Recovery per Well	0.87	24
Drilling Cost Reduction	1.81	37
Completion Cost Reduction	1.37	29
Improvement in Initial Production Rate	0.74	20
Infrastructure Cost Reduction	1.18	26
Fixed Operating Cost Reduction	1.00	22

* These numbers reflect the average of the parameters, not the actual parameters in the supply model.

Table S5-1. Technology Improvement Parameters for the Reactive Path Scenario Supply Model

It was appropriate to also look at a range of parameters that reflect a high and low pace of technology advancement and application. The Technology Subgroup developed parameters for these two additional cases, which are provided on a CD-ROM *[that is available from the National Petroleum Council]*. Again, for the purpose of understanding the relative magnitudes and comparison between cases, these parameters are averaged and shown in Table S5-2.

Technology Area	High Pace		Low Pace	
	% Annual Improvement*	% Improvement Extrapolated for 25 Years	% Annual Improvement*	% Improvement Extrapolated for 25 Years
Improvement in Exploration Well Success Rate	0.87	24	0.08	2
Improvement in Development Well Success Rate	0.87	24	0.13	3
Improvement in Estimated Ultimate Recovery per Well	1.49	45	0.23	6
Drilling Cost Reduction	1.60	49	1.02	23
Completion Cost Reduction	- 0.83	-19	0.34	8
Improvement in Initial Production Rate	1.13	32	0.24	6
Infrastructure Cost Reduction	1.73	35	0.63	15
Fixed Operating Cost Reduction	1.52	32	0.44	10

* These numbers reflect the average of the parameters, not the actual parameters in the supply model.

Table S5-2. Technology Improvement Parameters for High Pace and Low Pace of Technology Advancement and Application

As illustrated in Tables S5-1 and S5-2, not all technologies are expected to advance and improve performance at the same pace. It is expected that technological advancements in drilling, completion, and infrastructure will decrease costs at a higher rate than the improvements in exploration success rate. The lower parameter for exploration success reflects the flattening trend in 3-D seismic technology application and advancement. Also, moderate improvements from technology are anticipated in the area of increased ultimate recovery and operating expense reduction. In the high pace case, it is anticipated that the industry will focus more on improving ultimate recovery per well, and be willing to apply more advanced and somewhat more expensive drilling and completion technologies to achieve that result. Thus, the improvement parameters for the high pace case yield higher incremental improvement in EUR per well than the incremental improvement in cost to drill and complete wells. For the low pace, the improvement parameters are generally about half of the Reactive Path scenario.

VI. Summary of Special Sessions on Technology

The insights from the special technology sessions are summarized below. Although, separate special sessions were held around specific technology areas, these technologies were discussed in an integrated fashion at the Technology Subgroup workshops in order to understand their interrelationship.

A. Coal Bed Methane

Coal bed methane (CBM) is perhaps one of the best examples of how technology can have an impact on the understanding and eventual development of a natural gas resource. While gas has been known to exist in coal seams since the beginning of the coal mining industry, only since 1989 has significant gas from coal seams been produced and sold (See Figure S5-7).

Coal bed methane is a resource that was drilled through and observed for many years yet never produced and sold. New technology and focused CBM research ultimately resolved the resource complexity riddle and unlocked the production potential. Coal bed methane now provides over 1.6 trillion cubic feet (TCF) of gas production per year in the United States. This rapid increase from essentially zero in 1989 was accomplished through concerted efforts to assess the resource and understand the many reservoir properties controlling production. New well construction technologies and methods were also developed.

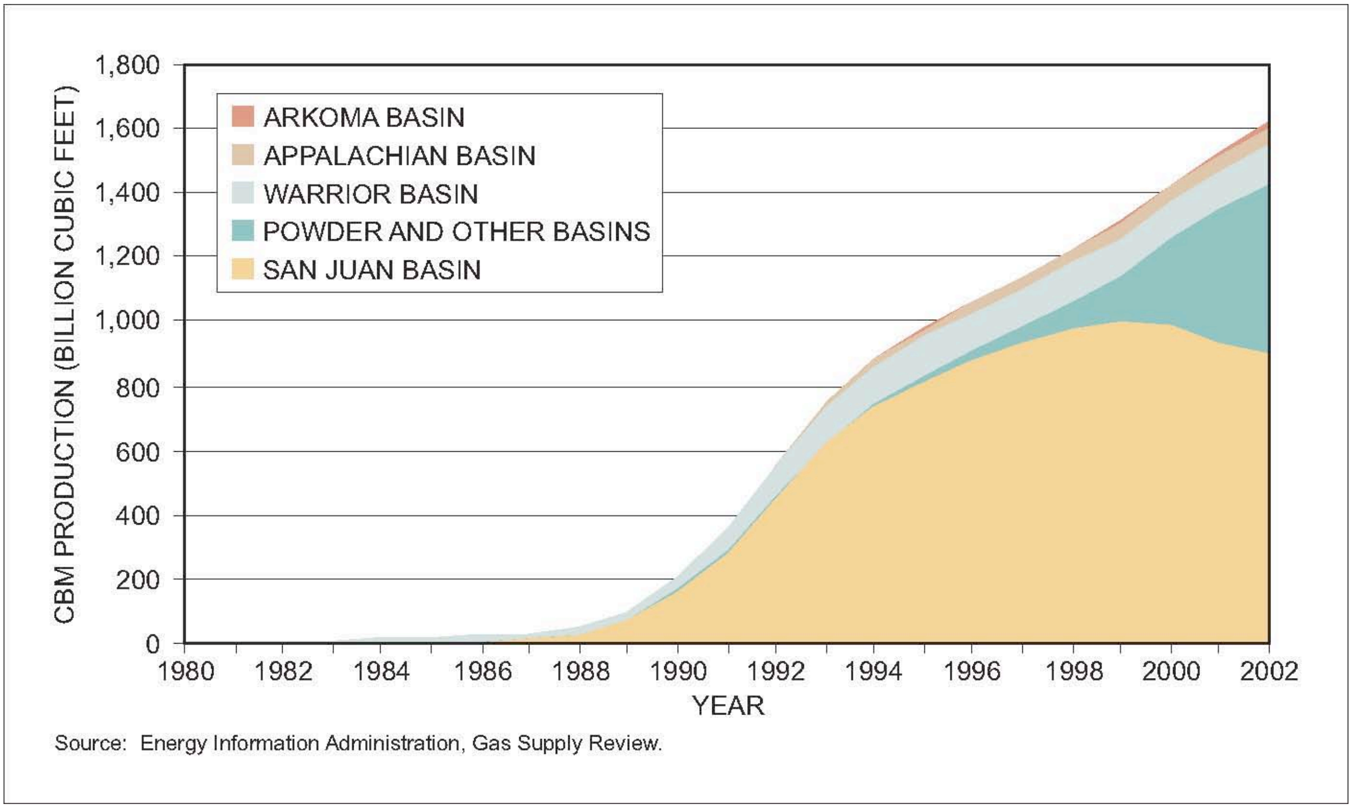

Figure S5-7. U.S. Gas Production from Coal Seams

To determine the potential and need for additional CBM technology in the future, the Technology Subgroup conducted a special session with industry experts to identify technology needs and quantify technology change over the next 25 years. Six major areas were identified as important for future CBM development (Table S5-3).

During the special session on coal bed methane, and subsequent Technology Subgroup workshops, technology improvement parameters for coal bed methane were developed for input into the supply model around coal bed methane. These parameters also apply to natural gas produced from shale formations, like the Antrim Shale in Michigan.

CBM operators in general felt that CBM technology would continue to develop at a significant pace and that technology from other oil and gas disciplines (i.e., well drilling, gas production) would continue to be effectively adapted by CBM operators. In particular, the potential for future development in Western Canada and new basins in the United States (new to the CBM industry) of better resource understanding and application of new CBM technology is believed to be significant.

Technology Area	Technology Needs
Multi-zone well completion	• Technology for construction of fishbone well patterns • Directional control within thin coal formations
Smaller well footprint	• Ability to drill and produce CBM wells on small surface locations • Technology allowing greater well spacing
Rapid technology transfer	• Information technology including use of the internet to rapidly share and disseminate best practices
Produced water technology	• Technology and understanding of issues related to changing produced water from a waste to a valued resource
Improved gas recovery per well	• More effective well stimulation techniques • Completion designs to enhance drainage • Down-hole fluid separation/injection and compression and power generation to maximize well performance
Technology integration – development planning	• A systematic approach to developing a CBM field integrating all technology needs development, including the ability to evaluate coal seams prior to completing wells • Effective methods to simulate coal bed performance

Table S5-3. Major Areas for Future Coal Bed Methane Technology Improvements

B. Drilling Technologies

The oil and gas drilling industry is currently operating in a mature environment. The equipment and procedures for drilling and producing hydrocarbons are much the same as what existed 25 to 30 years ago. In addition to promoting new drilling technology, North American drillers have directed their time and talents in capturing and implementing “drilling best practices.”

These "best practices" have made dramatic improvements in: (1) drilling safer, (2) drilling with less damage to the reservoir and less impact on the surface environment, (3) improving rig mobilization, and (4) drilling with less rotary drill time. All of these practices have improved as operators seek to lower their hydrocarbon finding cost and improve production performance of the wells.

To determine the challenges and technology needs in the area of drilling needs, the Technology Subgroup conducted a special session with industry experts to identify technology needs and quantify technology change over the next 25 years. Five major areas were identified as important in the area of drilling technologies (Table S5-4).

During the special session on drilling technologies, and subsequent Technology Subgroup workshops, technology improvement parameters were developed for input into the supply model. These parameters took into account the expected advancements in specific drilling technology areas and the forecasted behaviors of the industry based on experience from the experts attending these meetings.

Technology Area	**Technology Needs**
Rig designs to reduce "flat-time," and provide safer, environmentally friendly operations	• Small modular rigs with state-of-the-art pump equipment, automated pipe handling, and control systems • Casing drilling, coiled tubing drilling • Environmentally friendly drilling fluids • Multi-lateral with long-reach horizontal configurations to reduce number of surface locations
Deeper, high temperature/high pressure wells	• Develop drilling equipment and electronic sensors that can withstand the high temperature and pressure regimes • Expandable pipe to reduce weight and number of casing strings • Micro technologies to reduce size of equipment and allow smaller diameter wells
Deep wells drilled in deep water	• Expandable casing • Light-weight composite pipe • Dual gradient fluid systems • Lighter, smaller rigs capable of drilling in deeper water at greater depths

Low recovery wells	• Multi-lateral to increase effective drainage • More durable, high penetration rate drill bits for harder rock formations • Laser drilling
High cost exploration wells	• Micro technologies to reduce wellbore diameter requirements • Down-hole sensors for real-time measurements while drilling and steerable drilling

Table S5-4. Major Areas in Drilling Technologies

C. Well Completion Technologies

Well completions are a key step in the success of oil and gas production. A wide range of technologies and practices are associated with well completions. The trends of future wells will be deeper, more complex and in harsher environments. These trends will require more complicated completions over time. From the discussions at the sessions, five technology areas concerning well completions appear to be the focus of the industry to improve natural gas supply. These areas and their corresponding technology needs are summarized in Table S5-5.

During the special session on well completion technologies, and subsequent Technology Subgroup workshops, technology improvement parameters were developed for input into the supply model. These parameters took into account the expected advancements in specific well completion technology areas and the forecasted behaviors of the industry based on experience from the experts attending these meetings.

Technology Area	Technology Needs
Improved recovery efficiency	• Improved stimulation technologies for higher initial production and more effective drainage • Multi-lateral and multi-zone completion technologies to maximize recoveries with fewer wells • Real time bottom-hole measurements to monitor well and reservoir performance • Improved perforating technologies for deeper, more-effective penetrations • Down-hole controls to prevent water influx • Down-hole fluid separation/injection and compression and power generation to maximize well performance
Deeper, high temperature/ high pressure wells	• Completion equipment and electronic sensors that can withstand the high temperature and pressure regimes • Expandable pipe to allow for larger bottom-hole production equipment without adding number of casing strings • Drilling and frac-fluids that maintain their properties at high temperatures
Deep wells drilled in deep water	• Expandable casing • "Smart well" technologies to enable the multi-zone completion and controls while preventing costly future well intervention
Tight sands	• Improved fracture stimulation
Low recovery wells from small pools, thin sands, low porosity	• Technologies focused on reducing cost per mcf • Bottom-hole compression increase production of low pressure reservoirs • Multi-lateral, steerable, extended reach wells to maximize reservoir wellbore exposure to the reservoir

Table S5-5. Major Areas in Well Completion Technologies

There will continue to be counter-forces in play as completion technologies are developed and applied. For example, smaller pool sizes and more severe subsurface environments will drive the industry to reduce completion cost, yet the desire to maximize well recoveries and extend the reliability of the well will drive completion costs up. The industry will continue to address these issues by evaluating the overall value proposition of the additional costs associated with the more advanced wellbore designs. It is anticipated that these new approaches to wellbore completions and designs will gain more acceptance over time, with more experience and as the value is realized. These concepts are assumed in developing the parameters for the high technology advancement sensitivity case in the model where higher rates of improvement in well recoveries are realized with only moderate improvements in drilling and completion costs.

D. Subsurface Imaging Technologies

The current view of the seismic industry can best be characterized as a paradox. The field is rich with significant new ideas concerning acquisition hardware, processing, and interpretive technologies. The industry has realized significant contributions from 3-D seismic technologies.

[…]

[…] there is no shortage of ideas on how to improve seismic technology for both exploration and production applications. If implemented, these enhancements could further reduce the risk in drilling (currently at approximately 40% success rate), improve our ability to differentiate hydrocarbon strata in the subsurface, and monitor the effectiveness of our resource extraction plans. These technology areas and needs were discussed at the special session on subsurface imaging and are highlighted in Table S5-6.

The improvement parameters developed for the model and sensitivity cases are provided on the CD-ROM. Again, they reflect a more conservative view on the industry's ability to improve success rates of exploration and development wells, based on the above discussions.

The industry is still waiting for the next technology breakthrough of the magnitude the industry experienced when 3-D seismic became available. It is unclear what the next major technology breakthrough will be. One possible breakthrough would be the ability to accurately detect "sweet spot" areas of unconventional gas plays which are typically found by pattern drilling. By finding these sweet spots ahead of drilling, the number of poor performing, sub-economic wells would be reduced, thus improving the overall economics of the program and creating an incentive for more participation. It would also reduce the overall number of wells/drill-sites in a given geologic region, yet maintain the same overall recovery. This would create a more environmentally attractive development plan.

Technology Area	Technology Needs
Seismic data acquisition and resolution	• Lower cost and less destructive approaches to acquiring seismic data • Further advances in data management to reduce costs • Ability to obtain seismic data while drilling • Single sensor recording to improve resolution and accuracy of the data
Interpretation	• Further enhancements in pre-stack depth migration to enhance the seismic images • Increased computational technologies to apply advance interpretation methods • Multi-component imaging to identify fluid properties in the reservoir • Method to identify "sweet spots" in unconventional gas plays
Reservoir monitoring	• Further enhancement of 4-D technology to find un-depleted areas of the reservoir • Permanent sensors for real-time measuring and reservoir monitoring
Integration with other technologies	• Ability to quickly integrate seismic information with earth and reservoir models to provide quick visual images to multi-disciplined teams for better decision-making approaches • Advanced visualization technologies to better understand the reservoir and create the digital gas field of the future

Table S5-6. Major Areas in Subsurface Imaging Technologies

[…]

IX. Summary Issues and Challenges

Several issues and challenges will face the North American petroleum industry and governments as they pursue research, development, and application of new technologies to enhance the supply of natural gas.

Although many of the North American producing basins are maturing, significant technically recoverable resources still remain. However, their declining reserves and economics will make it difficult to justify major investments in new technology. Independent companies, which will play an increasing role in these mature basins, will have to increase collaboration with the service industry to fund and support the required technology development.

Industry must also speed up the acceptance and utilization of new technology. Having many producers spread across North America creates a challenge to efficient and effective technology collaboration due to competitive pressures. The shift toward more collaborative research increases the difficulty of testing and deploying new technologies. Professional societies, trade associations, academic and government research institutions, along with the industry will need to increase efforts to communicate and work together to deploy new applications.

Another challenge will be to effectively transfer the knowledge and replace the experience of the existing professional workforce to the new generation entering the industry and research institutions. Otherwise, the risk of "reinventing the wheel" will loom over the industry.

With the expected tight supplies of natural gas, potentially higher prices, and ever increasing technical challenges, the petroleum industry, research institutions, and governments need to quickly put in place strategic plans to respond to these challenges.

VII. Appendix A: Unconventional Gas Industry Workshop Technology Needs Assessments–Canadian Producers

Technology Challenges	Coalbed Methane	Tight Gas	Shale Gas	Gas Hydrates
Geosciences and Resource Characterization				
Advanced logging tools	♦	♦	♦	♦
Core sampling and measurement procedures	♦	♦	♦	♦
Permeability and fracture mapping	♦	♦	♦	
Real-time drilling data acquisitions	♦	♦	♦	♦
Better “sweet spot” identification	♦	♦	♦	♦
Reservoir characterization “tools”	♦	♦	♦	♦
Review public data with “new eyes”(data mining)		♦	♦	
Identification of “free gas” versus shale gas		♦	♦	
Kinetics of description	♦		♦	
Modeling				
Fracture modeling	♦	♦	♦	
Modeling heterogeneity of reservoir scale		♦		
Full 3D reservoir models	♦	♦	♦	♦
CH_4/CO_2 interaction of enhanced recovery via substitution	♦			♦
Reliable forecasting models for project life estimates	♦	♦	♦	♦
Drilling				
Specialized drilling practices	♦	♦	♦	♦
Specialized drilling fluids	♦	♦	♦	
Drill bits for less wellbore damage	♦	♦		
Application of coiled tubing	♦	♦	♦	
Slim hole tools	♦	♦	♦	♦
Horizontal and directional drilling technology	♦	♦	♦	♦

Multi-lateral drilling	♦	♦	♦	
Real time data gathering while drilling	♦	♦	♦	♦
Application of reserve circulation drilling	♦	♦		
Specialized under-balanced drilling	♦	♦	♦	
Borehole stability	♦			♦
Analysis of cuttings		♦	♦	
Arctic drilling				♦
Low cost observation wells				♦

Table VII.1. Assessment of technology needs from Canadian producers. Workshops conducted by Petroleum Technology Alliance Canada (PTAC); October 2005.

Technology Challenges	Coalbed Methane	Tight Gas	Shale Gas	Gas Hydrates
Completion and Stimulation				
Cementing technology	♦	♦	♦	
Stimulation technology and fracture fluids	♦	♦	♦	♦
Fracturing in horizontal wells	♦	♦	♦	
Proppants and applications	♦	♦		
Application of $C0_2$-enhanced recovery	♦			♦
Re-fracturing technology		♦		
Geo-mechanical issues from hydrate breakdown				♦
Lift Mechanisms				
Downhole pump plugging from coal fines	♦			
Pumping in varying water, gas, or hydrocarbon regimes	♦	♦	♦	♦
Downhole pumping systems	♦			
Downhole water re-injection	♦	♦		
Downhole compressors	♦	♦	♦	
Surface Infrastructure				
Low volume gas and water measurement	♦	♦	♦	
Low pressure gathering systems	♦	♦	♦	
Low noise compression	♦			
Low rate multi-phase meters	♦	♦	♦	
Special means for gas transport from gas hydrate reserves (e.g. pellets)				♦
Other technology gaps with environmental drivers are listed in Appendix B				

Table VII.2. Assessment of technology needs from Canadian producers. Workshops conducted by Petroleum Technology Alliance Canada (PTAC); October 2005.

VIII. Appendix B: Unconventional Gas Industry Workshop Technology Needs Assessments–U.S. Producers (Houston, Denver, and Pittsburgh)

Summary Topic	Total Votes	Industry Votes	Others
Integrated reservoir characterization–geologic, seismic, engineering, petrophysical, and reservoir size (scale) issues	15	8	7
Understanding the physics behind operations	15	10	5
Formation evaluation in shales, coals, carbonates, etc.	11	8	3
Net pay identification	10	7	3
Completing in low-pressure gas sands	8	3	5
Reducing cost—e.g. drilling improvements	6	4	2
Unloading and lifting technologies	6	5	1
Deep CBM, high-pressure, high-temperature gas sands	5	4	1
Production optimization	5	3	2
Microhole technology, production, exploration, and near surface extension reach	5	4	1
Effect of natural fractures on reservoir properties	5	3	2
Production analysis in stacked reservoirs	4	2	2
Genesis and preservation of natural fracture systems	3	2	1
Low-cost cased hole pressure evaluation	2	2	0
Evaluation of well logs	0	0	0
Totals	100	65	35

Table VIII.1. Houston workshop for unconventional technology needs; July 2005.

Summary Topic	Total Votes Received	Industry Votes	Other
Data collection and availability	18	11	7
Predictability of production	15	10	5
Advanced well construction	15	10	5
Basin-scale petroleum systems studies	15	8	7
Environmental and land access	14	6	8

Resource assessment	13	7	6
Field-based testing	12	7	5
Best practices	3	1	2
Technology transfer	0	0	0
Totals	105	60	45

Table VIII.2. Denver workshop for unconventional technology needs; August 2005.

Summary Topic	Total Votes Received	Industry Votes	Others
Reservoir, resource, and play characterization	12	4	8
Resource assessment	12	3	9
Database compilation	12	3	9
Production prediction and optimization	10	4	6
Stimulation technology	7	2	5
Manpower development	5	4	1
Re-working old wells	4	2	2
Operational limitations	3	2	1
Energy economics	3	1	2
Access to resources	1	0	1
Infrastructure	1	0	1
Best practices	0	0	0
Gas processing	0	0	0
Produced water	0	0	0
Impact of past innovations	0	0	0
Totals	70	25	45

Table VIII.3. Pittsburgh workshop for unconventional technology needs; August 2005.