NATIONAL ENERGY TECHNOLOGY LABORATORY

Multi-Seam Well Completion Technology Implications for Powder River Basin Coalbed Methane Production: 2008 Update

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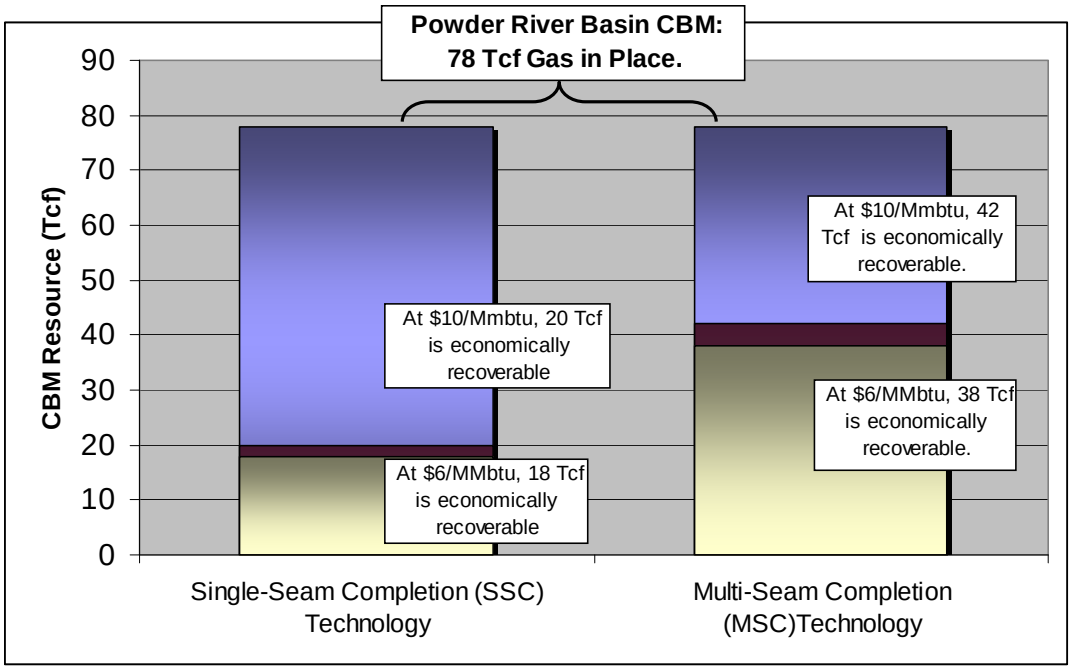
EXECUTIVE SUMMARY

The Powder River basin holds a large domestic natural gas resource, 78 Tcf of coalbed methane gas in-place, based on our latest assessment. However, only a small portion, 18 to 25 Tcf of this large in-place resource, under the natural gas prices used in this study, will be economically recoverable with currently used single seam well completion technology (SSC Technology). This technology, by economic necessity, bypassed much of the CBM resources held in the numerous thinner coal seams common to the Powder River Basin.

Successful application of multiple seam well completion technology (MSC Technology) would increase the economically recoverable portion of this large in-place resource to 38 to 42 Tcf, depending on natural gas prices, Figure EX-1. (The study used a natural gas price range of $6 to $10 per MMBtu, Henry Hub spot price). Even should the application of MSC Technology be less than optimum, achieving only 80% of theoretical efficiency, it would add significant volumes, 27 to 33 Tcf, of economically recoverable coalbed methane to domestic natural gas supplies.

Figure EX-1. Comparison of SSC and MSC Technology in the Powder River Basin



Given the significantly larger economically recoverable resource producible with MSC Technology, the benefits of successful development and application of the technology are compelling. In addition to adding 18 to 20 Tcf of affordable domestic natural gas supply, the use of MSC Technology would increase tax and royalty revenues to the states of Montana and Wyoming as well as to the Federal Treasury, as set forth below:

- Severance/Ad Valorem Taxes. Successful application of MSC Technology in the Powder River Basin would provide $21 to $39 billion in severance/ad valorem tax revenues, an increase of $13 to $21 billion over continued use of SSC Technology.
- Royalty Payments. Similarly, successful application of MSC Technology in this CBM basin would provide $18 to $34 billion in royalty revenues, an increase of $9 to $13 billion over continued use of SSC Technology.

Table EX-1: Tax and Royalty Payments Under SSC & MSC Technologies

	Tax and Royalty Revenues ($ billions)		
Payment	**SSC Technology**	**MSC Technology**	**Difference**
Severance/Ad Valorum Taxes	$18	$39	$21
Royalty Payments	$21	$34	$13

In addition, the states and the Federal Government would receive additional corporate income taxes as well as important economic stimulus and jobs from the increased level of investment and development resulting from successful application of MSC Technology in the Powder River CBM Basin.

However, despite successful application of multiple coal seam completions in other coal basins, attempts at using MSC Technology in the Powder River Basin have been disappointing. In some cases, a CBM well looking to connect and jointly produce three or four coal seams has actually produced less gas than a well completion in just one of these coal seams. In general, these multi-seam well completion projects have achieved less than 50% of their theoretical performance potential.

However, the technical problems inherent to using MSC Technology for more efficiently producing CBM from the Powder River Basin are not, in our view, unsolvable. The experience in the Warrior Basin of Alabama, where the Gas Research Institute established their multi-seam field research laboratory, provides one example of success. The experience in the Surat Basin of Eastern Australia, where several years of sound and diligent technical efforts enabled producers to link a series of thin coals, provides another. The challenge is to capture the "lessons learned" from these successes and adapt them to the geologic and reservoir conditions unique to the Powder River Basin.

It is the purpose and hope that this updated assessment of the potential benefits of applying MSC Technology provides motivation for launching a rigorous multi-seam well completion technology improvement program in the Powder River Basin.

SECTION 1. STUDY PURPOSE, APPROACH, FINDINGS

1.1 Study Purpose

The purpose of this study for U.S. DOE/NETL is to re-evaluate the feasibility and benefits of applying advanced coalbed methane (CBM) field development technology - - Multi-Seam Well Completion (MSC) Technology - - to the massive stack of low rank coals in the Powder River Basin. As such, this study is an update of previous work done for NETL in 2003, as published in the report - - *Multi-Seam Well completion Technology: Implications for Powder River Basin Coalbed Methane Production* (DOE/NETL 2003/1193). For this, the current study addresses the following tasks:

- Estimate how much additional CBM resource would become technically accessible and recoverable via MSC Technology, compared to single-seam well completion practices;
- Assess how the economics of CBM development in the Powder River Basin would improve, with timely development and implementation of MSC Technology; and
- Examine why past attempts by Powder River Basin operators to use multi-seam well completion technology, adapted from other basins, have experienced difficulties.

This study builds on the above cited 2003 study as well as the report “Powder River Coalbed Methane Development and Produced Water Management Study” (DOE/NETL-2003/1184) prepared by Advanced Resources International. These two reports contain many of the key references that underlie this current study.

1.2 Current Status of CBM Development

The Powder River Basin CBM play is located in northeastern Wyoming and southeastern Montana, Figure 1-1. The CBM play covers 12,000 square miles and encompasses parts of seven counties in two states. The coalbed methane is contained in Tertiary-age Fort Union Formation coal seams, such as the Anderson, Wyodak, Big George and deeper coals.

Although the basin's potential as a large CBM resource was recognized more than two decades ago, its low-rank coals discouraged development. By the mid-1990s however, the geology and reservoir properties of the Powder River Basin CBM play were beginning to be understood and activity surged. Over the past decade, development first increased dramatically and then reached a plateau, as issues over acceptable produced water management practices limited new well drilling. Since the end of 2007, growth in CBM production has resumed and is now, mid-2008, at 1.3 Bcfd. To date, 3.1 Tcf of CBM has been recovered from this basin, Figures 1-2 and 1-3.

Within the basin, CBM development is moving westward, toward the deeper basin center from the shallower coals on the eastern edge of the basin. Much of recent drilling has been in the Big George fairway, located predominantly in the central areas of the Powder River Basin (PRB), Figure 1-4.

In spite of the PRB's large CBM resource potential, numerous barriers exist that impede the effective recovery and production of this resource. Of particular note, as identified by our analysis, is that a significant portion of the gas in-place in the basin is being bypassed due to lack of efficient multi-seam completion technology.

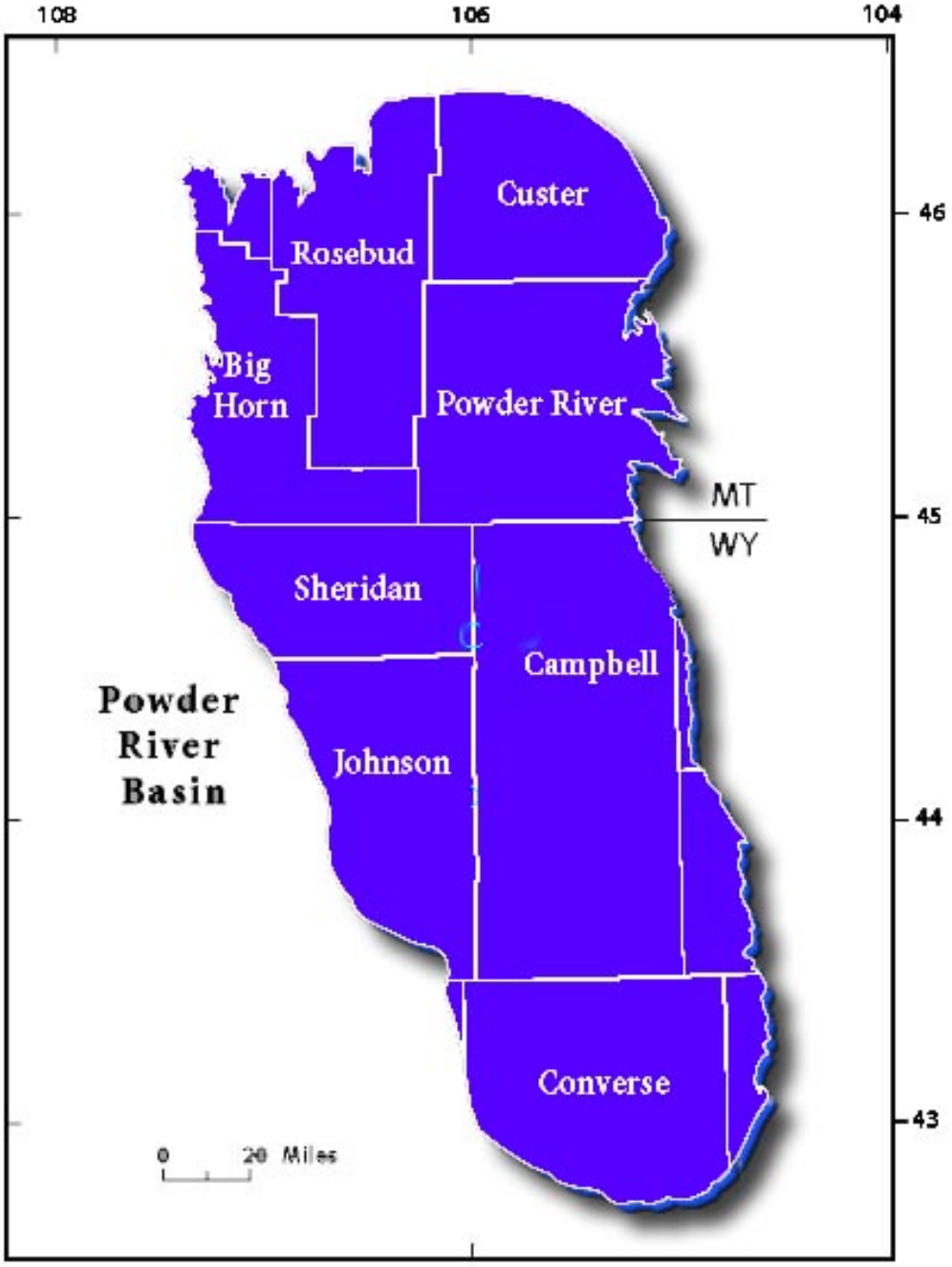


Figure 1-1. Outline and Location of the Powder River Basin.

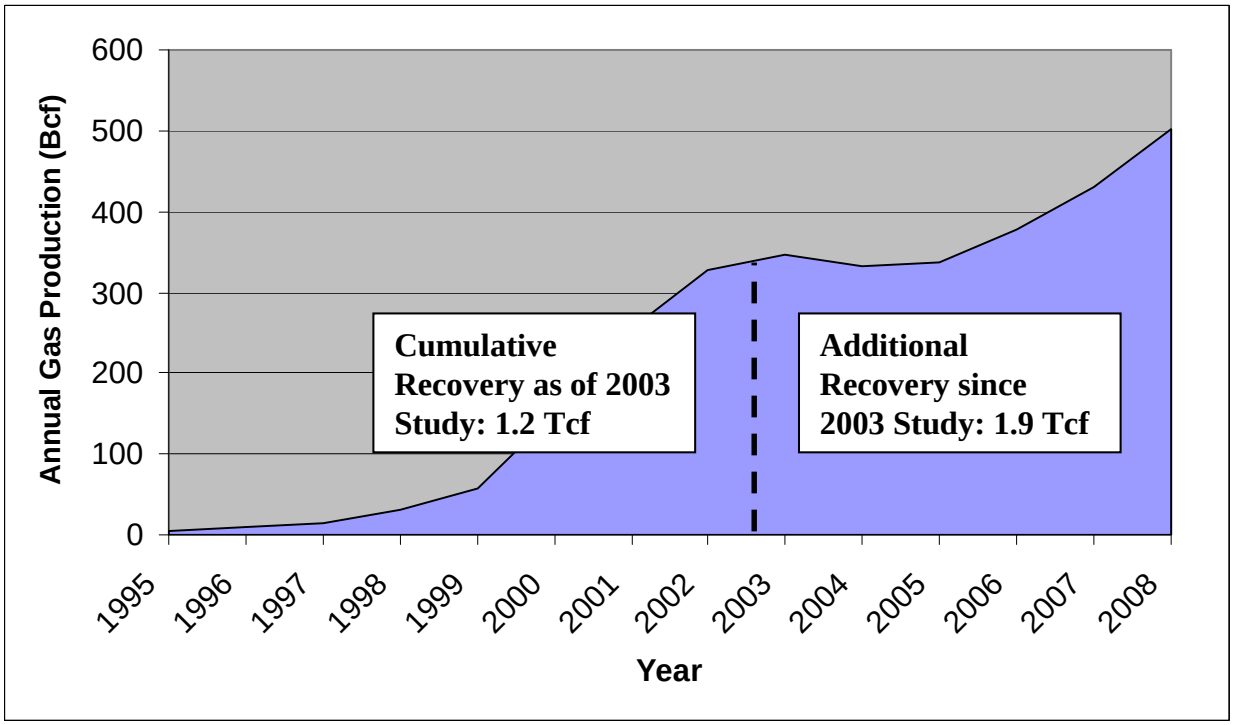


Figure 1-2. Annual CBM Production in the Wyoming PRB

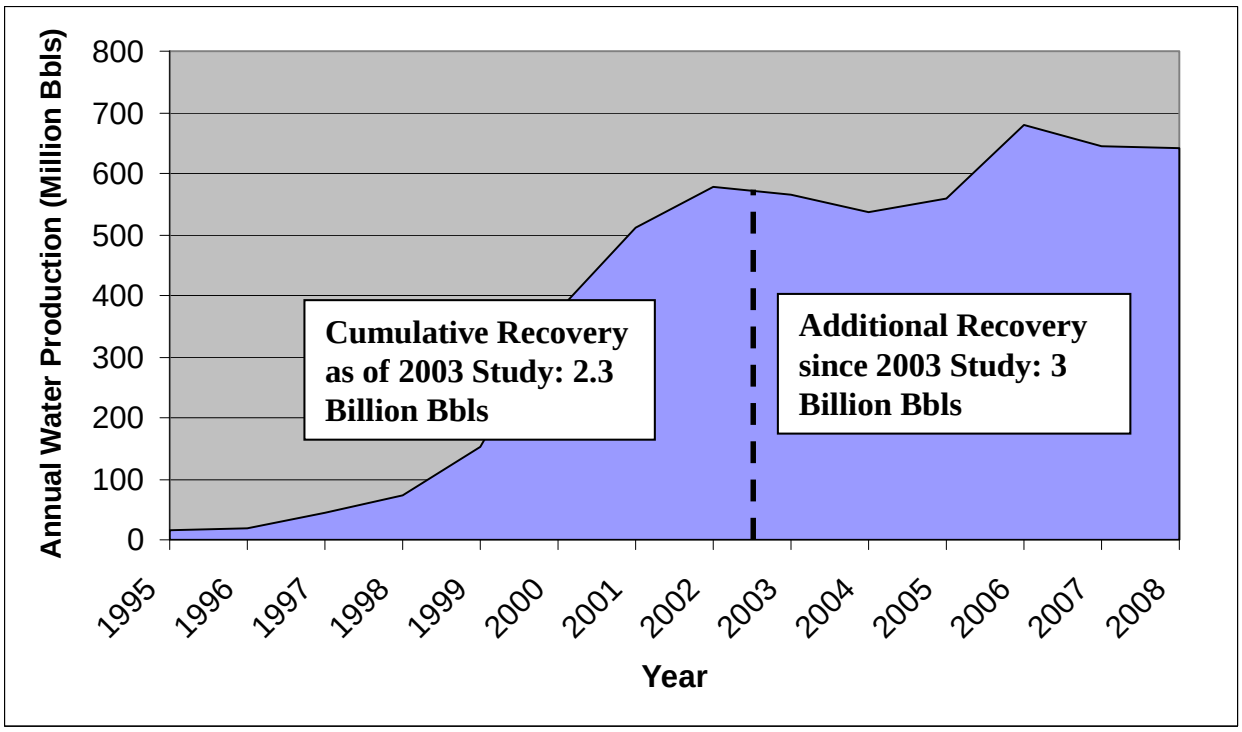
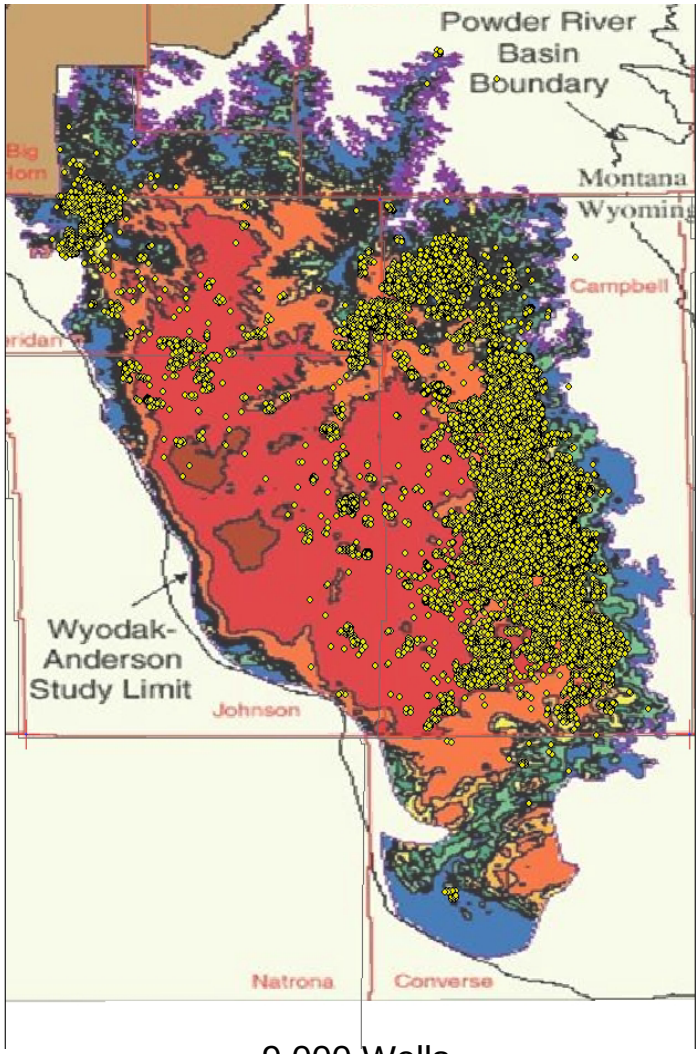


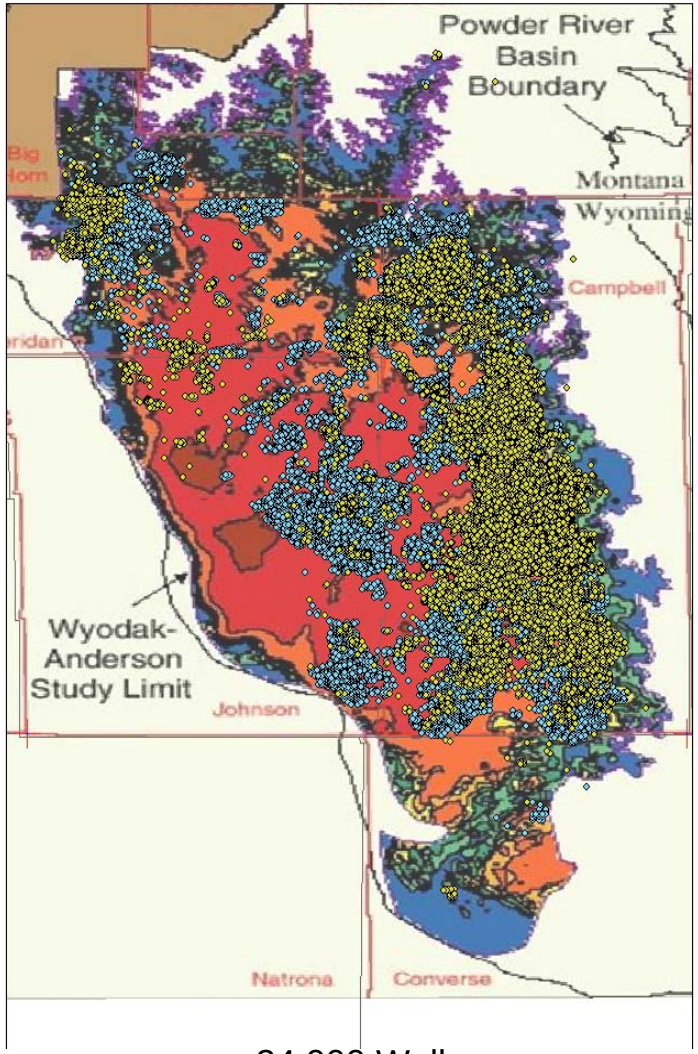
Figure 1-3. Annual Water Production in the Wyoming PRB

2003 Report



9,000 Wells

Present Report

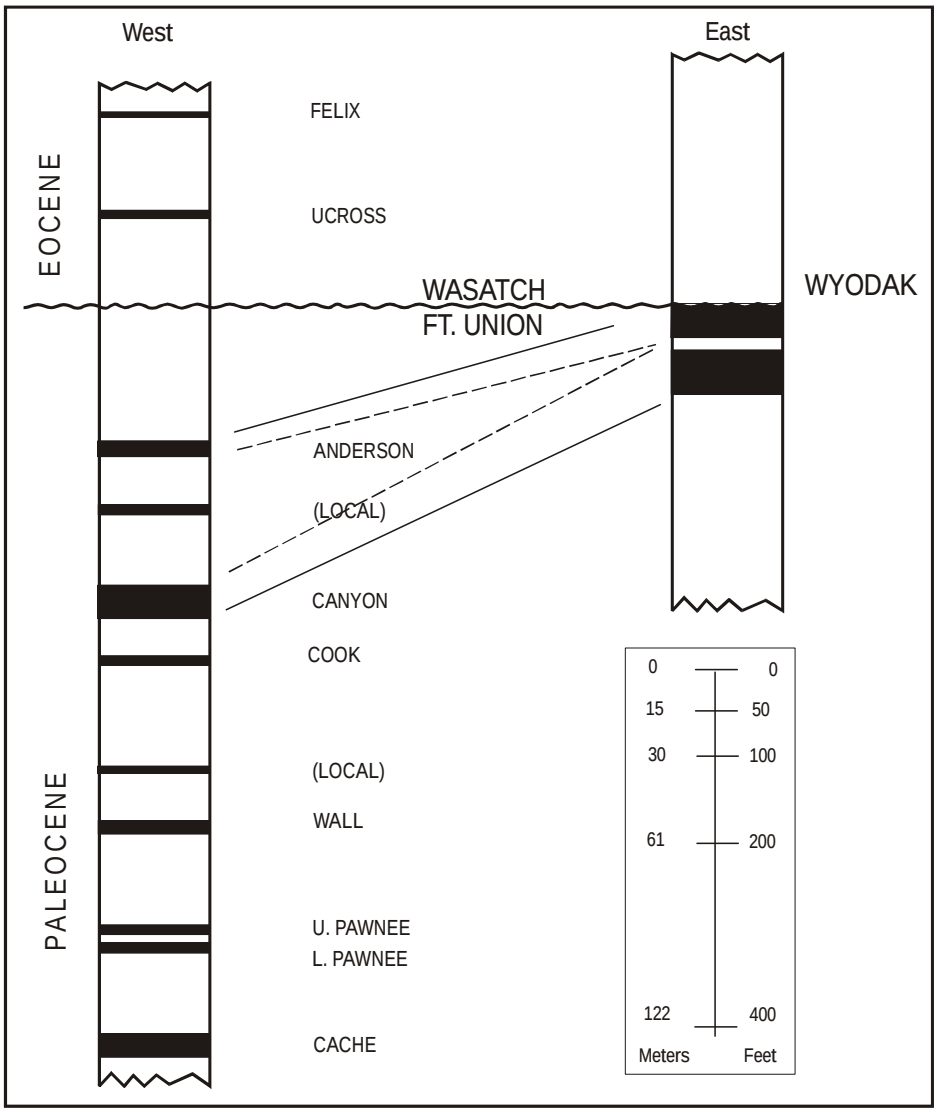


24,000 Wells

Figure 1-4. Location of CBM Drilling Activity within the Powder River Basin.

In the past, low drilling costs in the shallow, thick, easy-to-reach coal seams along the eastern edge of the basin provided favorable economic returns. With the depletion of these more favorable areas, development has moved toward the deeper and thinner coals in the central and northern portions of the basin, Figure 1-5. Here, currently used single-seam well completion technology, which bypasses the thinner seams and links the well with only one coal seam, will no longer be adequate.

Figure 1-5. E-W Cross-Section Showing Splitting of the Thick Wyodak Coal Seam into Thinner Coal Units Toward the West



Management of produced CBM water in the Powder River Basin poses another barrier that has been a most visible topic of late. In the arid West, water is a valuable resource and its prudent management is important. Significant volumes of water must be pumped from a coal seam to depressurize the coal and allow gas desorption to begin. While much of the CBM water in the Powder River meets US EPA guidelines for irrigation and stock watering, several areas do not. These areas will need to consider water management options such as reinjection or treatment, which will add costs to CBM development in this basin.

1.3 Importance of Multi-Seam Completion (MSC) Technology

One of the most effective means for improving the future outlook for coalbed methane in The Powder River Basin is developing advanced multi-seam well completion (MSC) technology, enabling producers to link multiple coal seams (including thin seams) with a single well. Under current practices, a CBM well targets a single coal seam with at least 20 or more feet of thickness. A thinner seam by itself simply does not contain enough gas to make an economic well. However, if several seams could be completed with a single well, CBM reserves would be significantly increased while adding little to drilling and completion costs.

CBM operators in the Powder River Basin have long recognized the potential utility of MSC Technology. Several operators have highlighted areas where such technology would be advantageous or even vital for further development, as shown on Figure 1-6. Unfortunately, because of the unique geological and reservoir properties of Powder River Basin geology, the application of MSC Technology transferred from other

CBM basins has not been successful. Details of these initial attempts to produce multiple coals are discussed in more detail in Section 3.

Set forth below are four specific examples of how MSC technology could provide significant benefits to the production of additional economic reserves of coalbed methane from the Powder River Basin:

- In **Example #1**, a series of thinner uneconomic, coals are jointly completed to make an economic CBM well. In Township 53N 74W, the Smith, Swartz and Anderson seams are either too thin or do not contain enough gas to be economically recoverable with SSC Technology. By linking these seams with MSC technology (Completion Package 1) it becomes possible to produce 60 Bcf of economic CBM resource from this area, Table 1-1.

- In **Example #2**, two economic seams are completed with the same well to reduce capital expenditures while cutting the required number of CBM wells in half. Township 53N 74W contains two thick coal seams, the Canyon and the Cook. Using SSC technology to produce from these seams in this township would require a capital investment of $0.90/Mcf. By completing both seams with a single well, MSC Technology would reduce the capital investment costs of accessing this CBM resource to $0.51/Mcf, Tables 1-2 and 1-4 below.

- In **Example #3**, several thin coal seams that are bypassed under present practices are completed along with a currently economic thicker coal seam to increase reserves per well while adding relatively little to capital costs. In Completion Package 3 in Township 53N 74W, the economic Pawnee seam is surrounded by the thin Wall, Lower Pawnee and Cache coal seams. MSC Technology is able to link these three thin seams with the Pawnee seam, adding 118 Bcf of economically recoverable gas from this township, Table 1-3.

- In **Example #4**, an area containing only “thin” coals is made economic by completing up to four seams in one CBM well. This case is of particular importance in the northern portions of the PRB play with numerous thin coal seams. Without MSC Technology, these areas would remain undeveloped. In Township 56N 78W, the Anderson, Canyon, Cook and Lower Cook seams are too thin to be completed using SSC technology. By completing all four seams with a single well, MSC Technology would make the 68 Bcf of CBM resource in these coal seams economic to produce, Table 1-5.

Table 1-1. Comparison of SSC and MSC Technology Performance (Completion Package 1), Township 56N 74W

	Single Seam Completion				Multi-Seam Completion		
Single Coal Seams	**GIP (Bcf)**	**Technically Recoverable (Bcf)**	**Economically Recoverable**		**GIP (Bcf)**	**Technically Recoverable (Bcf)**	**Economically Recoverable**
Smith	16	8	Thin		16	8	Yes(35% IRR)
Swartz	41	21	No		41	21	
Anderson	60	31	No		60	31	
Total	101	52	0		**117**	**60**	**60**

Table 1-2. Comparison of SSC and MSC technology Performance (Completion Package 2), Township 56N 74W

	Single Seam Completion				Multi-Seam Completion		
Single Coal Seams	**GIP (Bcf)**	**Technically Recoverable (Bcf)**	**Economically Recoverable**		**GIP (Bcf)**	**Technically Recoverable (Bcf)**	**Economically Recoverable**
Wall	35	28	Thin		35	28	Yes (86% IRR)
Pawnee	149	123	Yes (47% IRR)		149	123	
L. Pawnee	69	57	Thin		69	57	
Cache	40	33	Thin		40	33	
Total	**149**	**123**	**123**		**293**	**241**	**241**

Table 1-3. Comparison of SSC and MSC Technology Performance (Completion Package 3), Township 56N 74W

	Single Seam Completion				Multi-Seam Completion		
Single Coal Seams	**GIP (Bcf)**	**Technically Recoverable (Bcf)**	**Economically Recoverable**		**GIP (Bcf)**	**Technically Recoverable (Bcf)**	**Economically Recoverable**
Canyon	76	53	Yes (43% IRR)		76	53	Yes (123% IRR)
Cook	99	76	Yes (64% IRR)		99	76	
Total	**175**	**129**	**129**		**175**	**129**	**129**

Table 1-4. Comparison of SSC and MSC Well Capital Costs in T53N 74W

	Single-Seam Well			Multi-Seam Well
	Canyon	**Cook**	**Total**	**Completion Package 2**
Land Costs & Permits	$ 13.00	$ 13.00	$ 26.00	$ 13.00
Drilling and Completion	$ 122.38	$ 146.96	$ 269.34	$ 158.24
Lease Equipment	$ 11.28	$ 11.28	$ 22.56	$ 11.28
Gas/Water Gathering	$ 24.29	$ 24.29	$ 48.58	$ 24.29
G&A	$ 17.13	$ 19.59	$ 36.72	$ 20.71
Total Capital Costs	$ 188.08	$ 215.12	$ 403.20	$ 227.52
EUR (MMcf/Well)*	185	262	447	447
F&D Cost ($/MCF)**	$ 1.02	$ 0.82	$ 0.90	$ 0.51

* Estimated Ultimate Recovery (EUR) assuming 288 wells drilled per township (80 acre spacing)
** Finding and Development (F&D) costs are equal to the well capital costs divided by the EUR/well

Table 1-5. Comparison of SSC and MSC Technology Performance, Township 53N 74W

	Single Seam Completion			Multi-Seam Completion		
SSC	**GIP (Bcf)**	**Technically Recoverable (Bcf)**	**Economically Recoverable**	**GIP (Bcf)**	**Technically Recoverable (Bcf)**	**Economically Recoverable**
Anderson	23	12	Thin	23	12	Yes(79% IRR)
Canyon	34	24	Thin	34	24	
Cook	42	32	Thin	42	32	
L. Cook	37	29	Thin	37	29	
	-	-	-	**99**	**68**	**68**

1.4 Study Approach and Methodology

Advanced Resources undertook eight tasks to evaluate the impacts and benefits of using Multi-Seam Well Completion Technology in the Powder River Basin. Specifically, we:

1. Updated the township-level database for all coal seams in the Powder River Basin. This involved:
   - Analyzing over 200 new well logs (in addition to the 270 previously analyzed) from the Powder River Basin (PRB) CBM play area, Figure 1-7,
   - Rigorously updating our database of thin coals (with thicknesses of 5 to 20 feet), including providing depth, stratigraphic interval and areal extent data for these coals, and
   - Stratigraphically correlating the newly added thin coal seams with ARI's existing PRB coal seams database.

2. Established new optimum packages of coal seams, including thin and thick seams, for development with Multi-Seam Completion Technology.

3. Developed new gas content and methane adsorption isotherms from recently completed USGS and industry studies specific to the Powder River Basin, as shown on Figure 1-7.

4. Applied seam by seam coal reservoir properties and created over 30 unique well production profiles called "type wells." A "type well" is a production profile of a typical well producing from a given coal seam and area. By adapting a "type well" to the specific depth and coal thickness in a given area, it can be used to determine how much CBM and water a well in that area will produce.

5. Collected updated cost data on multi-seam well completions and water management practices from vendors and producers, and incorporated this data into ARI's existing Powder River cost model.
6. Ran ARI's economic model (CBM-ECON) under the following assumptions and scenarios:
   - A Base Case long-term (flat) price track of $8.00/MMBtu (Henry Hub, spot),
   - Alternative long-term price assumptions of $6.00 and $10.00/MMBtu, and
   - SSC Technology, optimum MSC Technology and sub-optimum MSC Technology.

7. Canvassed operators on the use and performance of MSC Technology in the Powder River Basin, updated the three in-depth MSC Technology case studies that were performed in the 2003 report and added additional MSC Technology case studies to the report.

8. Prepared a report summarizing our technical and economic assessment of Powder River Basin CBM development under SSC and MSC Technology.

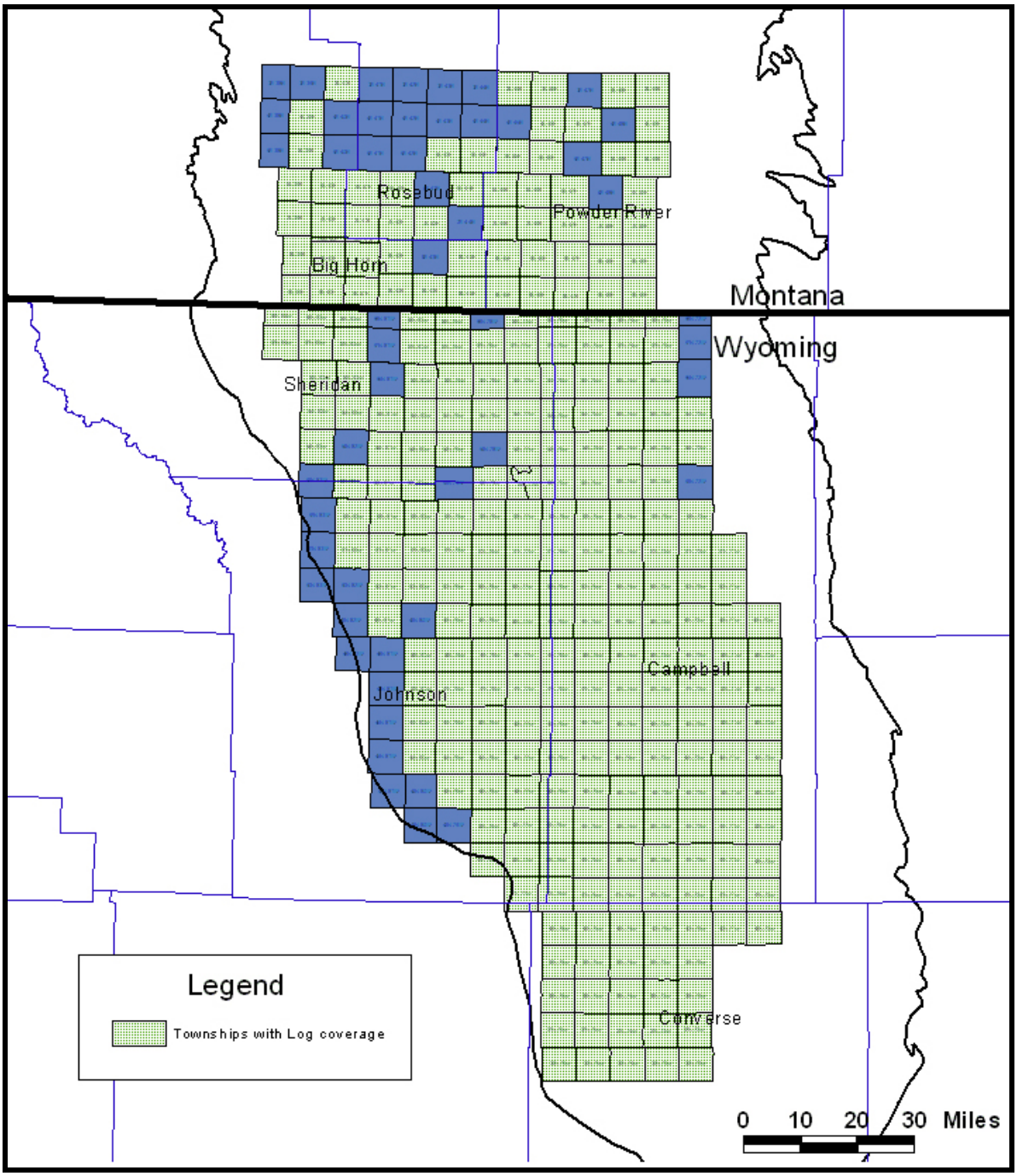


Figure 1-6. Townships Containing Logs Analyzed by the Study

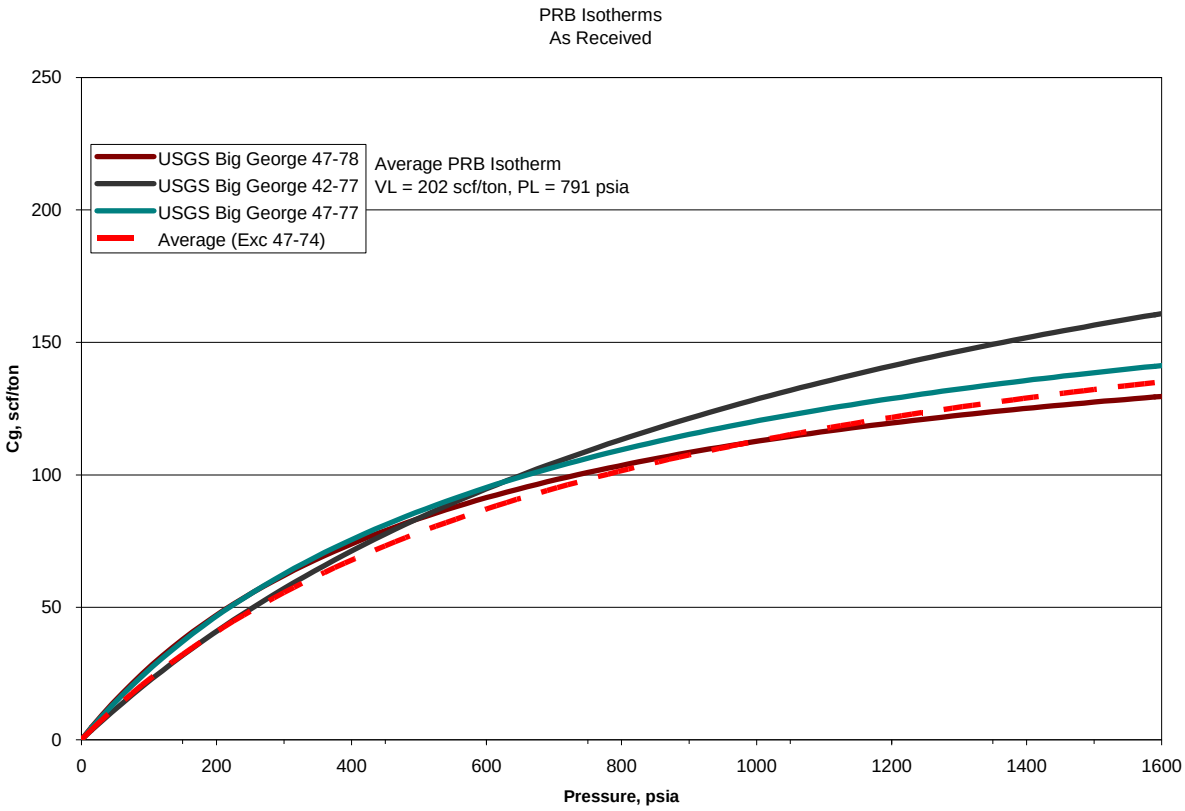


Figure 1-7. Methane Adsorption Isotherms Analyzed for the Study

1.5 Summary of Findings

The Powder River Basin has numerous thin coal seams that extend over major areas of the basin, particularly along the northern Wyoming and Montana portions of the basin. The completion of these thin (less than 20 feet of thickness) and other coals with a single well would significantly increase the technically recoverable CBM resource. Use of MSC Technology would also improve the economics and reduce the environmental impacts of CBM production in the Powder River Basin.

The updated outlook for coalbed methane in the Powder River Basin and the role of MSC Technology are summarized below:

1. *The CBM gas in-place in the Powder River Basin, under MSC technology, is estimated at 78 Tcf*. With currently used SSC Technology, only 58 Tcf of this CBM resource is accessible. MSC Technology provides access to 20 Tcf of additional CBM resource in the Powder River. Figure 1-8 compares accessible CBM gas in-place in the Powder River Basin under SSC and MSC Technologies.

2. *The technically recoverable coalbed methane resource in the Powder River Basin, using successful MSC Technology, is 52 Tcf.* With currently used SSC Technology, the technically recoverable resource is considerably less, estimated at 36.5 Tcf. MSC Technology enables the CBM resource in thin coals to be co-produced with thick coals, increasing the technically recoverable CBM resource in the basin by 15 Tcf, Figure 19.

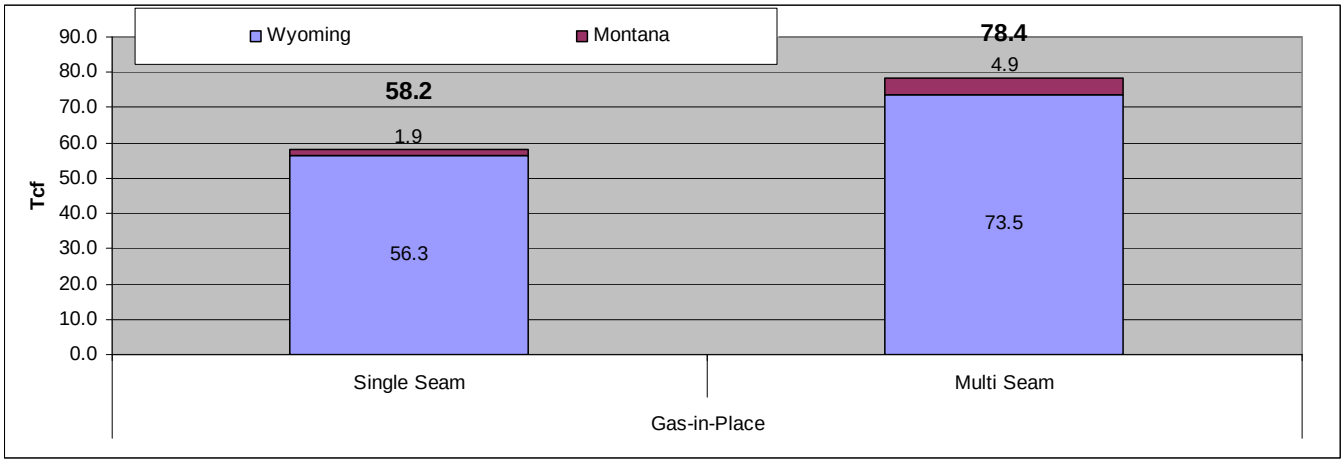


Figure 1-8. Gas-in-Place for Single Seam and Multi-Seam Technology, Powder River Basin

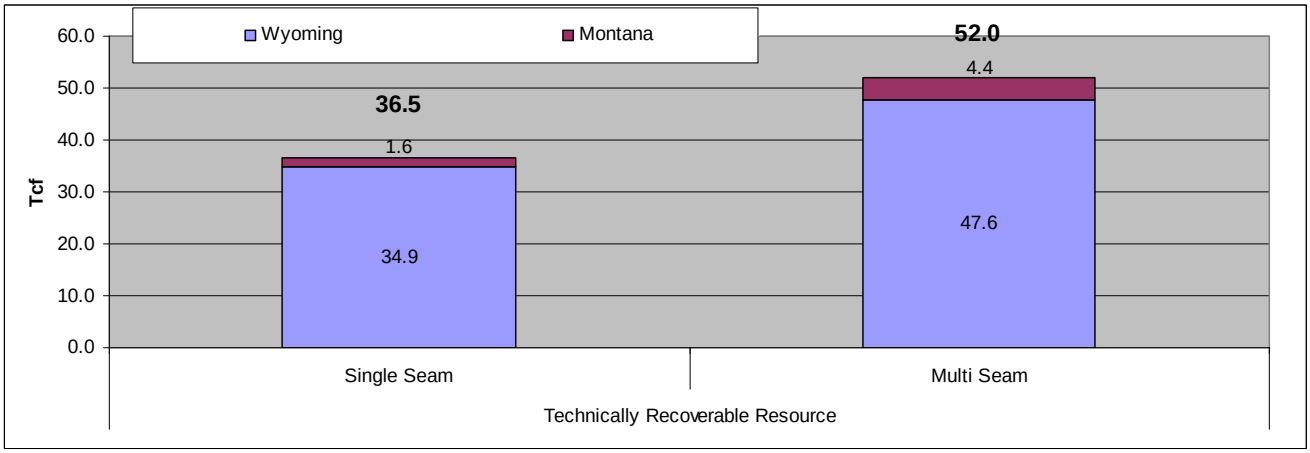


Figure 1-9. Technically Recoverable Resource for Single Seam and Multi-Seam Technology, Powder River Basin

3. *The economically recoverable CBM resource in the Powder River Basin (with successful MSC Technology) is 42 Tcf, at $8.00/MMBtu gas prices (Henry Hub spot).* Under SSC Technology, the economically recoverable resource in the basin is only 23 Tcf, Figure 1-10. As such, the application of successful MSC Technology to the Powder River Basin CBM play adds 19 Tcf of economically recoverable resource. (The CBM economics assume surface discharge water management. The effects of other scenarios are discussed later in the report.)

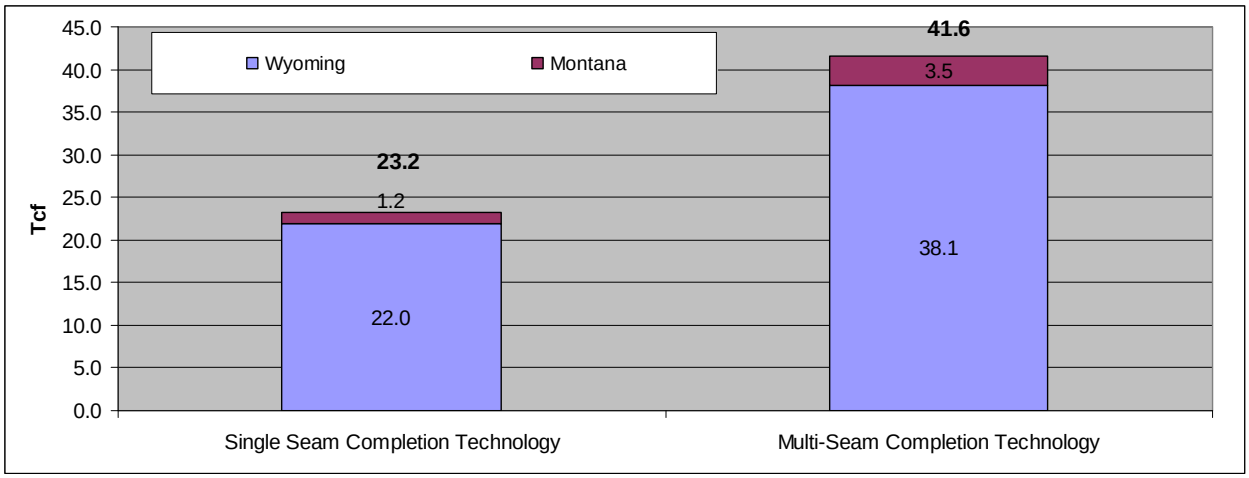


Figure 1-10. Comparison of PRB Economically Recoverable Resource under MMC and SSC completion technologies at a $8/MMBtu gas price.

4. *Use of MSC Technology would significantly increase revenues for Montana, Wyoming and the Federal Treasury.* Successful use of MSC Technology would provide increased royalty, severance, and ad valorem payments to state and federal governments. Under an $8/MMBtu (Henry Hub spot) gas price scenario, the economic resource of 42 Tcf would provide $23 billion in royalty payments to federal budgets, an increase of $10 billion over continued use of SSC Technology. In addition, $30 billion in severance and ad valorem taxes ($28 billion for WY; $2 billion for MT) would be generated from successful application of MSC Technology, an increase of $16.8 billion ($15.5 billion for WY; $1.3 billion for MT) over continued use of single-seam coal completion practices, Table 1-6.

Table 1-6. Royalty and Severance/Ad Valorem Tax Receipts Under Two Technology Options

Revenue Sources	With MSC Technology			With Single Seam Technology			Difference		
	MT	WY	Federal	MT	WY	Federal	MT	WY	Federal
Royalties (millions of $)	$264	$3,208	$22,833	$ 94	$1,851	$12,754	$170	$334	$10,079
Severance/Ad Valorem Taxes (millions of $)	$1,996	$28,190	-	$ 712	$12,605	-	$1,283	$15,585	-

5. *Alternative well head gas prices and levels of MSC Technology performance impact the economically recoverable CBM resource in the PRB.*

The economically recoverable CBM resource in the Powder River Basin was evaluated under two alternate price scenarios -- a low gas price of $6.00/MMBtu and a higher gas price of $10.00/MMbtu. The analysis indicates that lower gas prices of $6/MMBtu reduce CBM recovery by 4 Tcf, (from 42 to 38 Tcf). However, while higher natural gas prices would accelerate the development of the CBM resource in the basin, they appear to add only little to the amount of economically recoverable CBM in the basin. Increasing the gas price to $10/MMBtu from $8/MMBtu adds only 1 Tcf to the economically recoverable CBM resource, Figure 1-11.

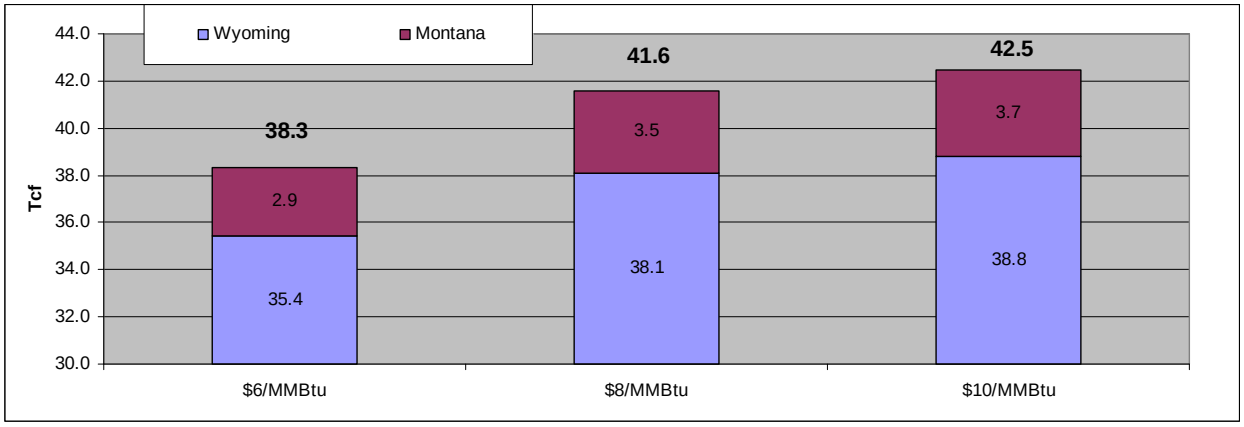


Figure 1-11. Economically Recoverable Resource Under Alternative Wellhead Gas Prices

It may turn out that MSC Technology performance is less than optimum. For example should MSC Technology may only achieve 80% of its theoretically optimum performance, at gas prices of $8/MMbtu (Henry Hub spot), the economically recoverable resource declines by 11 Tcf, from 42 Tcf to 31 Tcf, Figure 1-14.

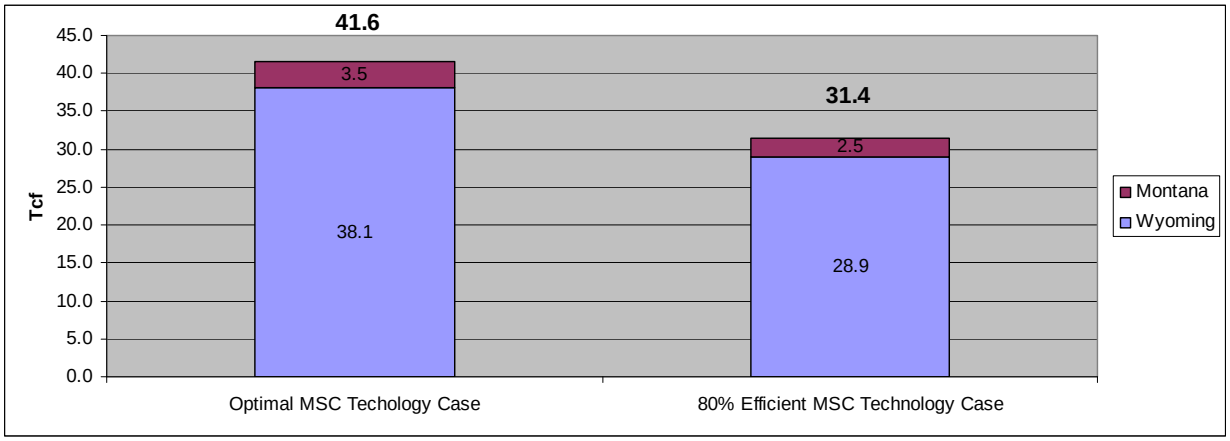


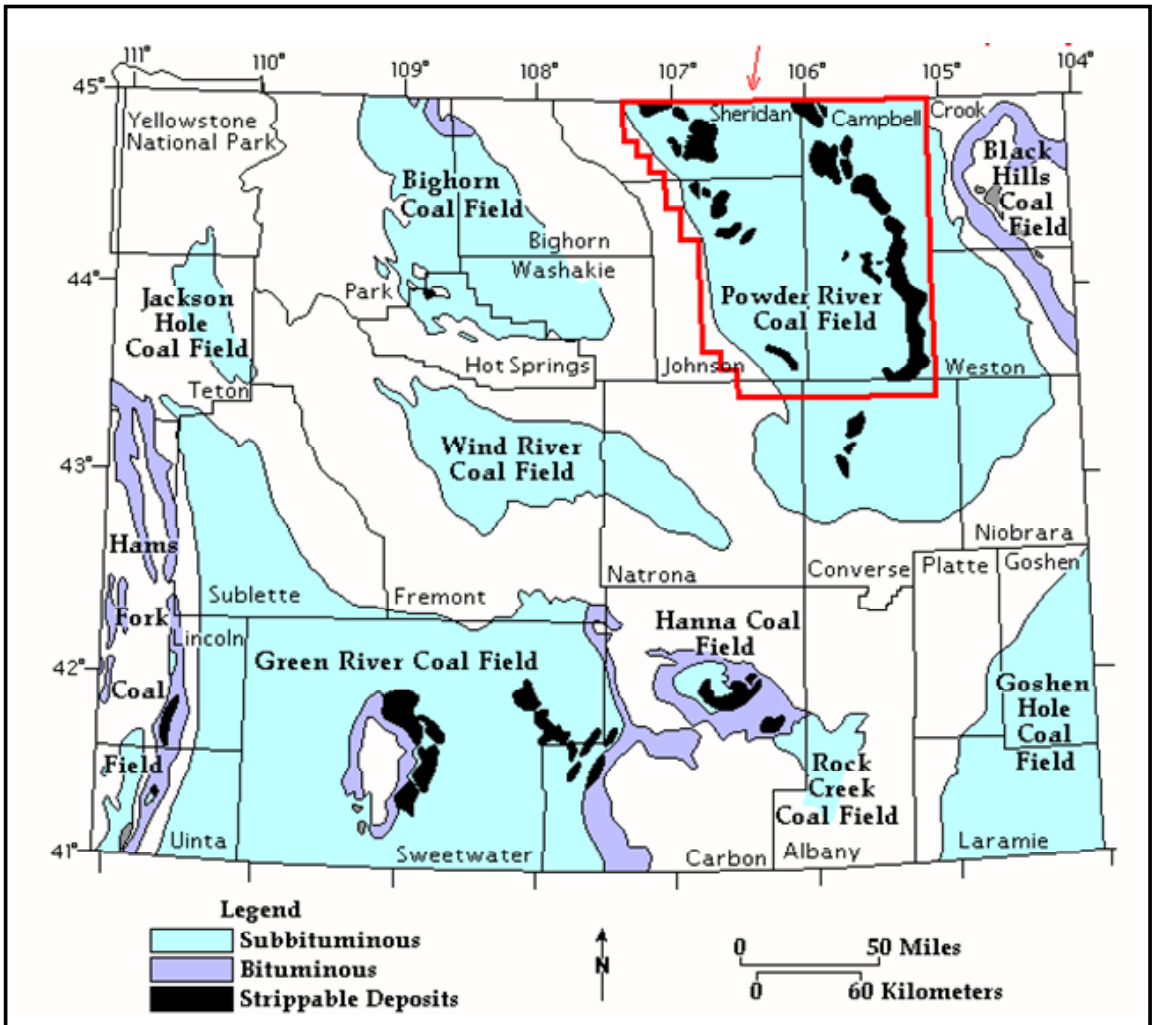
Figure 1-12. Economic Recovery of MSC and SSC Technologies in the PRB Under Varying Recovery Efficiency Scenarios at $8/MMBtu Henry Hub Spot Price.

SECTION 2. STUDY APPROACH AND METHOLOGY

2.1 Basin Area

The Powder River Basin is one of a series of coal-bearing basins along the Rocky Mountains, stretching from northern New Mexico to central Montana. The basin covers approximately 28,500 square miles, with about one-half of this area underlain by producible coals. The basin is bounded on the east by the Black Hills Uplift, on the north by the Miles City Arch, on the south by the Laramide Mountains, and on the west by the Big Horn Uplift and the Casper Arch. Figure 2-1 shows the outline of the Powder River Coal Basin in Wyoming and Montana.

The bulk of coalbed methane activity to date has been in the east and central portions of the basin, particularly near the town of Gillette, in Campbell County, Wyoming. To date, over 22,000 coalbed methane wells have been drilled in the Powder River Basin, providing a wealth of data for establishing the geologic setting and characteristics of the Wasatch and Fort Union Formation low rank coals in this basin.



Source: "Coalbed Methane Activity in the Powder River Basin, Wyoming", Wyoming State Geologic Survey.

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Figure 2-1: Outline and Location of Powder River Basin

2.2 Basin Structure

The eastern flank of the Powder River Basin dips gradually toward the basin center at an average of 1.5^{o}, with occasional normal faulting and folding, Figure 2-2. The basinal axis runs along the steeper western and southern margins, where the basin terminates against a complex of basement thrusts and reverse faults, as shown on the generalized cross-section of the Powder River Basin, Figure 2-3.

2.3 Basin Stratigraphy

The Powder River Basin (PRB) is filled with thick Tertiary-age marine and fluvial deposits. The Tertiary units contain the coal-bearing Fort Union and Wasatch formations that are the topic of this study, Figure 2-4.

The Tongue River Member, consisting of sandstone, conglomerate, siltstone, limestone and coal, is the principal coal-bearing unit of the Fort Union Formation. The Tongue River Member contains a large number of distinct coal seams, ranging from a few feet to over 100 feet in thickness, Figure 2-5.

The Tongue River Member can be further divided into upper and lower units. The Upper Tongue River unit contains the Smith/Swartz, Anderson (Deitz), Canyon (Monarch), Wyodak (where the Anderson and Canyon have merged), the Big George and the Cook (Carney) seams. The Lower Tongue River unit contains the Wall, Pawnee, Cache and deeper coal seams.

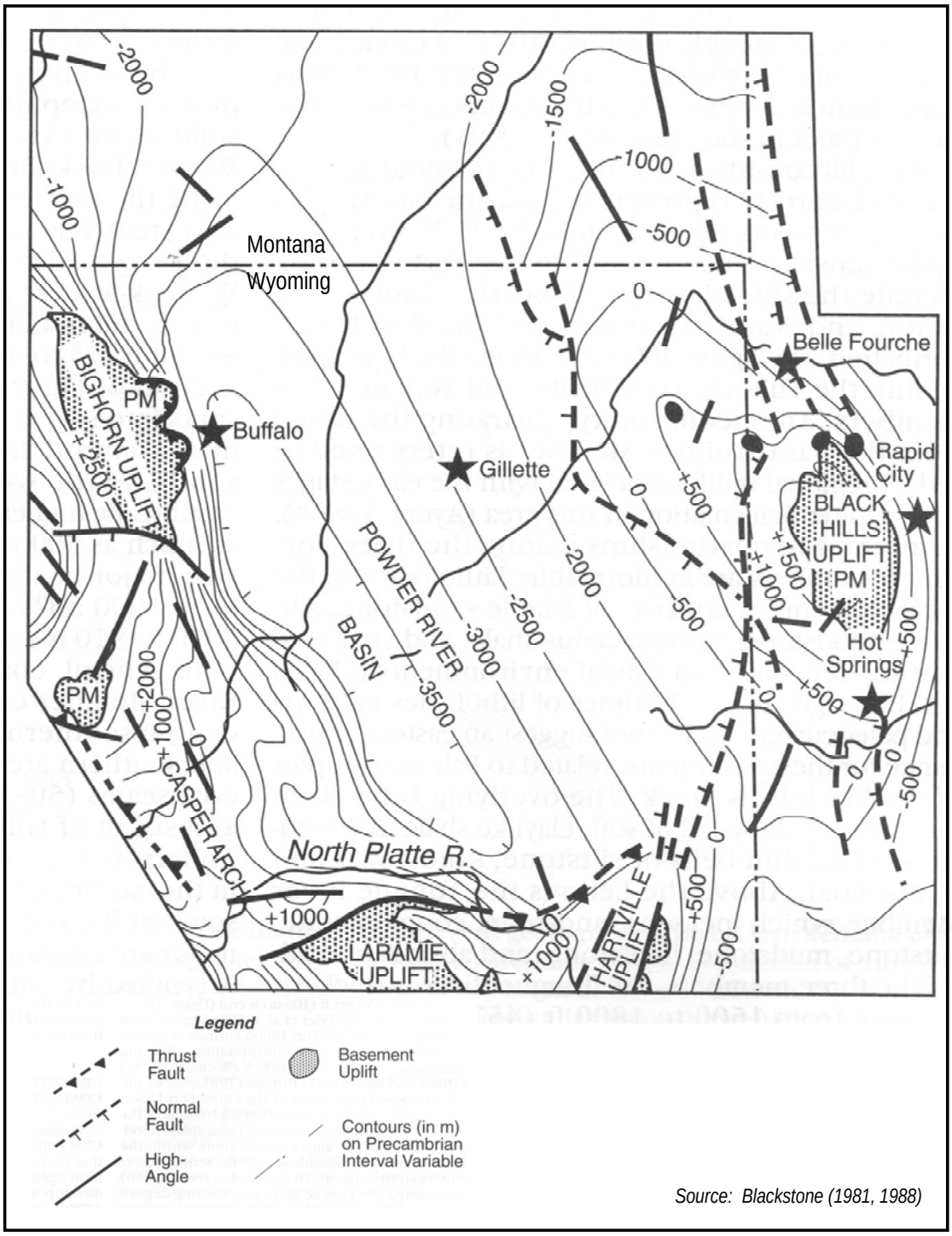
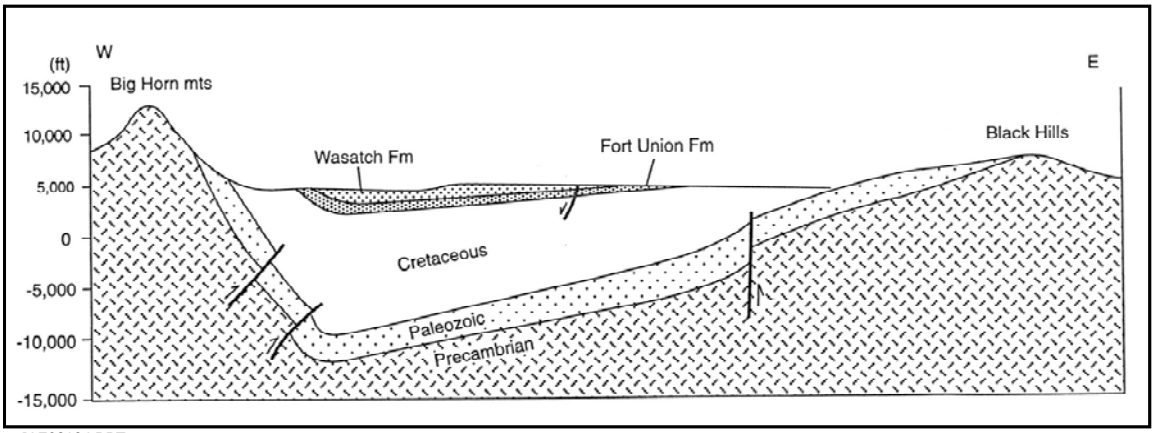


Figure 2-2. Regional Structure and Tectonic Map of the Powder River Basin.



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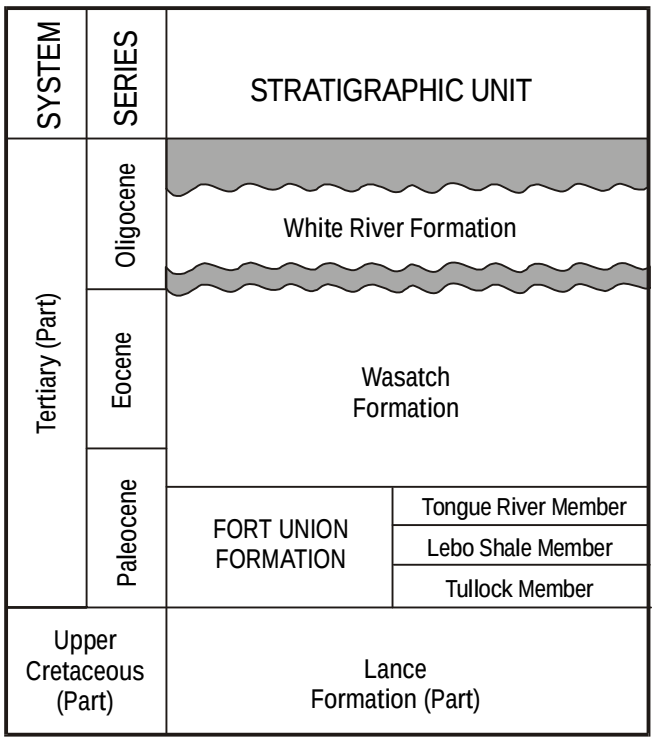
Source: Montgomery, 1999.

Figure 2-3. Regional Cross-Section of the Powder River Basin



Source: Law, Rice and Flores, 1991

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Figure 2-4. Upper Cretaceous and Tertiary Stratigraphic Chart for Powder River Basin

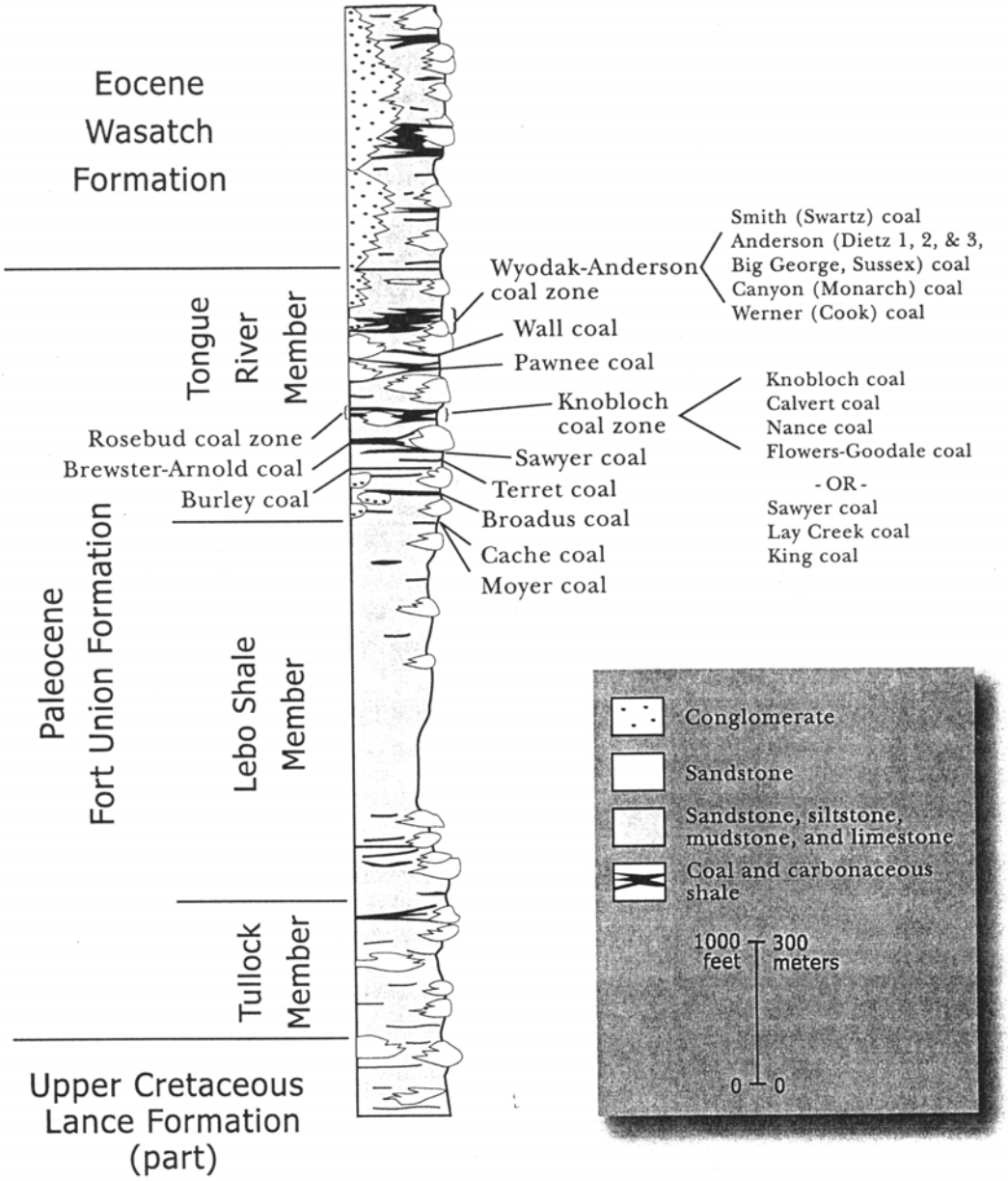


Figure 2-5. Coal Bearing Units of the Tongue River Member of the Fort Union Formation, Powder River Basin

A series of Wasatch Formation coals exist along the western edge of the basin and include the Cameron, Felix and Ucross seams. These coals coalesce into a thick coal package at Lake Desmet.

In the Montana portion of the PRB, the Tongue River Member coals become shallower and outcrop. Several deeper seams, without exact equivalents in the Wyoming portion of the basin, become available for CBM development in Montana, including the Knobloch coal seam that has been given particular attention in this study.

2.4 Reservoir Parameters

Knowledge of the coal seam reservoir parameters is integral to understanding how CBM wells will perform. Several properties, including coal depth and thickness, pressure gradient, gas content and gas saturation, were assessed to estimate gas-in-place for each coal seam in each township. Water in-place was estimated using coal fracture and matrix porosity. Reservoir permeability provided estimates of recoverable gas and water and their timing. Lastly, “type-wells,” constructed from over 18,000 Powder River Basin CBM wells, were created using Time Zero statistical analysis to estimate gas and water production streams over a 10 year well life. Key reservoir properties for a CBM development area in the east-central portion of the Powder River Basin (Partition 8) are shown in Table 2-1.

Table 2-1. Representative PRB Reservoir Properties in Partition 8

Coal Seam	Depth (Feet)	Thickness (Feet)	Gas Content (cf/t)	Pressure (Top of Coal) (psi)	Gas-in-Place (Bcf/Township)
Anderson	420	24	27	130	34
Canyon	560	28	36	180	49
Cook	760	23	44	250	54
Wall	930	18	52	310	60
Pawnee	1130	15	59	380	56
Cache	1480	11	68	570	46

2.4.1 Regional Pressure Gradient.

A regional pressure gradient versus depth relationship for PRB coal seams, Figure 2-6, was constructed to establish reservoir pressure for each of the coal formations. This was assembled using:

- Detailed hydrology data and pressure mapping by the Wyoming Bureau of Land Management (BLM),
- Actual pressure data from basin producers, and
- History matching of the pressure gradient data using long-term (4+ year) gas and water production in the PRB.

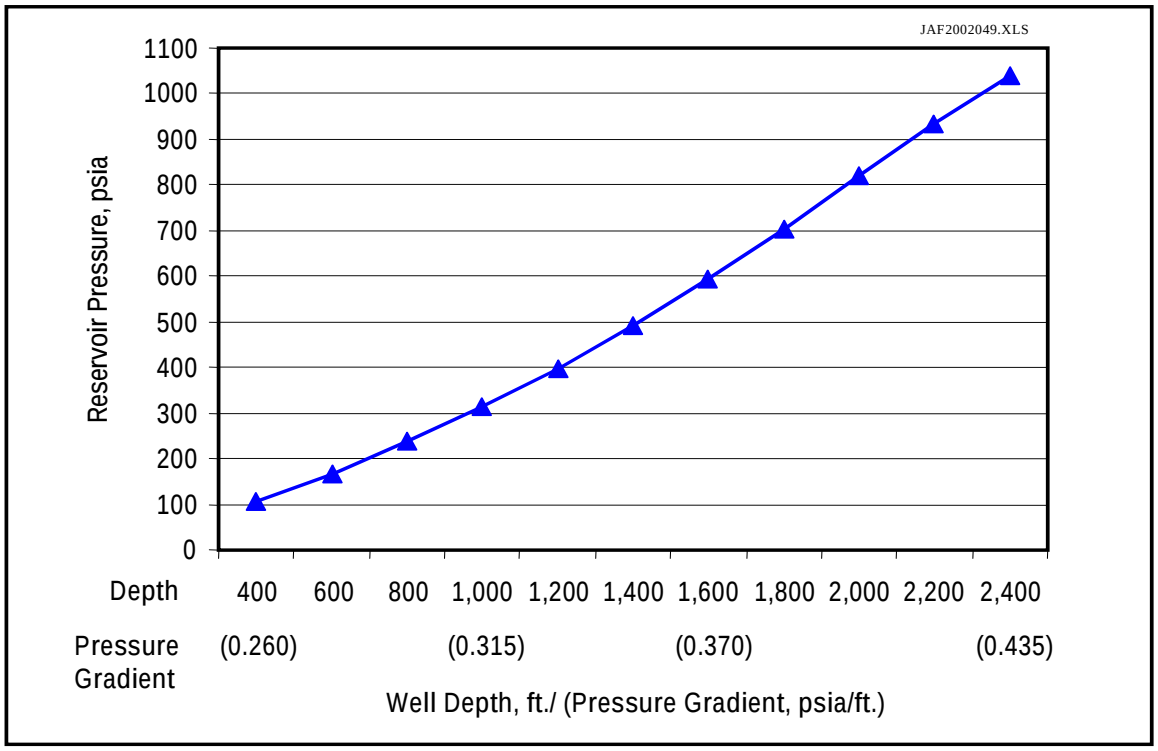


Figure 2-6. Regional Pressure Gradient for the Powder River Basin

2.4.2 Gas Content.

Gas content and isotherm data, for the low rank coals of the PRB, were assembled from the following sources:

- The valuable set of published gas content and isotherm data by the USGS as well as the BLM,
- Gas content and isotherm data collected by Advanced Resources in analogous low rank coals in other basins.
- Gas content and isotherm data published and donated by operators in the basin.

2.4.3 Coal Permeability.

In general, the coal cleat (fracture) permeability of PRB coals is favorable, ranging from 35 to 500 md. Coal matrix permeabilities are considerably lower and variable, ranging from 0.001 to 1.0 md. However, even the lower end of the range for cleat and matrix permeabilities for the coals in the PRB is sufficient to support reasonable gas recoveries (in 10 years) of 40 to 80% of the gas in-place.

2.4.3 Gas-In-Place.

Using the above mentioned reservoir data on coal seam thickness, depth, pressure and gas content, the gas-in-place (GIP) was calculated for each coal seam in each township. These gas-in-place data were then aggregated into completion packages of coals for assessing multi-seam completions. Table 2-2 provides the GIP data for each coal seam in the Wyoming part of the PRB as well as how much GIP exists for all 80 acre well locations for each coal seam in each basin partition. For example, all the Big George Coals combined contains 14.8 Tcf of GIP. A single 80 acre well located in partition 5 contains 1.14 Bcf of GIP.

Table 2-2: CBM Gas in-Place in Each Coal Seam and Basin Partition

Seam/Partition	P1	P2	P3	P4	P5	P6	P7	P8	P11	P12	Total
Felix						0.11	0.11				224
Ucross					0.08	0.22	0.22		0.04		426
Roland					0.11	0.17	0.15		0.08		1,254
Smith			0.06		0.12		0.22	0.09	0.12		1,560
Swartz			0.17		0.17			0.09			1,281
Anderson	0.08	0.12	0.22	0.15	0.26	0.26	0.17	0.24	0.15		3,758
Anderson 1						0.12			0.21		469
Anderson 2						0.14			0.23		421
Canyon	0.11	0.16	0.29	0.26	0.39	0.36	0.21	0.23	0.14		7,042
Canyon 1			0.24								68
Canyon 2			0.23								65
Wyodak		0.57		0.48	0.83						2,810
Big George		1.07	0.91		1.14	1.34				1.25	14,838
Cook	0.07	0.28	0.27	0.29	0.47	0.36	0.18	0.21	0.17		8,154
Cook 1								0.13			37
Wall	0.23	0.26	0.21	0.21	0.47	0.33	0.28	0.19			7,815
Pawnee	0.19	0.20	0.22	0.30	0.42	0.74	0.33	0.15	0.50		10,543
Pawnee 1	0.29	0.21	0.20	0.31	0.32	0.27	0.46	0.21			4,090
Pawnee 2			0.16								47
Cache	0.43		0.22	0.23	0.36	0.75	0.34	0.17			6,264
Oedekoven			0.19	0.32	0.25		0.29	0.49			1,896
Wildcat					0.75	0.78					445
Total											73,507

2.4.5 Estimating Gas and Water Production.

Gas production and recovery were estimated on a per well basis using data gathered from actual producing Powder River Basin CBM wells. These wells were sorted by seam and their production streams were normalized using Time-Zero plots. The data base included over 18,000 CBM wells with sufficient production data and confinement. Table 2-3 shows the 100 coal seams and basin partitions combinations with distinct CBM production "Type Wells." Figures 2-7 and 2-8 illustrate this data set for wells drilled into the Anderson coal seam in Partition 8.

- Production data from wells in each seam in each partition were sorted by time on production, allowing all production streams to begin production at a single starting point, a Time-Zero. The well data were then averaged to produce a characteristic "type well" for a particular coal seam in a particular partition.
- The available "type-well" production streams were extrapolated to 10 years of production to produce an estimate of ultimate CBM recovery (EUR).
- "Type-wells" for individual coal seams were combined into distinct coal packages (discussed further below) to create a series of multi-seam completed CBM wells.
- The estimated ultimate recovery for each "type-well" was matched with the gas-in-place associated with the "type-well" to determine how much of the CBM in each seam/township is recovered per year. This step is discussed in more detail below.

Table 2-4 provides the technically recoverable CBM data for each coal seam within the Wyoming portion of the PRB as well as how much CBM is estimated ultimately recoverable (EUR) for all 80 well locations for each coal seam in each partition.

Table 2-3. Type Wells and Analogues Used to Calculate Technically Recoverable Resource*

Seam/Partition	P1	P2	P3	P4	P5	P6	P7	P8	P11	P12
Other										
Felix						P11 Roland	P11 Roland			
Ucross					P11 Roland	P11 Roland	P11 Roland		P11 Roland	
Roland					P11	P6 Smith	P11		**x**	
Smith			P5		**x**		P6	P4	**x**	
Swartz			P5 Smith		P5 Smith			P4 Smith		
Anderson	P2	**x**	**x**	**x**	**x**	P11	P8	**x**	**x**	
Anderson 1						P11				
Anderson 2						P11				
Canyon	P2	**x**	P5	**x**	**x**	P11	P8	**x**	**x**	
Canyon 1			P5							
Canyon 2			P5							
Wyodak		**x**		P2	**x**					
Big George		P3	**x**		**x**	**x**				**x**
Cook	P4	P4	P8	**x**	**x**	P11	P8	**x**	**x**	
Cook 1								P8		
Wall	P5	P5	P8	**x**	**x**	P8	P8	**x**		
Pawnee	P8	P8	P8	P8	P8	P8	P8	**x**	P8	
Pawnee 1	P8	P8	P8	P8	P8	P8	P8	P8		
Pawnee 2			P8							
Cache	P8 Pawnee		P8 Pawnee	P8 Pawnee	P8 Pawnee	P8 Pawnee	P8 Pawnee	P8 Pawnee		
Oedekoven			P8 Pawnee	P8 Pawnee	P8 Pawnee		P8 Pawnee	P8 Pawnee		
Wildcat					P8 Pawnee	P11 Roland				

* Bold x characters indicate that "Type Wells" were created for that seam and partition combination. Cells containing other partition numbers and/or seam names indicate which Type Well was adjusted for depth and thickness for use in that partition and seam combination.

Table 2-4. Estimated Ultimate Recovery/Well Drilled in Each Seam and Partition

Seam/Partition	P1	P2	P3	P4	P5	P6	P7	P8	P11	P12	Total
Felix						0.09	0.09				179
Ucross					0.06	0.17	0.18		0.04		341
Roland					0.08	0.14	0.12		0.07		1,003
Smith			0.05		0.08		0.18	0.05	0.12		1,104
Swartz			0.12		0.12			0.04			864
Anderson	0.06	0.09	0.18	0.12	0.16	0.13	0.09	0.13	0.15		2,188
Anderson 1						0.06			0.11		236
Anderson 2						0.07			0.12		212
Canyon	0.08	0.12	0.12	0.19	0.16	0.24	0.15	0.16	0.14		4,449
Canyon 1			0.10								27
Canyon 2			0.09								26
Wyodak		0.27		0.23	0.21						1,218
Big George		0.27	0.23		0.39	1.08				0.41	5,460
Cook	0.02	0.07	0.21	0.07	0.36	0.17	0.14	0.16	0.17		5,423
Cook 1								0.10			29
Wall	0.18	0.21	0.17	0.17	0.37	0.26	0.23	0.15			6,252
Pawnee	0.15	0.16	0.18	0.24	0.34	0.59	0.26	0.12	0.40		8,434
Pawnee 1	0.23	0.16	0.16	0.24	0.25	0.21	0.37	0.17			3,272
Pawnee 2			0.13								38
Cache	0.35		0.18	0.18	0.29	0.60	0.27	0.14			5,011
Oedekoven			0.15	0.25	0.20		0.23	0.39			1,517
Wildcat					0.60	0.62					356
Total											47,640

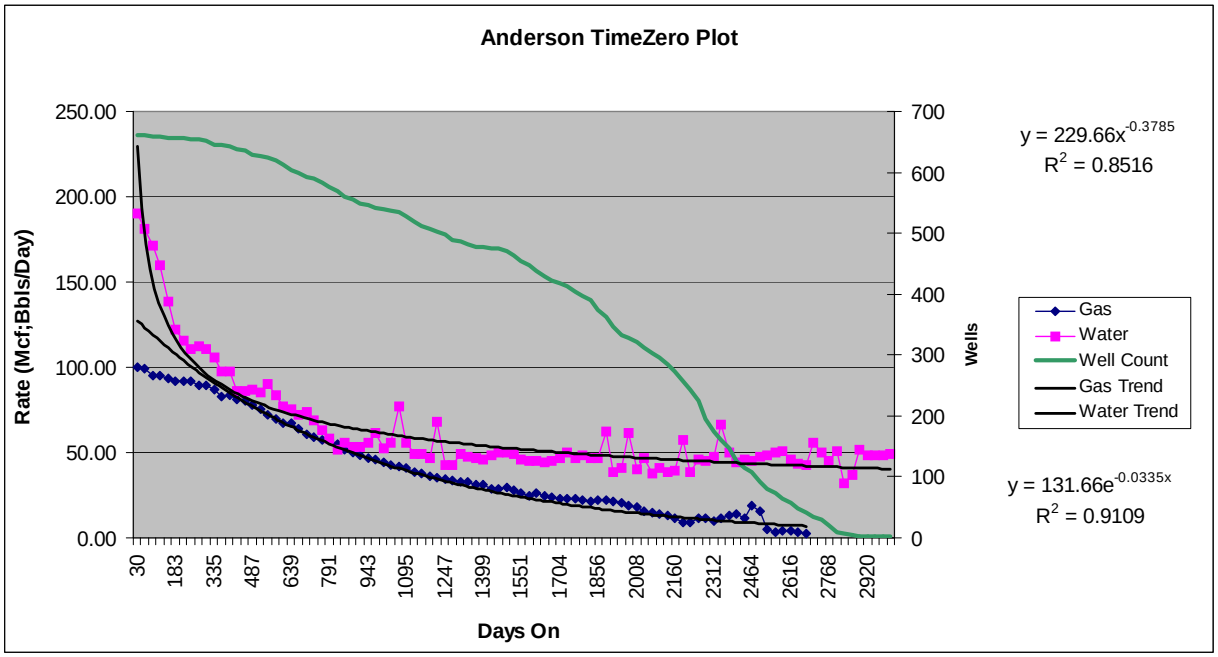


Figure 2-7. Graph Showing Averaged Production Data from Anderson Wells in Partition 8.

Year	Gas Production (Mcf)		Water Production (Bbls)	
	Yearly Gas	Cum Gas	Yearly Water	Cum Water
1	29,812	29,812	49,160	49,160
2	33,180	62,992	29,898	79,059
3	25,294	88,286	21,084	100,143
4	17,114	105,399	17,840	117,983
5	11,932	117,332	17,138	135,121
6	8,743	126,075	16,760	151,881
7	5,793	131,868	17,480	169,361
8	3,243	135,111	16,862	186,224
9	2,156	137,267	15,307	201,531
10	1,434	138,701	13,907	215,438

Figure 2-8. Table Showing "Type-Well" Production Characteristics for Wells Drilled into the Anderson Seam in Partition 8.

2.4.6: CBM Well Location and Drilling Data

Overall, the study estimates that the PRB has over 243,000 potential well drilling sites. Table 2-5 displaces the potential well sites by coal seam and basin partition for Wyoming. Table 2-6 tabulates the basin partition location of the 24,000 CBM wells already drilled in the Wyoming portion of the PRB, including the coal seams targeted by the wells.

Table 2-5. Potential Well Drilling Sites in the PRB by Seam and Partition

Seam/Partition	P1	P2	P3	P4	P5	P6	P7	P8	P11	P12	Total
Felix						1728	288				2,016
Ucross					576	1440	288		576		2,880
Roland					288	3744	3168		1728		8,928
Smith			1728		4896		2304	3456	1152		13,536
Swartz			1440		4320			3456			9,216
Anderson	576	864	864	1152	4032	2592	2880	7200	2304		22,464
Anderson 1						864			2016		2,880
Anderson 2						576			1440		2,016
Canyon	576	864	576	2016	5184	6048	2880	9504	2592		30,240
Canyon 1			288								288
Canyon 2			288								288
Wyodak		2304		2592	576						5,472
Big George		576	4608		8064	1440				288	14,976
Cook	288	1152	2016	2592	8352	2880	2304	8928	2304		30,816
Cook 1								288			288
Wall	288	2016	576	2016	8640	3456	2592	7200			26,784
Pawnee	576	2880	1440	3168	7776	3168	4032	6336	288		29,664
Pawnee 1	288	2016	1152	288	5184	2016	1152	2592			14,688
Pawnee 2			288								288
Cache	1440		1440	2016	6912	288	3168	3168			18,432
Oedekoven			288	576	3168		1152	1440			6,624
Wildcat					288	288					576
Total	4,032	12,672	16,992	16,416	68,256	30,528	26,208	53,568	14,400	288	243,360

Table 2-6. Numbers of Wells Already Drilled in PRB by Seam and Partition

Seam/Partition	P1	P2	P3	P4	P5	P6	P7	P8	P11	P12	Total
Felix					78	19	20				117
Ucross						8	7				15
Roland									327		327
Smith				64	135	23	57	8	345		632
Swartz								21			21
Anderson		158	32	705	896	20	235	931	995		3,972
Anderson 1											-
Anderson 2											-
Canyon		282	26	696	508	17	187	1336	760		3,812
Canyon 1											-
Canyon 2											-
Wyodak		1361	182	1048	1641		1		1		4,234
Big George		1	1793		2622	784	1			130	5,331
Cook				19	93	8	248	1478	871		2,717
Cook 1											-
Wall				47	402	2	71	1646			2,168
Pawnee	25	1		24	10	2	39	659			760
Pawnee 1											-
Pawnee 2											-
Cache								25			25
Oedekoven			146		104		16				266
Wildcat											-
Total	25	1,803	2,179	2,603	6,489	883	882	6,104	3,299	130	24,397

2.5 Multi-Seam Coal Model

2.5.1 Coal Inventory.

A revised township-level coal database was assembled for all seams within the Powder River Basin, for coals thicker than 5 feet and deeper than 200 feet. To add greater resolution to the coal database, Advanced Resources (ARI) evaluated an additional 200 recent Powder River Basin CBM well logs (in addition to the previously analyzed 270 well logs). These logs span the full Fort Union coal interval throughout the Powder River Basin CBM play. Ultimately, well log data representing over 9,700 sq. mi. of the CBM play were collected. Table 2-7 shows the coal seam data assembled for the ten partitions in the Wyoming portion of the PRB.

Areas of missing data were primarily along the basin margins, where little or no CBM activity has occurred. In addition, a notable absence in data is along the northern edge of the play. Much of this area is on the Crow Indian Reservation that has not yet been explored or drilled for coalbed methane. Figure 2-11 displays the townships from which data were collected and used by this study.

Table 2-7: Location of Coal Seams Analyzed in This Study

Seam/Partition	P1	P2	P3	P4	P5	P6	P7	P8	P11	P12
Other										
Felix										
Ucross										
Roland										
Smith										
Swartz										
Anderson										
Anderson 1										
Anderson 2										
Canyon										
Canyon 1										
Canyon 2										
Wyodak										
Big George										
Cook										
Cook 1										
Wall										
Pawnee										
Pawnee 1										
Pawnee 2										
Cache										
Oedekoven										
Wildcat										

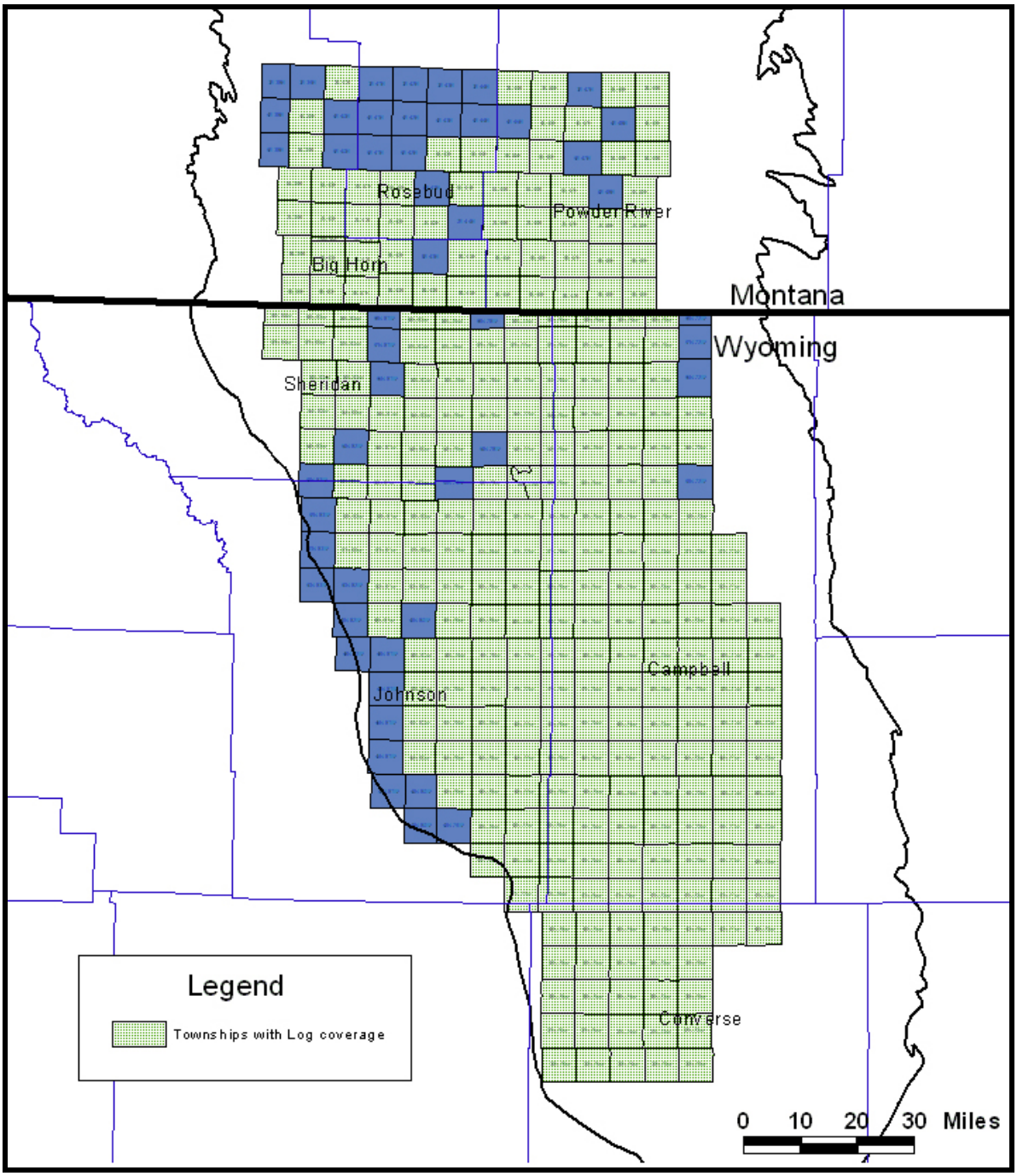


Figure 2-9. Areas with Coal Seam Thickness and Depth Data from Well Logs

2.5.2 Coal Packages and Completion Criteria.

For consistency and comparison, three distinct coal packages were defined (each with a maximum of four individual coal seams). These were:

- Package #1: The shallow Upper Fort Union, consisting of Wasatch through Anderson coal seams;
- Package #2: The deeper Upper Fort Union, consisting of Canyon through Cook coal seams; and
- Package #3: The Lower Fort Union, consisting of the Wall and deeper coal seams.

To be included in one of the coal packages in Wyoming, a coal seam had to be at least 300 feet depth and have a thickness of 10 feet or more. In Montana, the depth and thickness criteria were relaxed to include seams at least 200 feet deep and 5 feet in thickness to more fully capture the smaller coal resource in this portion of the basin. In Montana, special efforts were made to collect and include stratigraphically-deeper coal seams, such as the Knobloch seam, which exist near the northern edge of the Powder River Basin CBM play.

Figure 2-10 provides an example of the coal seam database assembled for this study, showing the individual coal seams, their composite multi-seam completion “packages”, and the aggregate coal thickness for each coal package.

		Completion 1			Completion 2		Completion 3						
TR	Partition	Smith	Swartz	Anderson	Canyon	Cook	Wall	Pawnee	Pawnee 1	Cache	**Completion 1**	**Completion 2**	**Completion 3**
P_8 - 53N 73W	8	16	22	20	43	21	15				58	64	15
P_8 - 53N 74W	8	17	24	32	34	35	12	44	18	10	73	69	84
P_8 - 53N 75W	8	38			33	50	33	38	20		121		91
P_8 - 53N 76W	8	25	34		48	13		19	35		120		54
P_8 - 53N 77W	8	15	19		42	23	56			21	99		77
P_8 - 54N 72W	8				50	29	12			18	79		30
P_8 - 54N 73W	8				40	35	35	15		13	75		63
P_8 - 54N 74W	8			19	33	43	10	12			95		22
P_8 - 54N 75W	8	40		42	28	44	24	14		12	154		50
P_8 - 54N 76W	8	21	13	42	35	29	24	20			76	64	44
P_8 - 54N 77W	8	15	18	41		10	30	12			84		42
P_8 - 55N 72W	8						30	11			0		41
P_8 - 55N 73W	8			33	36	21	19	20		10	90		49
P_8 - 55N 74W	8			20	35	25	35	22			80		57
P_8 - 55N 75W	8			27	60	31	30				118		30
P_8 - 55N 76W	8	16		18	36	39	22	12			109		34
P_8 - 55N 77W	8	11	21	31	11		22	28	20	18	74	22	111
P_8 - 55N 78W	8		14	20	10	21	13	26			65		39
P_8 - 56N 73W	8			21	36			12		11	57		23
P_8 - 56N 74W	8		10	12	30	30					82		0
P_8 - 56N 75W	8			27	36	44	28	15			107		43
P_8 - 56N 76W	8			14	33	12	26	15	10	11	59		62
P_8 - 56N 77W	8			11	26	13	12		10	14	50		36
P_8 - 56N 78W	8			13	14	14			10		52		27
P_8 - 57N 73W	8			20	14	18		18	11		52		29
P_8 - 57N 74W	8			23	25	10	11				58		11
P_8 - 57N 75W	8		12	17	15	24	18	14			68		32
P_8 - 57N 76W	8			11	29	24	14	10			64		24
P_8 - 57N 77W	8			46	11	26	11				83		11
P_8 - 57N 78W	8		12	14	20	10		10	10		56		37
P_8 - 58N 73W	8				12	11					23		0

Figure 2-10. Example Partition 8 Coal Thickness Database Compiled for this Report

2.5.3 CBM Production Curves.

With the reservoir gas in-place and EUR data in hand, the next step was to estimate annual CBM and water production for each 80 acre coal seam well in each township.

Annual gas and water production were determined by the percentage of a "Type-Well's" EUR that was produced each year. These percentages were applied to the calculated technically recoverable EUR for each coal seam in each partition. Figure 2-11 shows the "type-well" recovery percentages calculated in selected partitions of the PRB.

Partition 8	Percent of Cum Recovery Produced Each Year										
	Gas 1	**Gas 2**	**Gas 3**	**Gas 4**	**Gas 5**	**Gas 6**	**Gas 7**	**Gas 8**	**Gas 9**	**Gas 10**	**Total**
Completion 1_2	0.17	0.18	0.14	0.09	0.10	0.09	0.07	0.06	0.06	0.05	1.00
Completion 1	0.240	0.213	0.161	0.117	0.085	0.061	0.044	0.036	0.025	0.018	1.00
Completion 2	0.243	0.202	0.152	0.116	0.086	0.060	0.046	0.042	0.030	0.022	1.00
Completion 3	0.104	0.110	0.116	0.112	0.112	0.102	0.092	0.087	0.084	0.081	1.00

Partition 11	Percent of Cum Recovery Produced Each Year										
	Gas 1	**Gas 2**	**Gas 3**	**Gas 4**	**Gas 5**	**Gas 6**	**Gas 7**	**Gas 8**	**Gas 9**	**Gas 10**	**Total**
Completion 1_2	0.24	0.20	0.15	0.12	0.09	0.06	0.05	0.04	0.03	0.02	
Completion 1	0.186	0.190	0.183	0.138	0.098	0.071	0.051	0.037	0.027	0.020	1.00
Completion 2	0.232	0.245	0.177	0.129	0.078	0.052	0.038	0.023	0.015	0.010	1.00
Completion 3	0.094	0.095	0.103	0.107	0.114	0.106	0.098	0.096	0.094	0.093	1.00

Partition 12	Percent of Cum Recovery Produced Each Year										
	Gas 1	**Gas 2**	**Gas 3**	**Gas 4**	**Gas 5**	**Gas 6**	**Gas 7**	**Gas 8**	**Gas 9**	**Gas 10**	**Total**
Completion 1	0.04	0.09	0.14	0.16	0.14	0.12	0.10	0.08	0.07	0.06	1.00

Figure 2-11. Production factors used to calculate the Recovery Profiles of MSC wells in selected partitions.

2.6 Basic Cost Model

Introduction. This study uses an updated version of ARI's coalbed methane cost and economic model, CBM-ECON (CBM-Economics), to assess the feasibility of developing coalbed methane with Multi-Seam Well Completion Technology. The model contains five main components: (1) revenues from the production and sale of CBM; (2) basic capital costs; (3) basic operating and maintenance costs; (4) gas transportation and compressions costs; and (5) other costs.

2.6.1 Revenues from CBM Production and Sales.

The economic model incorporates forecasts for future natural gas prices (at the Henry Hub), current and anticipated Wyoming "basis differentials", as well as royalties, production taxes and other factors that impact CBM costs and economics. The economic model is an industry-standard discounted cash flow (DCF) model that provides both an internal rate of return and the net present value (NPV) of an investment at various discount rates and at various net gas prices.

2.6.2 Capital Costs for PRB CBM Well.

The basic capital costs for a PRB CBM well include outlays for land, permits, drilling and completion, infrastructure, and water management. These costs vary considerably by well depth, location and number of seams completed. For illustrative purposes, Table 2-8 shows the costs for a Powder River Basin coalbed methane well at 1,400 feet of depth, spaced on 80 acres, with 2 wells per pad. Capital costs are per well assuming a 16 well, 8 pad development unit. Gas treating and compression is assumed provided by a third party contract and is included in annual operating costs.

This study assumes that surface impoundments would be used for produced CBM waters. (For a full description of the capital cost module and other water disposal alternatives, see DOE/NETL-2003/1184). The basic capital costs for an example 1,400' PRB CBM well are estimated at $233,310.

Table 2-8. Capital Costs for Illustrative CBM Well, Powder River Basin.

	Cost Item	**Capital Costs**
1	Land Costs and Permits	$13,000
2	Well Drilling and Completion (@1,400 feet)	184,400
3	Gas and Water Gathering	24,290
4	Lease Equipment	11,280
5	Miscellaneous	340
	Total	**$233,310**

2.6.3 O&M Costs for PRB CBM Well.

The basic lease and well operating and maintenance (O&M) costs for a Powder River coalbed methane well vary by year of production, with higher costs during the initial years because of higher water production and pump replacements, Table 2-9.

Table 2-9. PRB Operating and Maintenance Costs for Illustrative CBM Well

	O&M Costs/Well			
	Basic O&M*		O&M Inc. G&A	
	Annual	Monthly	Annual	Monthly
Year 1	$26,295	$2,192	$30,485	$2,540
Years 2 - 4	$24,648	$2,054	$28,838	$2,403
Years 5 - 10	$19,564	$1,630	$23,754	$1,980
TOTAL (Years 1 - 10)	$217,623	$1,814	$259,523	$2,163

*A G&A charge of 20% for engineering, accounting, legal and other indirect costs is added to basic well costs.

For example purposes, assuming CBM recovery of 0.35 Bcf (gross) per well, the O&M/G&A costs are $0.73 per Mcf.

2.6.4 Water Treatment Costs

A series of alternatives are being used or considered for CBM water disposal in the Powder River Basin, including:

- Untreated or passively treated water with surface discharge.
- Infiltration impoundment with enhanced evaporation and/or land application.
- Shallow re-injection of the produced water.

- Actively treated water with infiltration, evaporation, land application, and/or surface discharge, and disposition of the residual concentrate by trucking or deep re-injection.

The capital costs for the alternative CBM water disposal options add from $2,200 to $42,500 to the cost of a CBM well, as shown in Table 2-10 below for a well producing 350 barrels of water per day in its first year on production. Additionally, O&M costs are calculated for each water disposal option, which range from $.03-$.36/Bbl of produced water.

Table 2-10: PRB CBM Well Water Disposal Capital and O&M Costs

		Water Disposal Costs	
		Capital Costs/Well	O&M Costs/Bbl*
1. CBM Well		$88,000	
2. Water Disposal			
	A. Surface Discharge	$2,190	$0.03
	B. Infiltration Impoundment	$27,440	$0.09
	C. Shallow Re-Injection	$40,050	$0.09
	D. Active Treatment W/Disposal of Residual Concentrate		
	• Trucking	$42,520	$0.36
	• Deep Re-Injection	$42,520	$0.21

*Per Barrel of water produced.

2.6.5 Gas Transportation, Compression, and Fuel Use.

The costs for gas treatment, compression and transportation are subtracted from the PRB netback price to establish a PRB CBM wellhead price. The costs will vary depending on the gathering system charges for transporting natural gas from the compressor to the Colorado Interstate Gas (CIG), or another hub, and on the nature and extent of contracted third-party compression. These costs depend on the location of the CBM development in the PRB, as follows:

- A charge of $0.43 per Mcf is used for third party compression and dehydration (assuming no lease compression) and for transportation, for the central and southern portions of the PRB (Partitions #1, 2, 3, 4, and 5).
- A charge of $0.52 per Mcf is used for third party compression and dehydration (assuming no lease compression) and for transportation, for the northeast and southwest portions of the PRB (Partitions #6, 8, 9 and 10).
- A charge of $0.77 per Mcf is used for third party compression and dehydration (assuming no lease compression) and for transportation, for the northwest and western portions of the PRB (Partitions #7, 11, 12 and 13).

A fuel adjustment (shrinkage) for operating gas powered compressor stations, estimated at 4 to 6% of gross production, is subtracted from the sales volume. A second fuel adjustment (shrinkage), involving the BTU adjustment for CBM, generally 2 to 8% (to account for 920 to 980 Btu content gas), is also subtracted from the sales volume.

2.6.6 Other Considerations.

Royalties. Royalty payments for PRB CBM production depend on mineral ownership, as set forth below:

- Royalties on Federal lands are 12.5%.
- Royalties on state lands are 16.7%.
- Royalties on private lands range from 15% to 20%.

State Severance and Ad Valorem Taxes. State and county tax payments for PRB CBM production are state specific, as set forth below:

- Wyoming severance and ad valorem taxes are 12%.

- Montana severance taxes are 9.3%.

2.6.7 Basis Differentials.

Because of higher transportation costs and other market conditions, the gas price at the CIG (or another Wyoming/Rocky Mountain) hub is discounted from a marker price, set by the Henry Hub or NYMEX. (This is commonly called the basis differential). The model assumes the basis differential is equal to 15% of the Henry Hub spot price.

2.6.8 Economic Scenarios.

Three price scenarios were run, assuming Henry Hub spot prices of $6, $8 and $10/MMBtu.

2.6.9 Sensitivity Analyses.

The performance of MSC Technology was evaluated under two scenarios:

- Scenario #1. MSC wells produce the full theoretical technically recoverable CBM from each competed coal seam.
- Scenario #2. MSC wells produce 80% of the full theoretical technically recoverable CBM from each competed coal seam.

SECTION 3. PERFORMANCE OF MULTI-SEAM CBM WELL COMPLETION TECHNOLOGY IN THE POWDER RIVER BASIN

3.1 Background

One of the major objectives of this study is to evaluate the performance of currently used multi-seam completion practices for coalbed methane in the Powder River Basin. This task involves:

1. Reviewing technical papers and state commission filings on the number and types of multi-seam completions in the PRB;

2. Holding discussions with basin operators to identify and discuss their use of multi-seam completions for CBM recovery;

3. Collecting and assessing data on the performance of this technology, particularly from state regulatory filings for comingling approval; and

4. Identifying aspects of multi-seam well completion technology requiring adaptations and improvements for successful use in the Powder River Basin.

3.2 Overview of CBM Well Completions

The dominant well completion method for coalbed methane wells in the PRB is open-hole, single zone completion. As shown in Figures 3-1 and 3-2, this method provides a low cost, relatively simple access to a coal seam. In brief, the completion procedure is:

- Set surface casing to 60 feet or 10% of the well depth,

- Drill into the top of 2 to 3 feet of the target coal seams, using a light mud system,

- Case across the formation and cement; then drill out and under-ream the coal, and

- Enhance the coal, primarily to clean the coal face and remove near wellbore damage, using injection and circulation of high rates of water, typically 60 barrels per minute.

While using single-zone (or single seam) well completion technology is relatively simple, it has a number of limitations:

- It bypasses the numerous thin (less than 20 feet) coal seams in the basin, as illustrated in Figure 3-3;

- It leads to the drilling of a much larger number of CBM wells, with increased capital investment costs and land disturbance; and

- It leads large areas of the basin to be uneconomic, particularly with the high "basis differentials" and gas gathering costs common to the Powder River Basin.

A striking illustration of these problems is the analytical map showing the large areas of the basin that are currently uneconomic, or only marginally economic. to develop with current single-seam well completion technology, Figure 3-4. This map was submitted to the State of Wyoming by one of the basin's main CBM operators. It dramatically illustrates, for the northern portion of the basin, the critical need for multi-seam well completion technology.

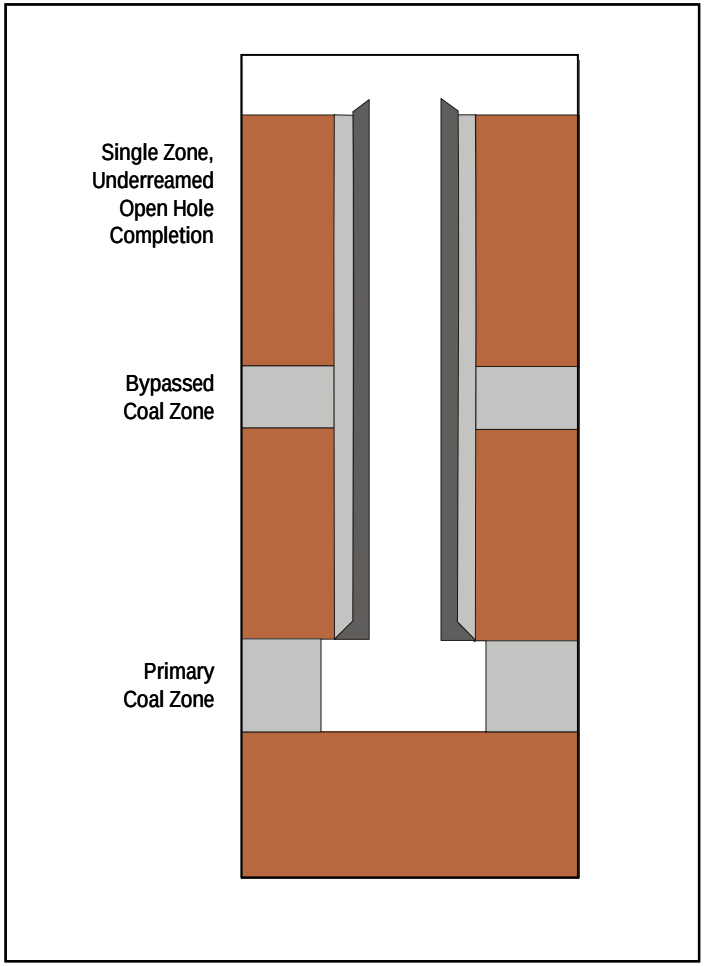
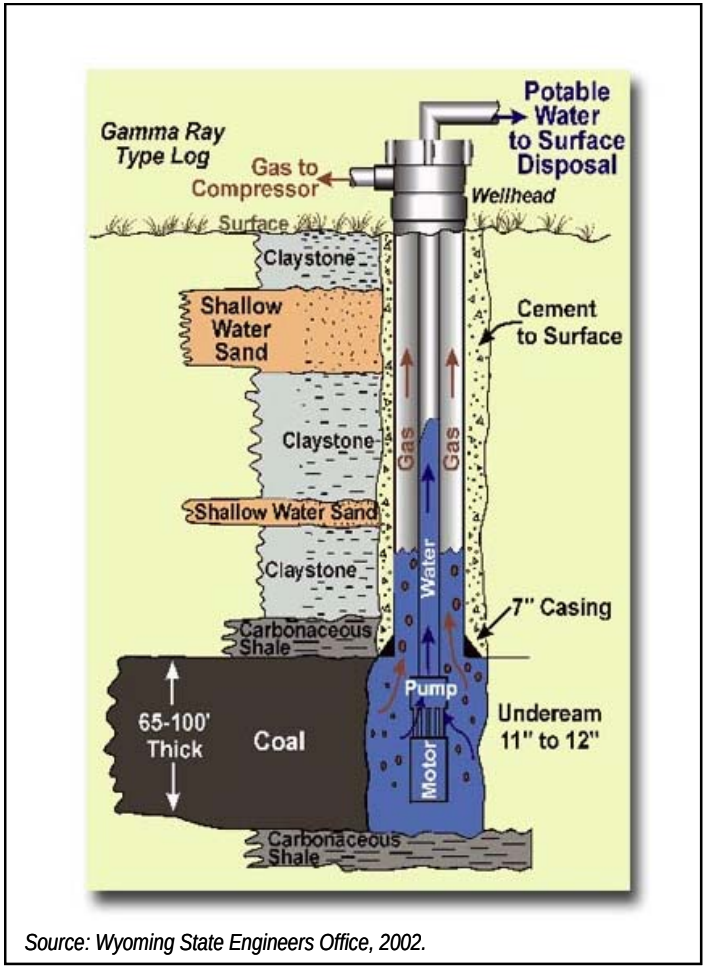


Figure 3-1. Typical PRB CBM Well Completion Practice



Source: Wyoming State Engineers Office, 2002.

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Figure 3-2. Single-Seam Coalbed Methane Well, Powder River Basin

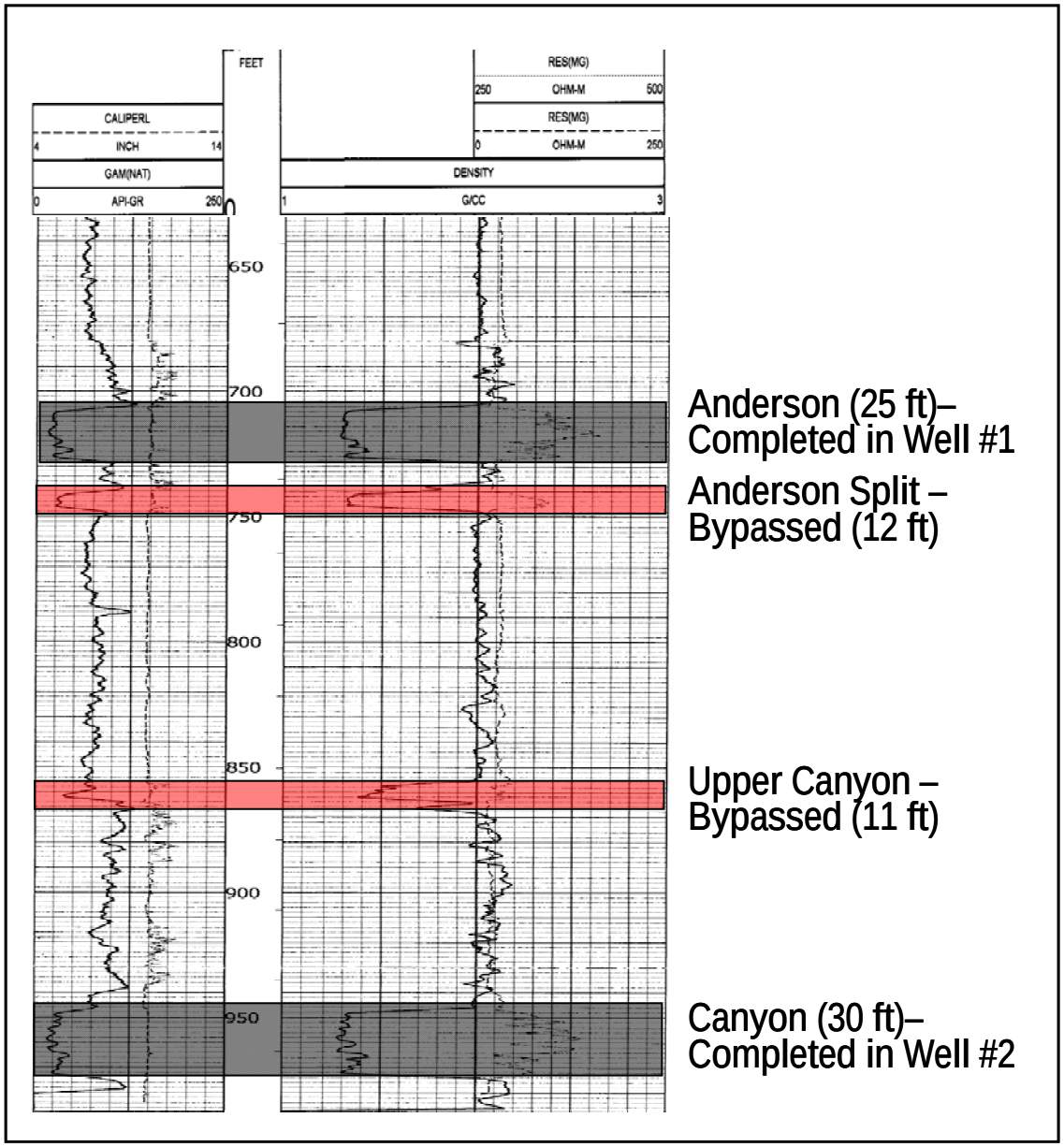

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Figure 3-3. Well Log Showing Typical Fort Union Stratigraphy, Coals Less than 20 Feet Thick Are Not Completed

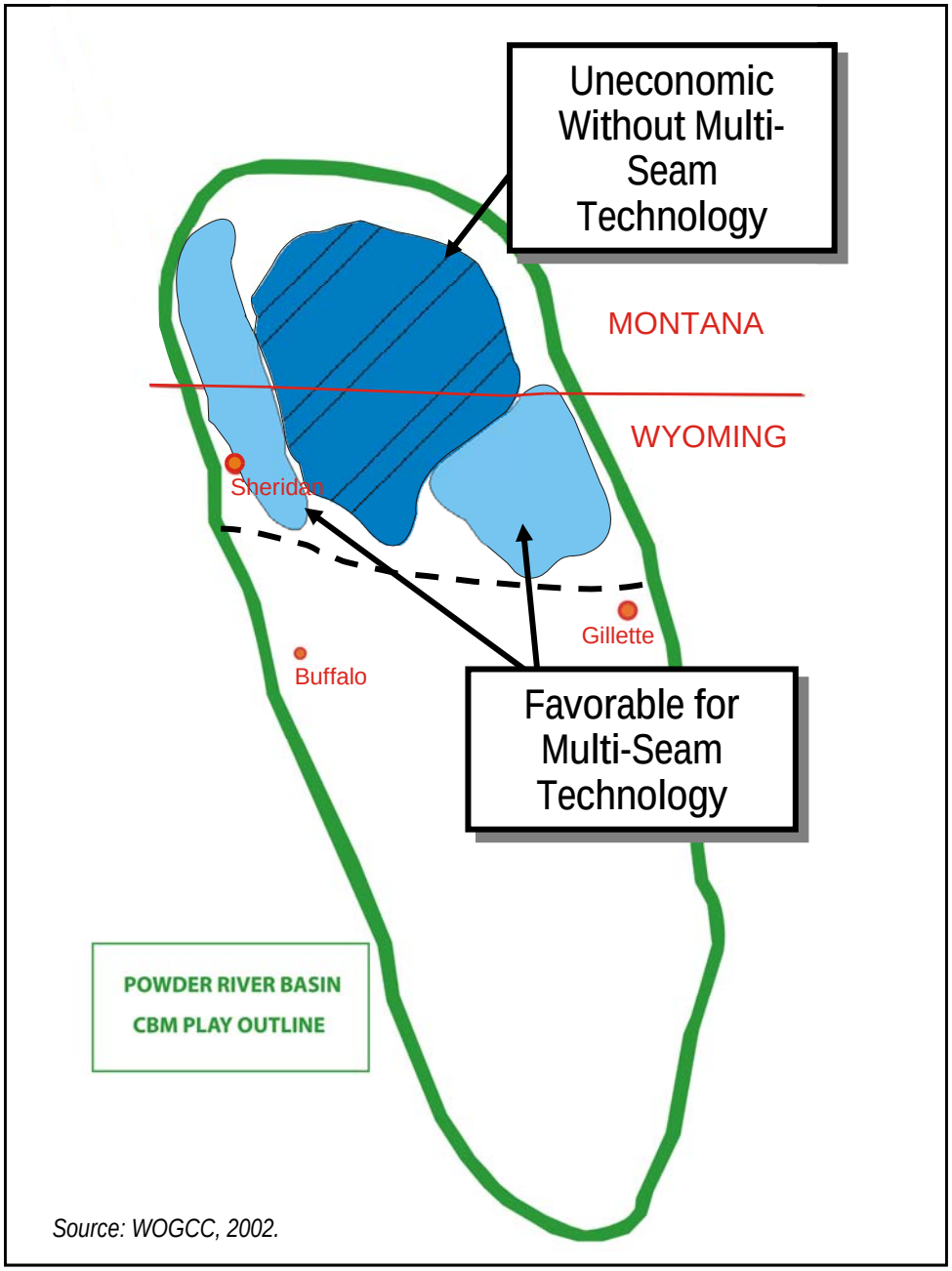

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Figure 3-4. Map, Submitted by Powder River Basin Operator, Showing Areas Where MSC Technology is Vital for Future CBM Development

Several options, adapted from well completion practices in other CBM basins, exist for multi-seam well completion technology, as illustrated in Figures 3-5 and 3-6.

- In the first option, the approach is to complete two (or more) coal seams as open-hole and then hang a perforated steel liner across the open-hole interval. A variant on this option is to hang a PVC liner, and then under-ream the liner to assure access to the coal.
- In the second option, the approach is to drill and case across the coal and then perforate the casing to gain access to the multiple seams.
- The third option is to use a combination of the above. The deepest coal is completed open-hole; casing is set and the up-hole coals are perforated.

The problem is that these relatively straight forward applications of multi-seam well completion technology have not proven to be successful in the Powder River Basin. In many cases, because of damage to the coal seams, a multi-seam well produces less CBM than a single-seam well.

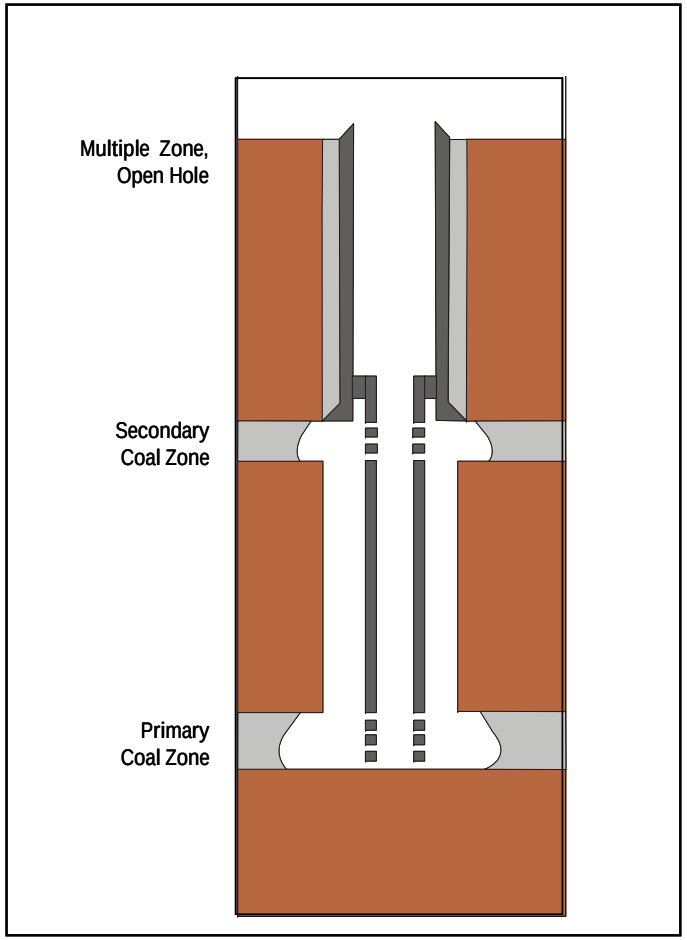

Figure 3-5. Multi-Seam Completion Option 1. Coals Are Completed Open Hole; Perforated Steel or PVC Liner is Hung Across the Open Hole Interval

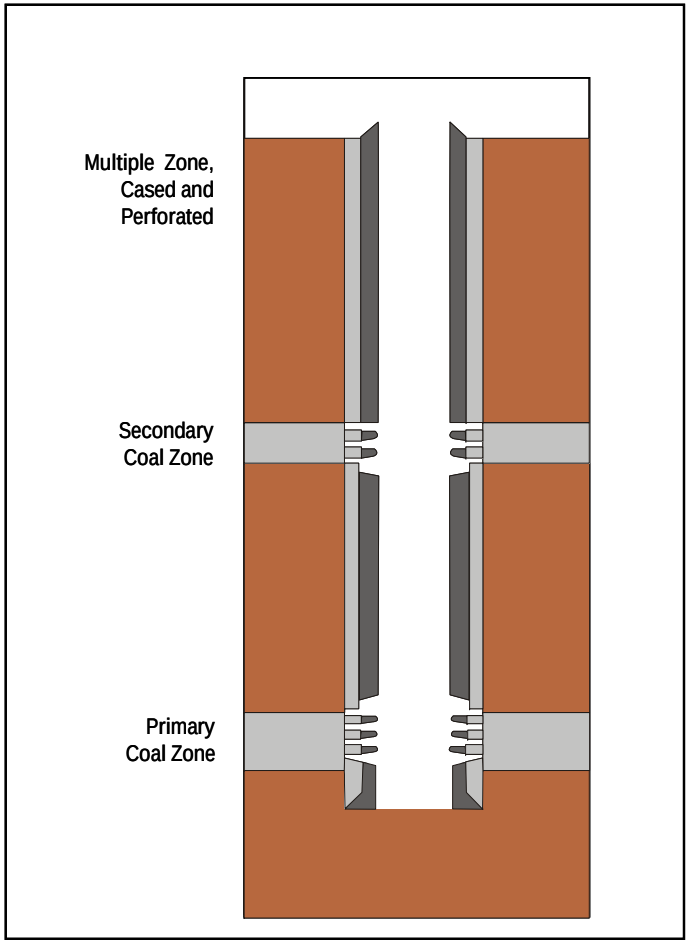

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Figure 3-6. Multi-Seam Completion Option 2. Entire Coal Interval is Drilled and Cased; Then Perforated to Gain Access to Coal Seams.

3.3 Field Case Studies

To better understand the performance and problems with multi-seam completion technology, we examined four significant, long-term, multi-seam CBM well completion projects in the PRB. These projects are located in the northern Wyoming portion of the Powder River Basin, Figure 3-7 and are representative of the current state of multi-seam well completion technology and performance in the basin. In addition, we included a successful adaptation of multi-seam coal completion technology developed for producing multiple, thin coals in the Surat Basin of Eastern Australia

3.3.1 Methodology.

Production data from the wells in each project were collected and aggregated. The single-seam completions served as the control wells for each project, establishing a baseline of expected CBM production performance. The performance of multi-seam well completions (producing from these same and additional coal seams) was judged using this control set of single-seam wells.

In all four field case studies, the single-seam CBM wells were completed open-hole. Casing was set just above the coal interval and the coal itself was under-reamed. After flushing the coal with high rates of injected water, the CBM well was placed on production. For the multi-seam wells, the coal interval was cased with the lowest coal completed open-hole. The shallower coal seams were then accessed through perforations in the casing.

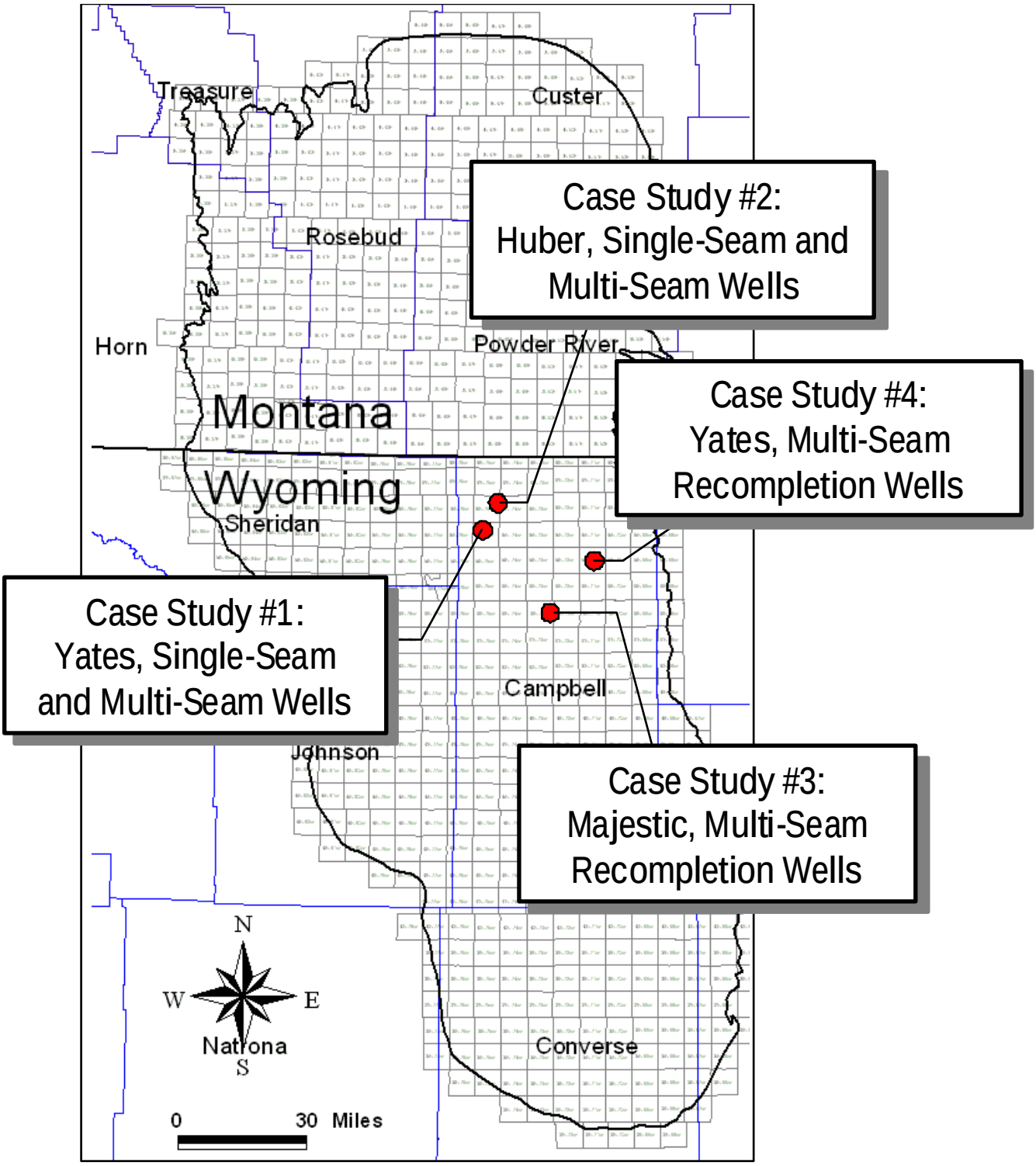

Figure 3-7. Location Map for Multi-Seam Case Studies

In an ideal multi-seam well, all completed zones would contribute their full potential to CBM production. Well damage and ineffective perforations during completion, however, appear to limit CBM production mainly from the open-hole primary seam, which the up hole coal seams performing as highly damaged coal completions.

3.3.2 Field Examples.

Case Study #1

Case Study Design. Case Study #1 involves a side-by-side comparison of the performance of nine single-seam completed Canyon coal wells and five multi-seam completed Canyon, Cook and Wall coal seam wells. All of the wells are in S.16 of T55N R75W, providing geologic and reservoir uniformity to the comparison of performance.

The wells are operated by Yates Petroleum, one of the Powder River Basin's technically strong operators. The Case Study #1 field site and the location of the nine single-seam Canyon wells and the five multi-seam Canyon-Cook-Wall wells are shown in Figure 3-8.

Target Coal Seams. The main coal completion objective, the Canyon seam, is a 50 to 60 foot coal at 500 to 600 feet of depth. The second completion objective, the Cook seam (called Lower Canyon by the operator), is a 30 foot coal at 800 to 900 feet of depth. The third completion objective, the Wall seam, is a 30 foot coal at 1,000 to 1,100 feet of depth. Ideally, producing the Cook and Wall seams with the Canyon seam, a package of over 100 feet of net coal, would lead to a well with gas flow rates and reserves about two times higher than producing the Canyon seam alone.

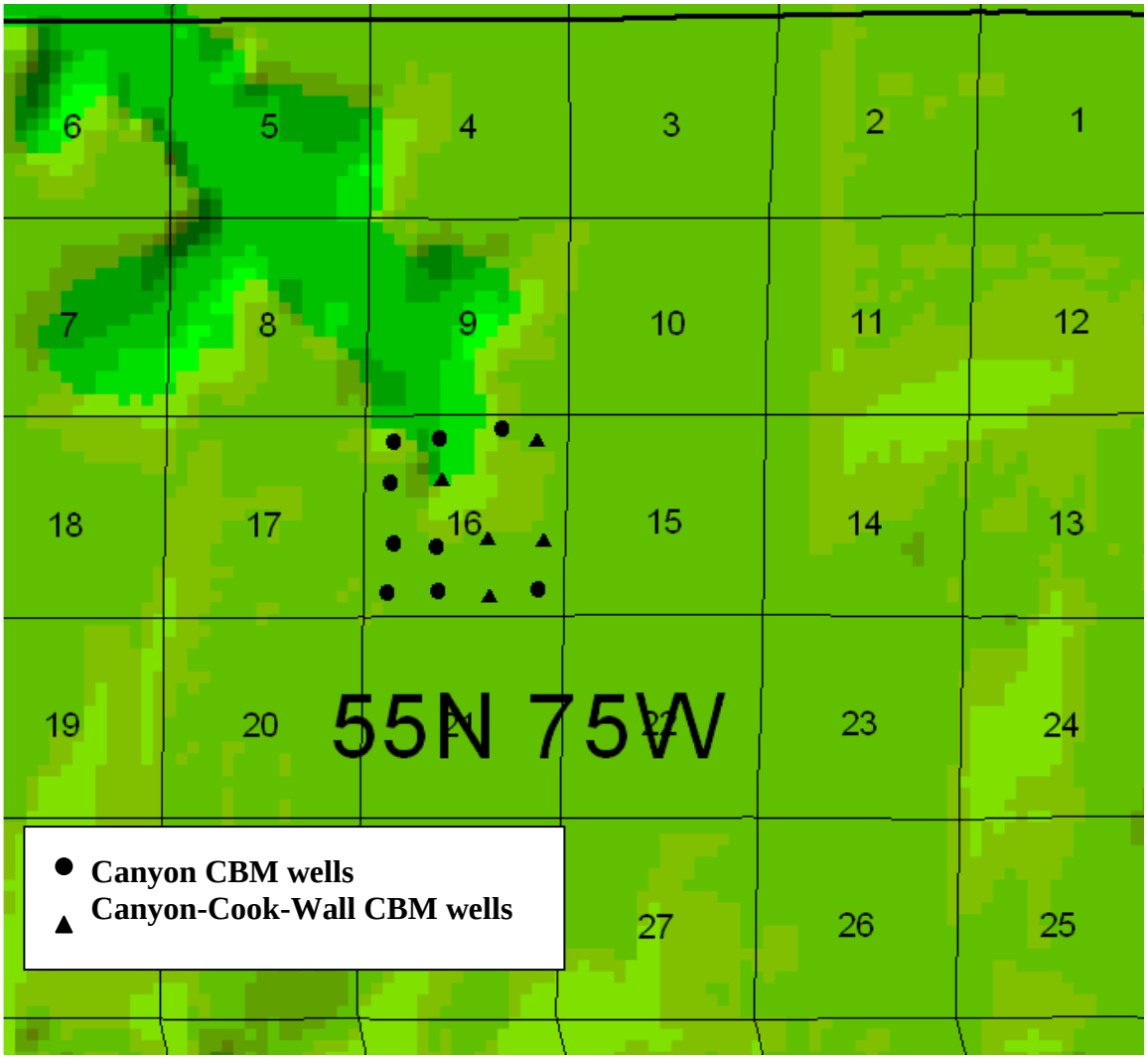

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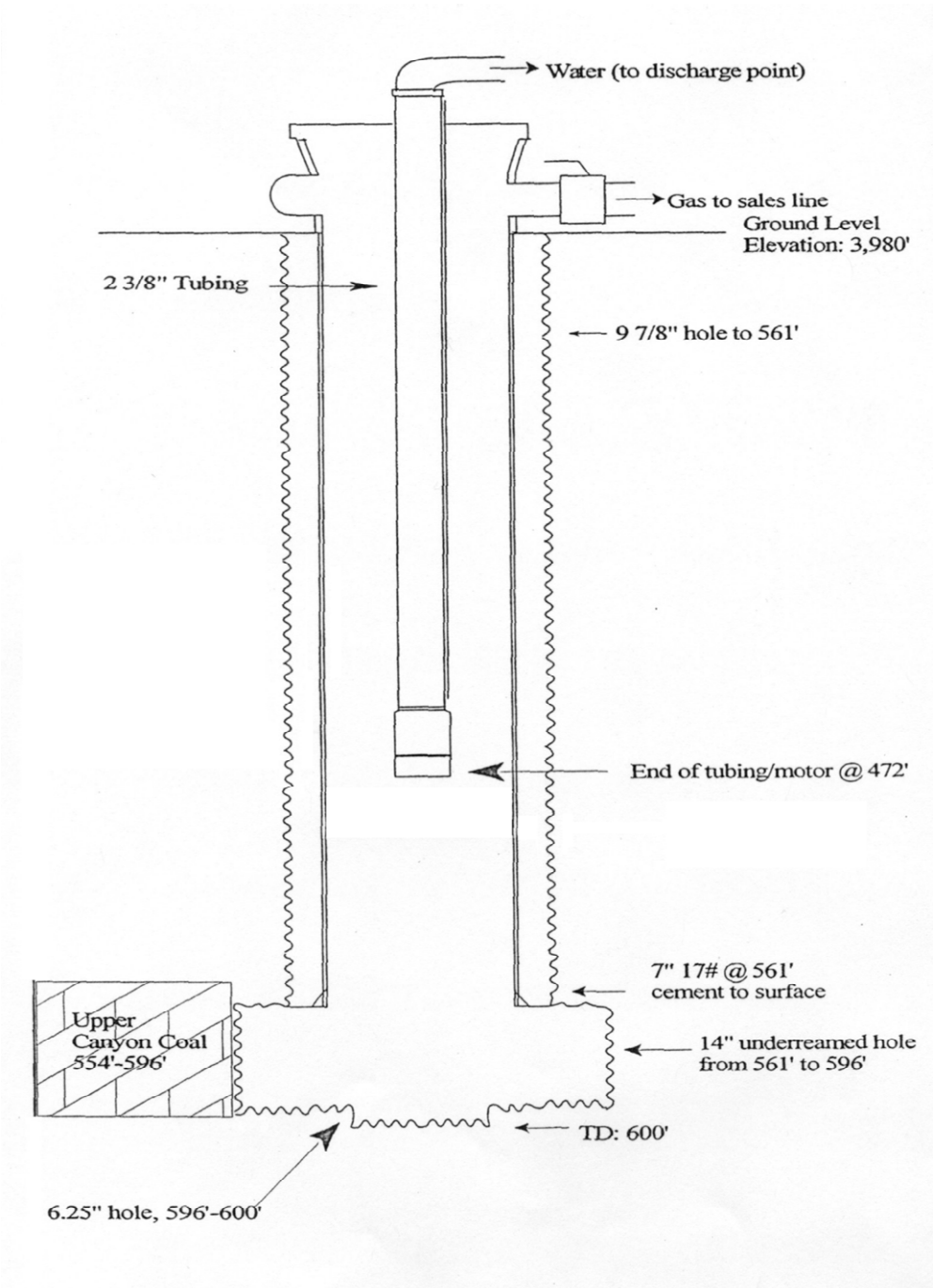
Figure 3-8. Location of Yates CBM Wells Included in Case Study #1.

Single-Seam Well Completion Strategy and Performance. The nine single-seam Canyon wells were completed open-hole. This mode of well completion is shown for one of the Case Study wells, the Spotted Horse CS State #13, Figure 3-9. These wells are moderate CBM producers, having recovered 49 MMcf of gas during their first year on line and 91 MMcf during their first 20 months of production, on average. This set of wells provide the "control set" against which current multi-seam well completion technology is judged for this area of the basin.

Multi-Seam Well Completion Strategy and Performance. The five multi-seam wells are completed with the lowermost Wall coal kept open-hole and with the shallower Cook (Lower Canyon) and the main Canyon seams cased and perforated. This mode of well completion is shown for one of the Case Study wells, the Spotted Horse CS State #3, Figure 3-10.

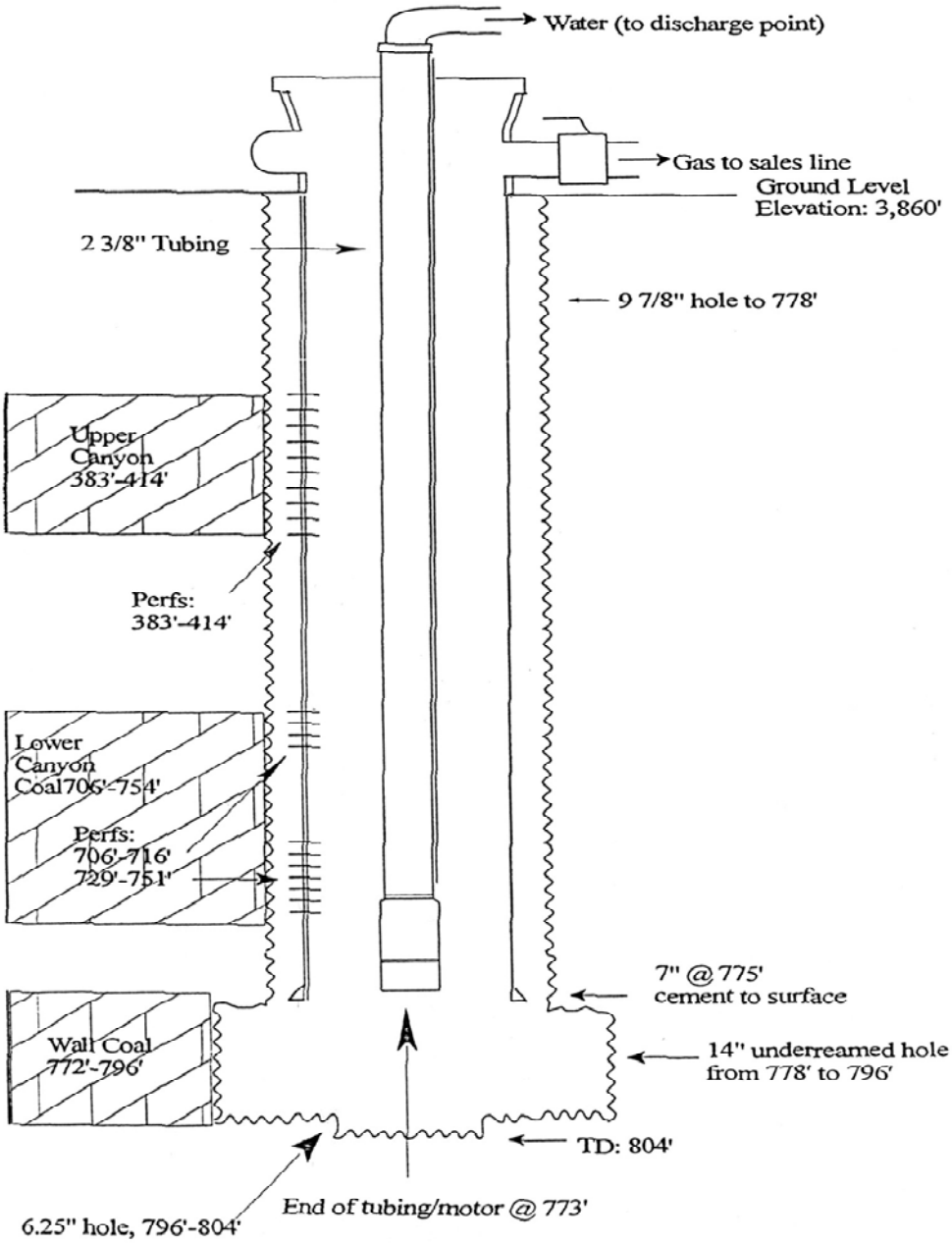
At the time of the last study, the performance of the five multi-seam wells was disappointing. The cumulative gas production during their first year online was 40 MMcf and only 80 MMcf during their first 20 months, on average. These multi-seam wells, though in contact with over twice as much net coal as the single-seam wells, had a lower recovery than the single-seam Canyon well, as shown in Table 3-1.

The data in Table 3-1 show that CBM production from the MSC wells was increasing as water production was declining. However, at the time of the last study, not enough data was available to determine to what extent the accelerated dewatering in the MSC wells would lead to higher CBM production.



Source: WOGCC, 2002.

Figure 3-9. Case Study #1 Single-Seam Well. Lowest Coal is Completed Open-Hole.



Source: WOGCC, 2002.

Figure 3-10. Case Study #1 Multi-Seam Well. Lowest Coal is Completed Open-Hole. Access to Up Hole Seams is Through Perforations.

Table 3-1. Performance of SSC and MSC Wells, as of 2003

	Single Seam Wells Canyon	Multi-Seam Wells Canyon/Cook/Wall
Cumulative Recovery (MMcf)		
Month 12	49	39
Month 20	91	80
Daily Gas Rate (Mcfd)		
Month 12	119	30
Month 20	169	128
Daily Water Rate (Bbls/Day)		
Month 12	75	136
Month 20	113	81

Update of Well Performance Since the Last Study. The production data for the five years since the last study show that, once dewatered, the MSC wells now outperform the single seam Canyon well completions. Figures 3-11 and 3-12 show the annual water production and the cumulative CBM production for the SSC and MSC wells in Case Study #1. After 80 months of production, the MSC wells have recovered 397 MMcf of gas and are still producing at 79 Mcfd. The SSC wells have only recovered 255 MMcf and are producing at 26 Mcfd, Table 3-2. In addition, the table provides our estimates of the estimated ultimate recovery (EUR) for the SSC and the MSC wells after ten years (120 months).

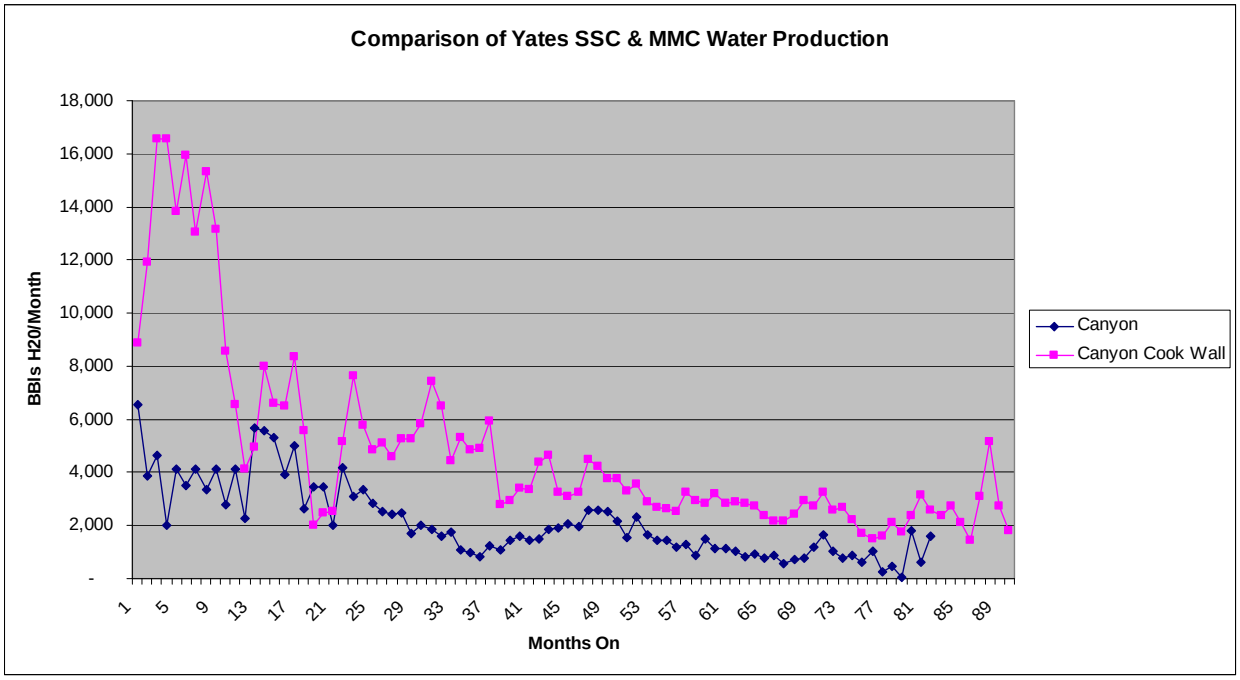


Figure 3-11. Comparison of Yates SSC and MSC Wells Water Production

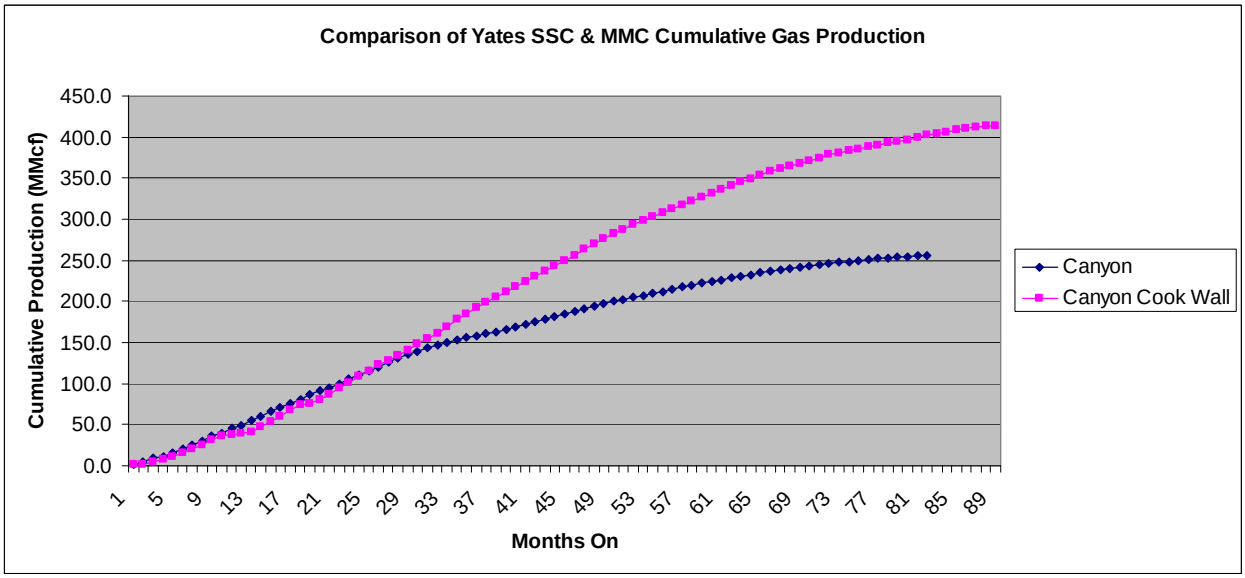


Figure 3-12. Comparison of Yates SSC and MSC Wells Cumulative Gas Production

Table 3-2. Performance of SSC and MSC Wells as of 2008

	Single Seam Wells Canyon	Multi-Seam Wells Canyon/Cook/Wall
Cumulative Recovery (MMcf)		
Month 12	49	39
Month 20	91	80
Month 36	159	192
Month 60	224	332
Month 80	**255**	**397**
EUR	**270**	**450**
Daily Gas Rate (Mcfd)		
Month 12	119	30
Month 20	169	128
Month 36	84	239
Month 60	75	161
Month 80	**26**	**79**
Daily Water Rate (Bbls/Day)		
Month 12	75	136
Month 20	113	81
Month 36	27	162
Month 60	37	104
Month 80	**59**	**79**

The current evaluation is that the larger coal package contacted by MSC Technology required a longer period of dewatering before the wells reached peak CBM production. After the coals in the MSC wells were sufficiently dewatered, their performance improved markedly, surpassing that of the SSC wells.

However, the MSC wells in this case study, while surpassing the performance of the SSC wells, are still underperforming relative to their theoretical potential. The MSC well that accessed the Canyon, Cook and Wall coal seams should have (theoretically) recovered 730 MMcf. However, the MSC wells analyzed in this case study will only achieve an estimated ultimate recovery (EUR) of 450 MMcf, equal to about 60% of their theoretical potential, Table 3-3. This CBM production underperformance is likely caused by damage to the Canyon, Cook and Wall coal seams during well drilling and cementing, which could not be efficiently overcome with traditional well perforations or fluid circulation.

Table 3-3. Theoretical MSC CBM Recovery from Canyon, Cook and Wall Seams in Case Study #1

Seam	Depth (Feet)	Thickness (Feet)	Gas Content (scf/ton)	GIP/Well* (MMcf)	Expected Ultimate Recovery**
Canyon	550	60	36	384	270
Cook	875	30	51	269	210
Wall	1060	30	58	307	250
Total (Expected MSC Recovery)					730
Projected MSC Recovery					450

* Assuming 80 acre/well spacing
**Combining individual SSC recovery efficiencies for Canyon, Cook and Wall seams

It is encouraging to see the improved, though still less than optimum, performance in the five MSC wells. However, the much lower performance of these MSC wells during the initial two years on-line severely hurts their economics. Higher volume pumps, to promote faster dewatering and use of larger diameter well casings, as discussed in the Australia Case Study, may help accelerate gas production in the MSC wells.

Case Study #2

Case Study Design. Case Study #2 involves a side by side comparison of 23 single-seam completed wells and 18 multi-seam completed wells. The wells are clustered in a 10 section area, in T55N, R74W and T56N R75W. The location of the Case Study #2 CBM wells is provided on Figure 3-7 and Figure 3-13. This large well population in a relatively confined area provides a valuable data set for examining the performance of single seam and multi-seam technology.

The wells are operated by Huber, one of the more experienced operators in the basin. The Case Study #2 field site is located in the northern portion of the basin, close to the Wyoming and Montana border.

Target Coal Seams. The coal seams targeted with single-seam completions are the Wall (with 17 wells) and the Cook (with 6 wells). In this area, the Wall coal is 28 to 35 feet thick, at a depth of 660 to 945 feet. The Cook coal is 25 to 45 feet thick, at a depth of 460 to 820 feet.

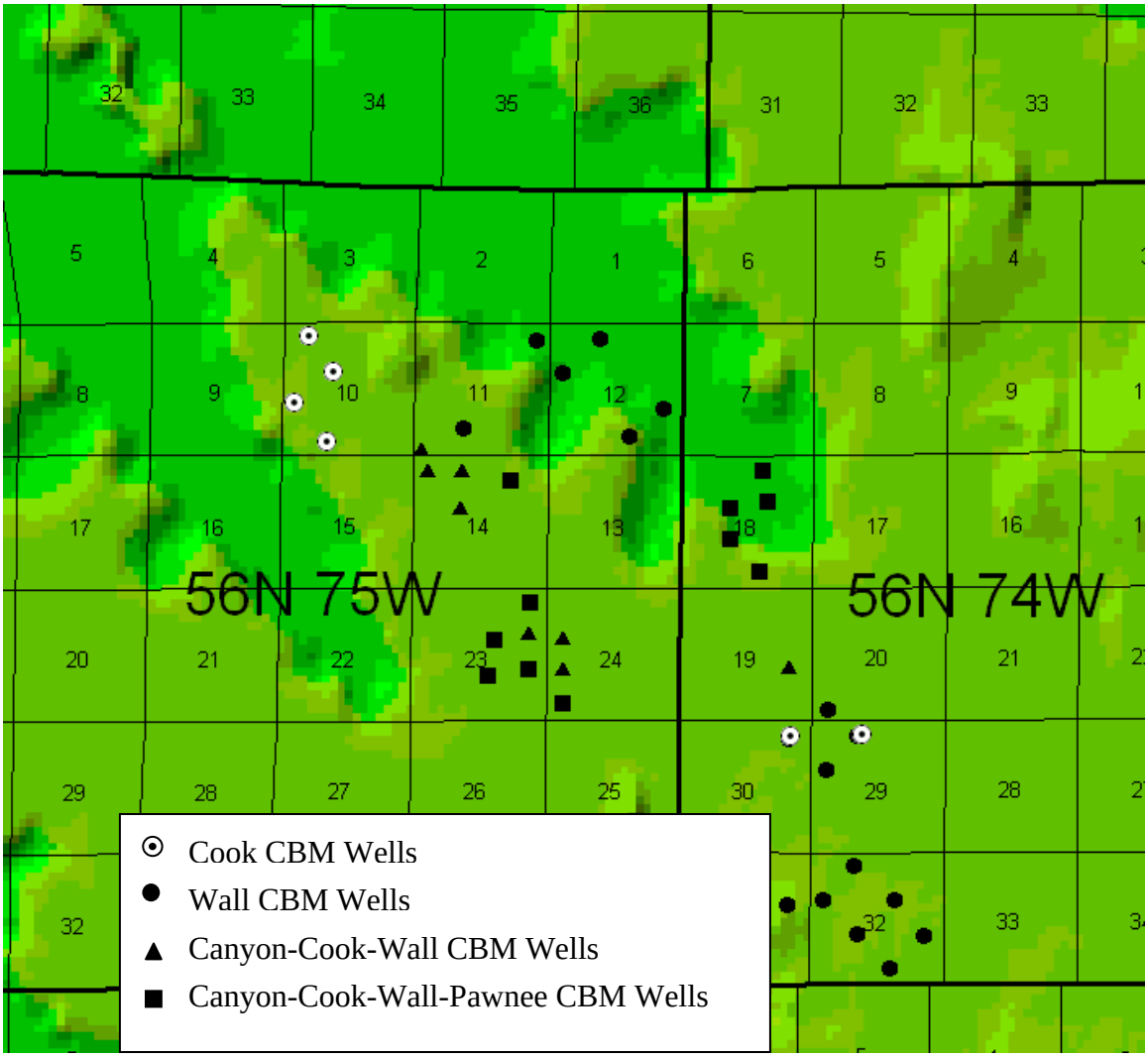


Figure 3-13. Location of Huber CBM Wells Included in Case Study #2.

The 18 multi-seam completed wells combine the Cook and Wall seams with the Canyon (Upper Cook) in 6 wells and combine the Cook and Wall seams with the Canyon and Pawnee in 12 wells. The shallower Canyon coal in this area is 35 feet thick, at a depth of 370 to 570 feet. The deeper Pawnee coal is 15 to 25 feet thick, at a depth of 870 to 1,010 feet.

Successfully combining the Canyon, Cook, Wall and Pawnee coals with multi-zone completed wells (targeting over 100 net feet of coal) should lead, ideally, to a well with about three times as much gas production as a single-seam Wall or Cook well completion (with 30 to 35 feet of net coal).

Single-Seam Well Completion Strategies and Performance. The single-seam Wall and Cook wells are completed open hole. After the first twelve months online, the average Wall CBM well had recovered 45 MMcf and was producing at 138 Mcfd; the average Cook CBM well had recovered 51 MMcf was producing at 152 Mcfd. At this point, both the Wall and the Cook wells had reached peak gas production following a period of significant dewatering.

After six years online, the Wall single-seam wells have produced an average of 179 MMcf of gas per well and the Cook single-seam wells have produced an average of 176 MMcf per well, Table 3-4. The expected ultimate recovery is 210 MMcf for the average Wall well and 180 MMcf for the average Cook well.

Table 3-4. Average Case Study #2 Single Seam And Multi Seam Well Performance. (The Numbers Of Wells Included In "Time-Zero" Averages Are In Parentheses.)

	Single-Seam Wells		Multi-Seam Wells	
Months On Production	**Wall (17 wells)**	**Cook (6 wells)**	**Canyon-Cook-Wall (6 wells)**	**Canyon-Cook-Wall-Pawnee (12 wells)**
Daily Gas Rate (Mcfd)				
12	138	152	100	168
24	111	115	89	128
48	57	51	82	128
72	28	10	41	50
Daily Water Rate (BBls/d)				
12	314	403	263	509
24	157	120	286	312
48	98	108	119	175
72	57	29	95	158
Cumulative Gas Recovery (MMcf)				
12	45	51	25	39
24	90	97	68	95
48	153	150	132	208
72	179	176	181	268
EUR	210	180	220	310

Multi-Seam Well Completion Strategy and Performance. The multi-zone wells are completed with the lowest-most coal kept open-hole and the shallower coals cased and perforated. The performance of the multi-zone wells compared to the single-seam wells is disappointing, Figures 3-14 and 3-15.

After 12 months on-line, the average three-seam well - - with Wall, Cook and Canyon coals - - had recovered just 25 MMcf and was producing 100 MMcfd. After six years, the average three-seam well, despite theoretically being in contact with almost three times more coal than a single seam well, has recovered 181 MMcf of gas and is producing at 41 Mcfd. The expected ultimate recovery is 220 MMcf for the average three-seam well. More detailed results are presented in Table 3-4. Production analysis suggests that a well contacting the 103 feet of coal contained in the Canyon, Cook and Wall seams in this area should ultimately recover 530 MMcf. As such, the three-seam well completion in Case Study #2 has recovered only about 40% of its theoretical potential, Table 3-5.

After 12 months on-line, the average four-seam well - - with Pawnee, Wall, Cook and Canyon coals - - had recovered 39 MMcf and was producing at 168 Mcfd, also less then either of the SSC wells. Since then, gas recovery and production have improved. After six years of production, the average four-seam well has produced 268 MMcf of gas and is producing at 50 Mcfd. The estimated ultimate recovery is of 310 MMcf for the four-seam wells. Production analysis suggests that a MSC well containing the 120 feet of coal in the Canyon, Cook, Wall and Pawnee seams should ultimately recover 680 MMcf of gas. As such, the four-seam well completion in Case Study #2 has recovered less than 50% of its theoretical potential, Table 3-5.

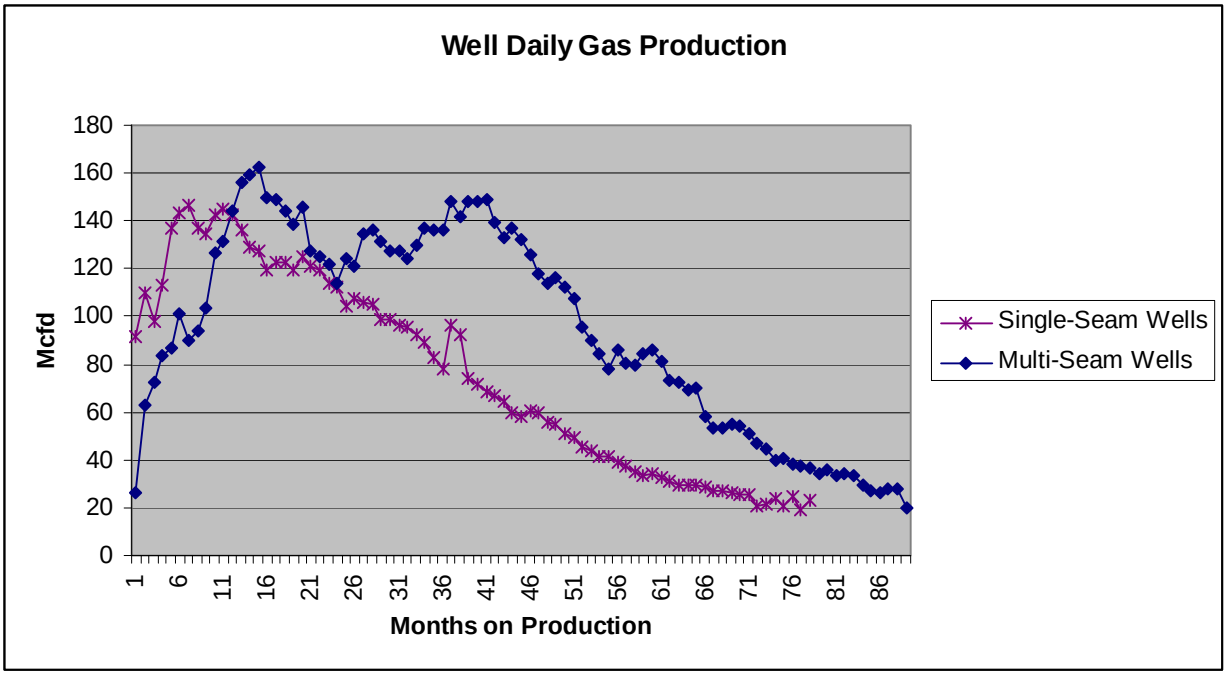


Figure 3-14. Comparison of Huber SSC and MSC Average Well Daily Gas Production

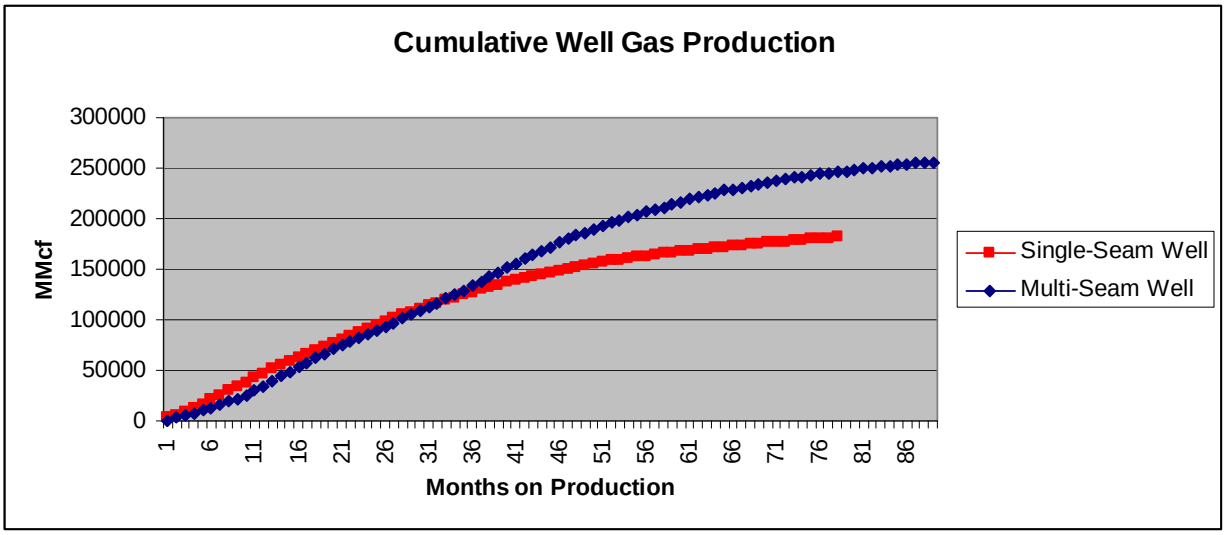


Figure 3-15. Comparison of Huber SSC and MSC Average Well Cumulative Gas Production

Table 3-5. Theoretical MSC Recovery from Canyon, Cook and Wall Seams in Case Study #2.

Seam	Depth (Feet)	Thickness (Feet)	Gas Content (scf/ton)	GIP/Well* (MMcf)	Expected Ultimate Recovery**
Canyon	470	36	31	198	140
Cook	640	35	40	247	180
Wall	800	32	48	270	210
Pawnee	940	19	54	181	150
Expected 3 Zone MSC Well Recovery					530
Actual 3 Zone MSC Well Recovery					220
Expected 4 Zone MSC Well Recovery					680
Actual 4 Zone MSC Well Recovery					310

* Assuming 80 acre/well spacing

**Combining individual SSC recovery efficiencies for Canyon, Cook and Wall & Pawnee

The poor performance of the MSC wells analyzed in Case Study #2 is likely due to excessive coal damage caused during the multi-seam well completion, involving drilling and cementing. It appears that traditional coal perforating and fluid circulation is not able to fully penetrate past three zones of well damage.

Case Study #3

Case Study Design. Case Study #3 involves the use of multi-seam technology to add the Anderson seams to five existing single-seam CBM wells, initially completed in the Canyon coal. Three of the wells are in S.11 and S.12 of T52N R72W and two of the wells are in an adjoining area, S.18 and S.19 of T52N R73W. The wells are operated by Majestic Petroleum LLC, a small independent operator in the Powder River Basin. The Case Study #3 field site is located in the east-central portion of the basin, as shown in Figure 3-7 and Figure 3-16.

Target Coal Seams. The main target, the Canyon seam, is a 40 to 60 foot coal at 330 to 430 feet of depth. The shallower Anderson seam has 18 to 35 net feet of coal at a depth of 280 to 340 feet. Successfully adding and producing the Anderson coal seam with the Canyon seam would, ideally, lead to a well with about 40% higher gas reserves as a single-seam Canyon coal completion.

Single-Seam Well Completion Strategies and Performance. The initial coal completions in the five Canyon coal wells were open-hole single-seam. After three years of operation, the five Canyon wells had recovered 175 MMcf of CBM (on average) and were producing at about 100 MMcf.

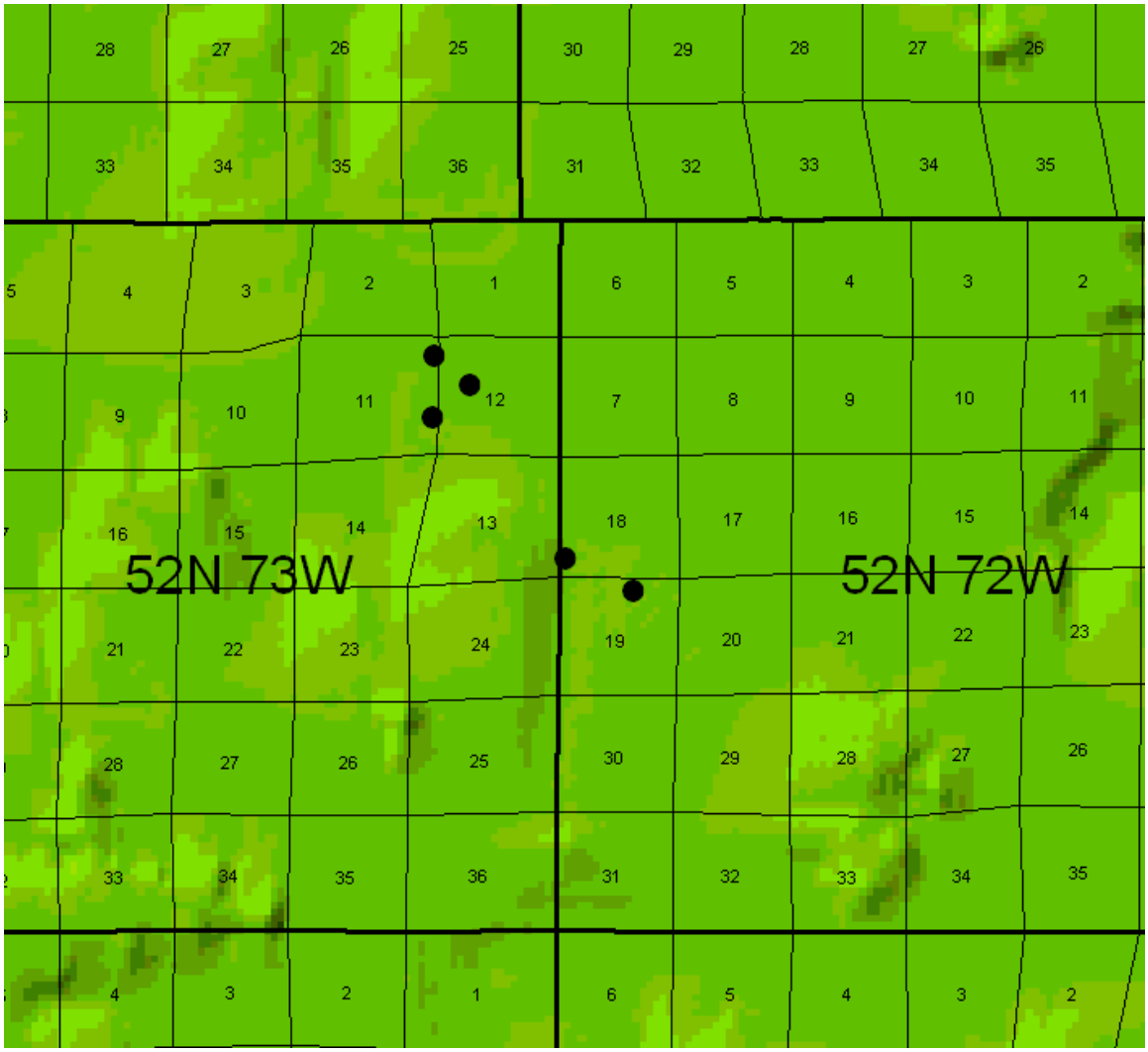


Figure 3-16. Location of Majestic CBM Wells Included in Case Study #3.

Performance of Multi-Seam Technology. In August of 2001, with gas production in modest decline (about 2% per month), the operator recompleted these five wells to add the Anderson coal seam and began reporting the data on a commingled basis. For the five multi-zone recompletions, initial results were promising as production rose by about 20% from what was expected from the Canyon seam alone. In addition, since the recompletion, the production rate of the recompleted wells has remained above what would have been expected from the Canyon seam alone (assuming a constant 2% production decline).

By April 2008, the recompleted wells had produced, on average 332 MMcf, and were producing at a rate of 22 Mcfd. Assuming a constant production decline of 2% annually, the single seam completed Canyon wells would have produced 296 Mcf in this same period, see Table 3-6 and Figure 3-17.

Table 3-6. Average Case Study #3 Single Seam and Multi-Seam Recompleted Wells

Cumulative Recovery (MMcf)	Canyon Single Seam*	Anderson Recompletion	Total Well Performance
36 Months	175	N/A	175
60 Months	233	10	243
80 Months	263	22	285
117 Months (To Date)	296	36	332

* Performance after 36 Months is estimated based on assumed 2% production decline

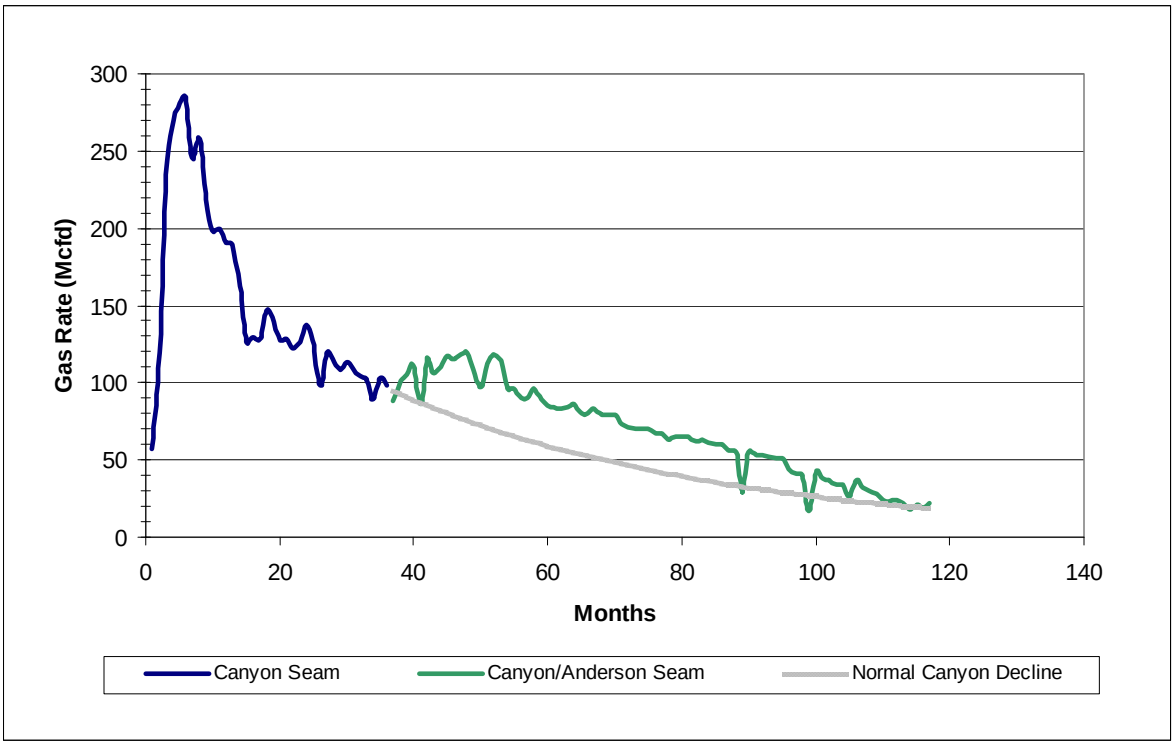


Figure 3-17. Performance of the Case Study #3 Wells Before and After Being Recompleted into the Anderson Seam.

Though recompleting into the Anderson seam improved the overall recovery of these five wells, the addition of 36 MMcf from the Anderson seam is far below what would be expected based on its depth and coal thickness. Figure 3-18 compares the expected (theoretical) CBM recovery performance of the Anderson seam of nearly 100 MMcf, with the actual performance of the Anderson well of only 36 MMcf, implying 36% performance factor.

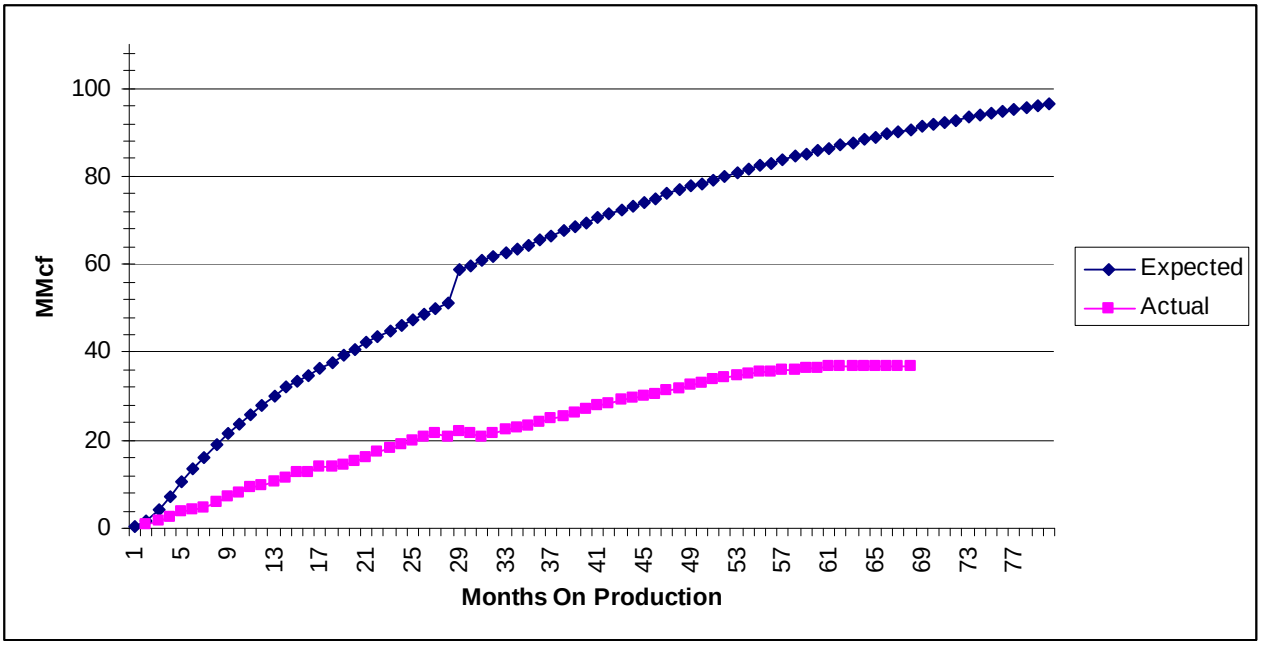


Figure 3-18. Expected and Actual Performance of the Recompleted Anderson Seam in Case Study 3 Wells

Case Study # 4

Case Study Design. Case Study # 4 provides a comparison of a group of 16 wells drilled in June 2000 in Township T54N R73W. Each well was drilled into the Cook coal seam on 40 acre spacing. Eight of the original 16 wells were recompleted in 2003 to also produce from the overlying Canyon coal seam. The wells are divided equally into four adjacent 160 acre parcels, each of which contains two single-seam wells producing from the Cook seam and two recompleted multi-seam wells producing from the Canyon and Cook seams. The location and completion timing of these wells allows for an excellent comparison of the performance of SSC and MSC Technologies.

The Case Study #4 wells are operated by Yates Petroleum, the same operator discussed in Case Study #1. The field site is located in the northeastern portion of the basin, as shown in Figure 3-8. The locations of the 18 wells analyzed in the case study are shown in Figure 3-19.

Target Coal Seams. The coal seam initially targeted by the 16 wells, the Cook (called Lower Canyon by the operator), is at 340 to 370 feet of depth and is 21 to 25 feet thick. The later completed Canyon coal seam is at 180 to 200 feet of depth and is 16 to 18 feet thick. Optimally, producing the Canyon and Cook seams together would lead to a well with 50% to 70% higher CBM recovery than from the Cook seam alone.

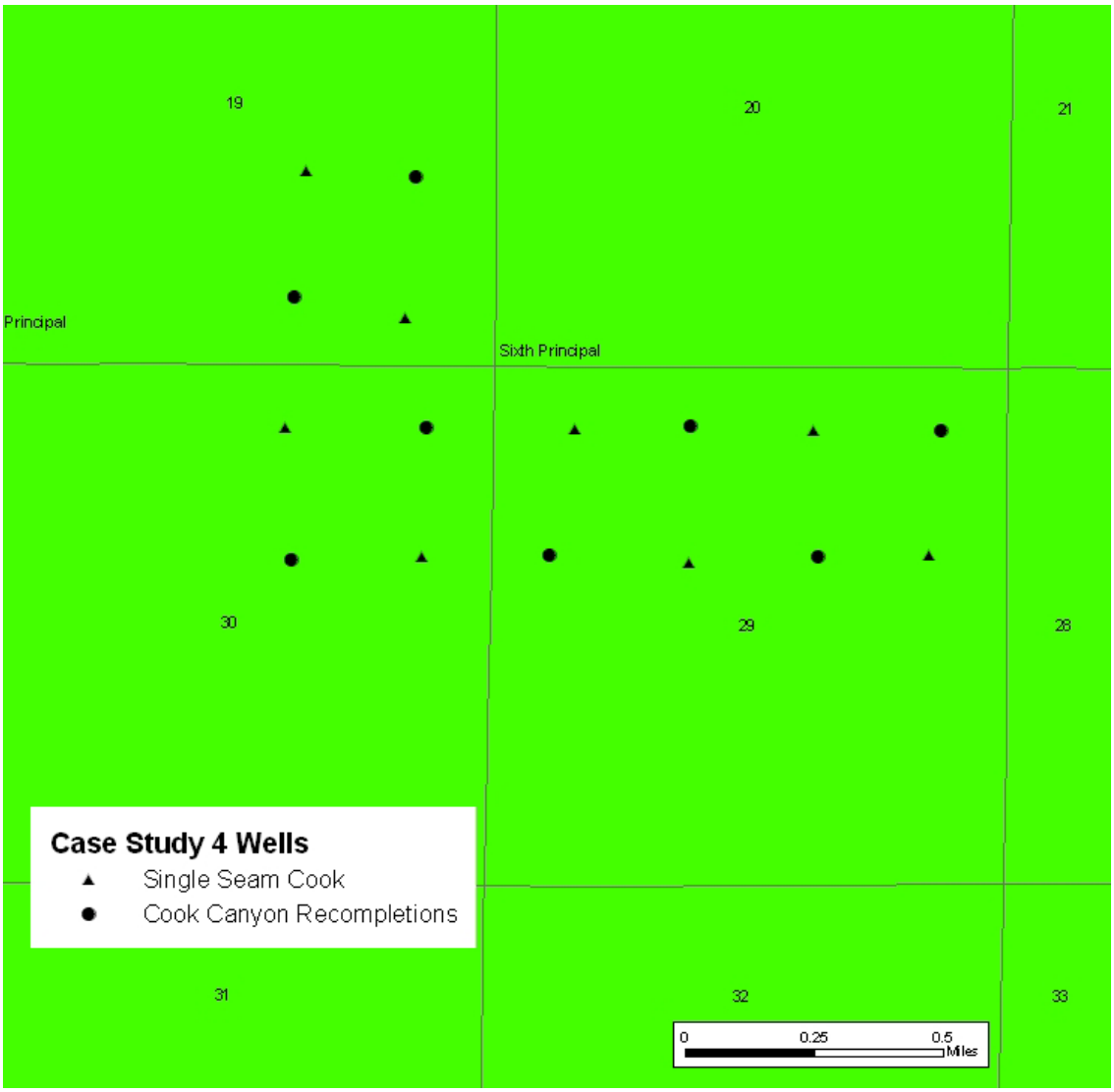
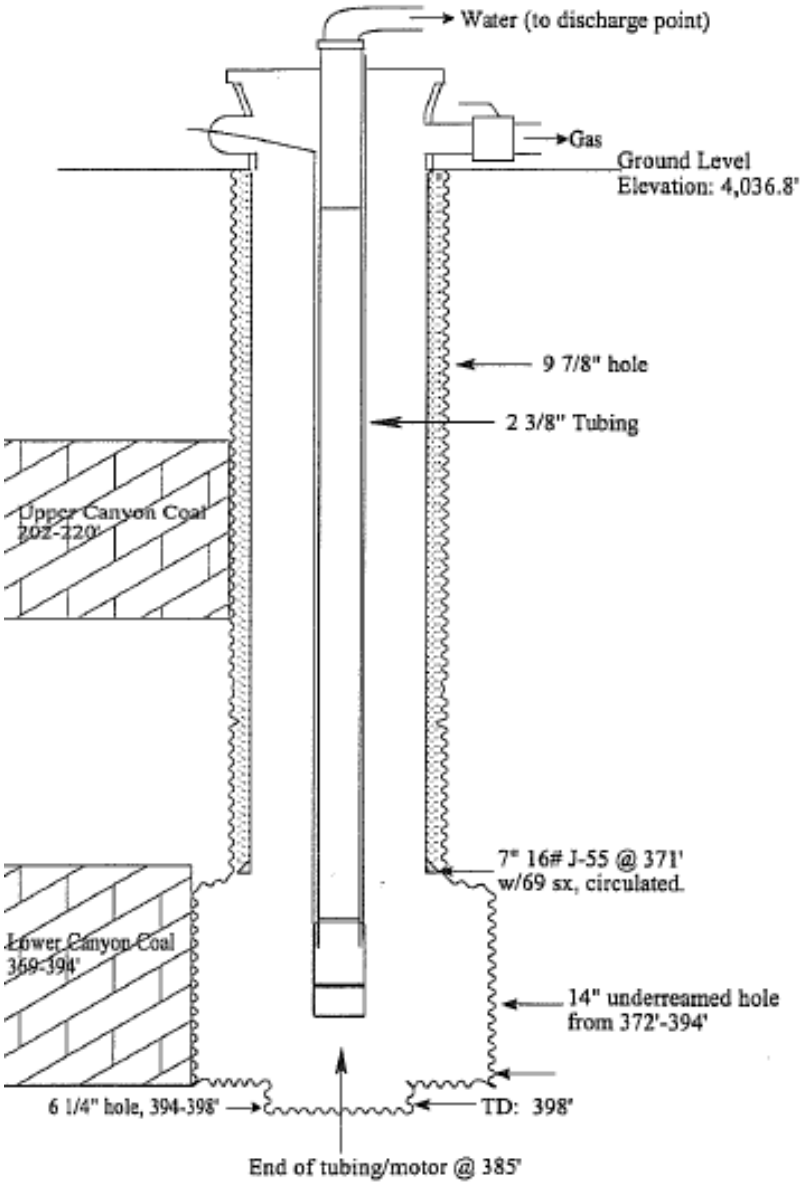


Figure 3-19: Location of Case Study #4 Wells in T54N 73W

Single-Seam Well Completion Strategy and Performance. All 16 original wells were drilled and cased to the top of the Cook seam and then completed open hole in the Cook coal. This typical single-seam well completion is shown for one of the Case Study wells, the Carson East CS State #4, Figure 3-20. These wells are low CBM producers, having recovered, on average, 55 MMcf during their first 36 months. Eight of the sixteen wells were recomplete in the Canyon Coal. The remaining eight wells provide the "control set" against which multi-seam well completion technology is judged in Case Study # 4.

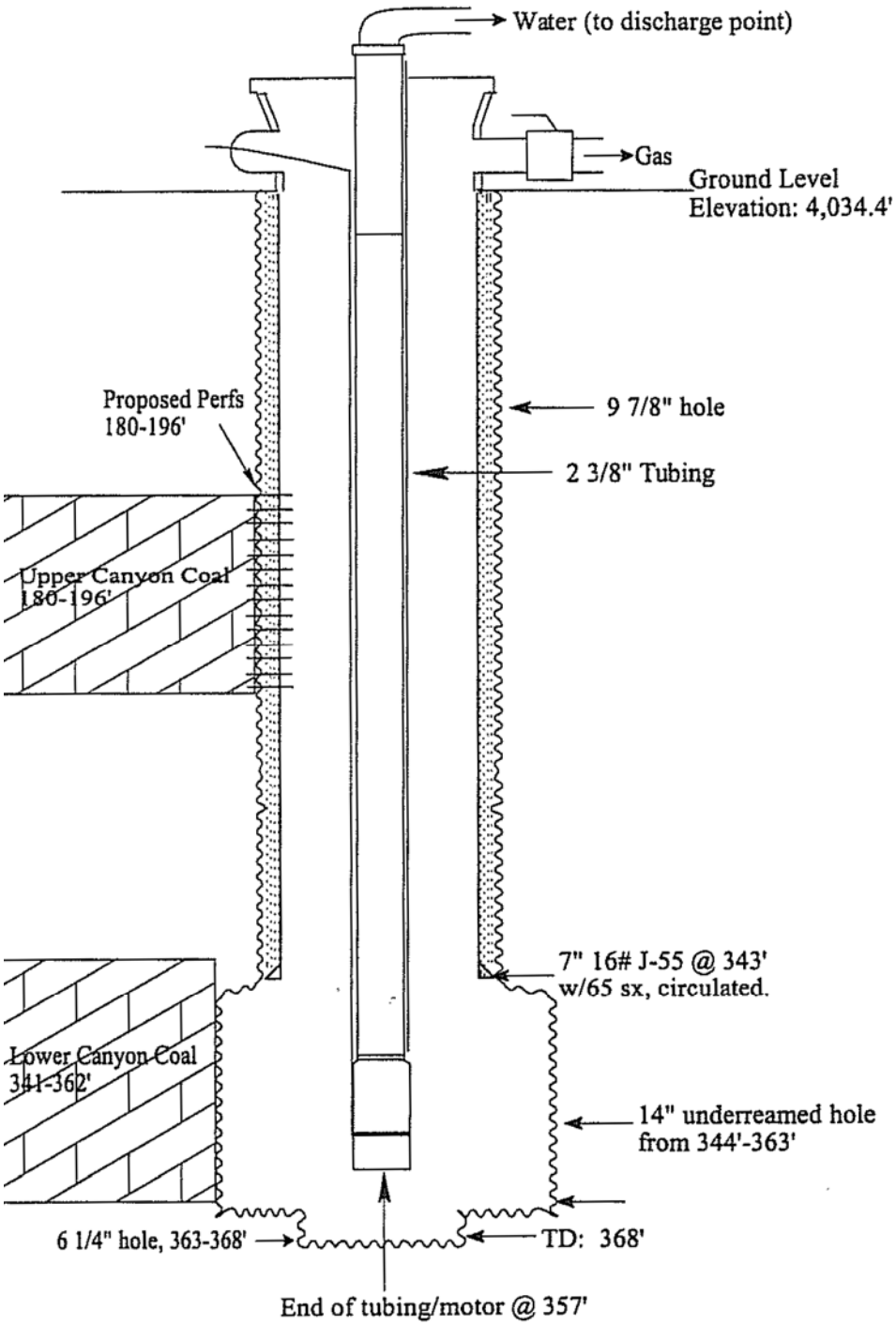
Multi-Seam Well Completion Strategy and Performance. In the 8 recompleted wells, Yates perforated into the bypassed Canyon seam through the wells' existing casing. This mode of well completion is shown for one of the Case Study wells, the Spotted Horse CS State #3, Figure 3-21. Though the addition of the Canyon seam did increase CBM production, their increased production was modest relative to the amount of additional coal the recompleted wells were accessing.

Two years after their recompletion, the MSC wells had recovered an additional 64 MMcf of gas and were producing at 14 Mcfd. During the same period of time, the single seam wells had recovered an additional 50MMcf of gas and were producing at 5 Mcfd, Figure 2-22 and Table 3-7. Even assuming the EUR of the average recompleted wells reaches 140 MMcf, the added Canyon seam will provide only 24 MMcf of additional gas recovery compared to an expectation of at least twice as much.



Source: WOGCC, 2000

Figure 3-20: Case Study 4 Single-Seam Well.



Source: WOGCC, 2003.

Figure 3-21: Case Study 4 MSC Completed Well

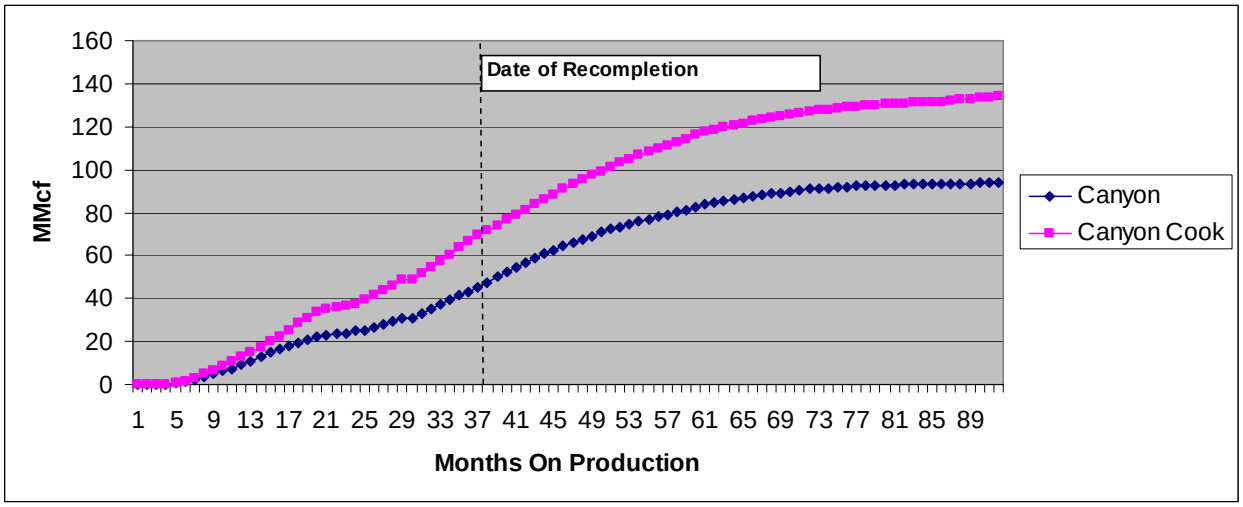


Figure 3-22: Comparison of Production from SSC and MSC Technology Wells in Case Study #4

Table 3-7. Comparison of the Performance of MSC and SSC Technologies in Case Study #4

	Single Seam Wells Cook		Multi-Seam Wells Canyon/Cook*	
Cumulative Recovery (MMcf)	Total	Increase	Total	Increase
Month 12	9		13	
Month 24	25		38	
Month 36	43		66	
Month 48	68	25	95	29
Month 80	93	50	130	64
EUR	**93**	**50**	**140**	**74**
Daily Gas Rate (Mcfd)				
Month 12	55		70	
Month 20	68		80	
Month 36	75		98	
Month 48	52		71	
Month 80	**5**		**14**	

*These wells are still single-seam completed into the Cook seam until month 37.

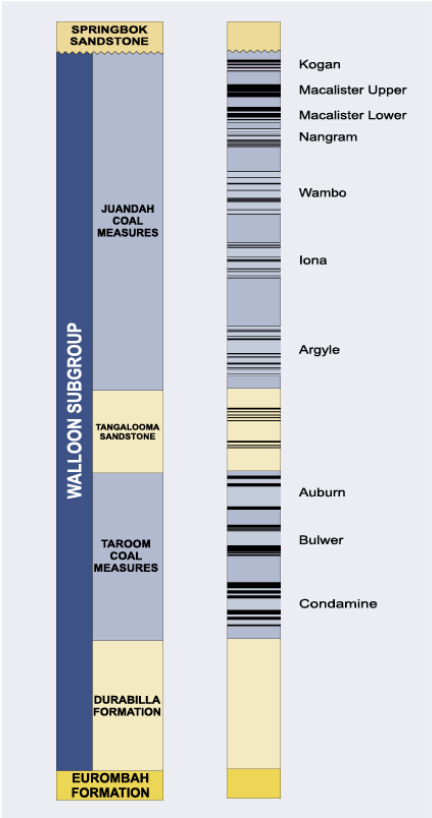
Case Study #5

Background. The Jurassic-age Walloon Coal Fairway is a large, low rank, multi-seam coal deposit in Eastern Australia, with geologic and coal setting analogous to the Powder River Basin. Independent studies estimate the resource in-place for the Walloon Coal Fairway at about 70 Tcf.

Figure 3-23 provides the stratigraphic column for the Walloon Coal Subgroup and its extensive sequence of coals. The ten named coals in Figure 3-23 distributed over an interval of 1,200 feet and range in depth from near outcrop to over 4,000 feet of burial.

While a large and geologically favorable CBM prospect, the initial attempts to produce this extensive stack of coals were unsuccessful. As a result, alternative and more effective well completion practices were formulated and then tested in this CBM play over a five year “learning” period. A portion of this experience is summarized below

Berwyndale South Pilot. In September 2002, a 5 well pilot (wells BS#1-5) was started to appraise this CBM prospect. The initial wells used cemented 5-1/2 inch casing completions with jet perforating and hydraulic fracturing to stimulate the coals. Influx of coal fines and frac sand was observed, leading to severe pumping problems. After installation of high volume pumps, enabling higher volumes of water production, first gas was achieved in March, 2003.



Source: Queensland Gas Company, 2005

Walloon Coals Stratigraphic Column

The Walloon coals contain two coal measures:

- The Juandah, a 250 meter thick section, and
- The Taroom, a 100 meter thick section

Including the Tangalooma Sandstone, the entire coal section (from the top of Kogan to the base of Condamine) encompasses nearly 400 meters.

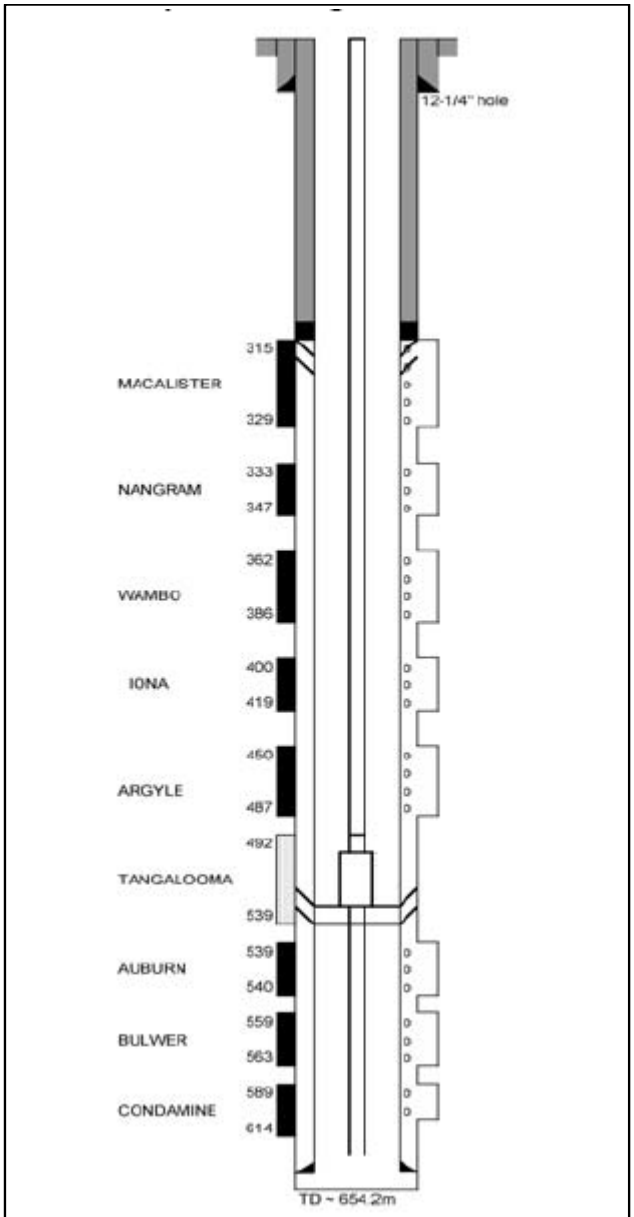
Figure 3-23. Walloon Coals Stratigraphic Column

However, the production performance of the CBM wells was much less than expected based on DST permeabilities measured in the wells. Three additional wells were added in February, 2003 to test a lower cost completion method using a pre-perforated liner. These wells were completed in a similar manner except that a low-density cement slurry was used to lessen damage to the coals. A series of small hydraulic fracturing treatments were used to bypass near wellbore skin damage. Still, while overall flow improved, the rates were less than expected.

Two new wells were drilled in May, 2004 to test “third generation” well completion designed to improve connectivity of the well to the multiple coals. The wells were completed open-hole, under-reamed and lined with 7” casing, Figure 3-24. Gas production reached 1,250 Mcfd plus 7,500 BW/D in early July, 2004. In May, 2005, the original Berwyndale S. Pilot was shut in after reaching a peak of 1.7 MMcfd, with one of the two new wells, BS#9, contributing more than 1 MMcfd. The Berwyndale South pilot demonstrated that, with proper well completion technology, the CSG resource in the Walloon coals could be efficiently produced.

Next, a 23 well development program was launched at Berwyndale South in late 2005 and, based on successful results from the new well completion design, the area was expanded to full-field development in late 2006 and early 2007. CBM production climbed rapidly, reaching 35 MMcfd at the end of 2006 and nearly 50 MMcfd in mid-2007, Figure 3-25. In August, 2007, after 73 CBM wells were connected, an average well at Berwyndale South was producing at 1.2MMcfd. Importantly, the 23 wells in the development program that have been on-stream and dewatered the longest, are flowing at over 2MMcfd (on average).

Summary. The case study at the Berwyndale South demonstrates that, with investment of time and dollars, a proper multi-seam well completion practice can be developed to “unlock” a CBM play, Figure 3-26.



Drawing not to scale
Source: SPE 101109

Figure 3-24 Present All-Walloon SC Completion

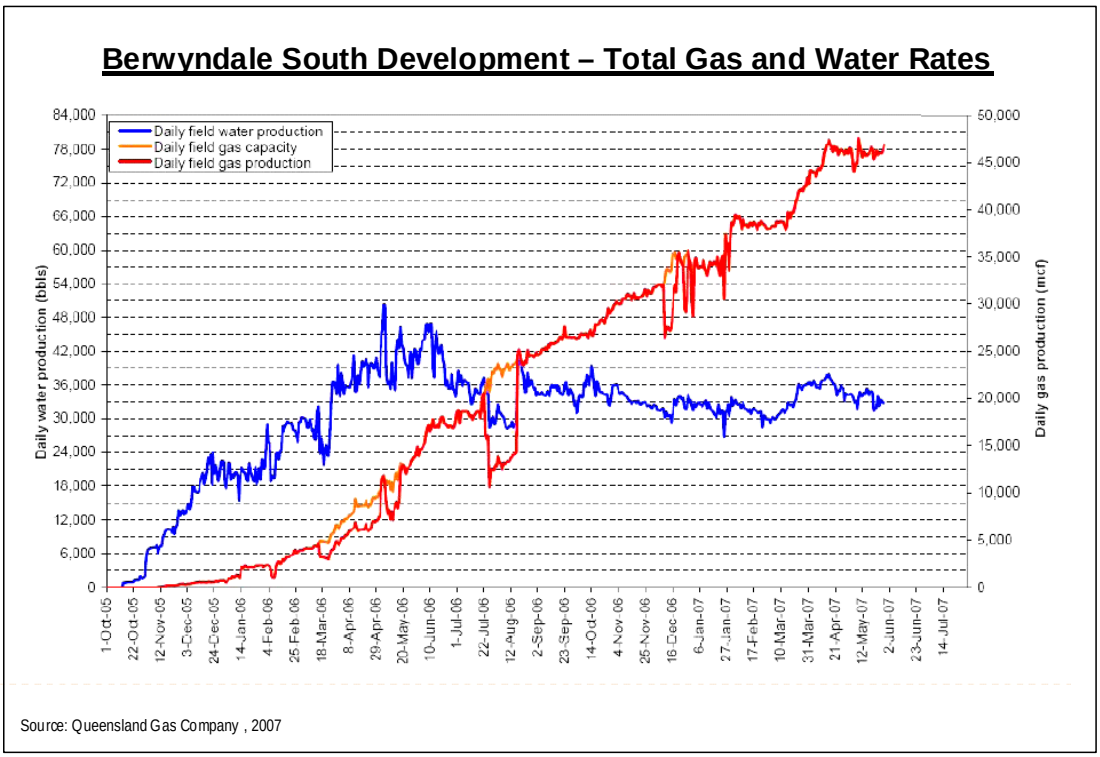


Figure 3-25 Berwyndale South Development –Total Gas and Water Rates

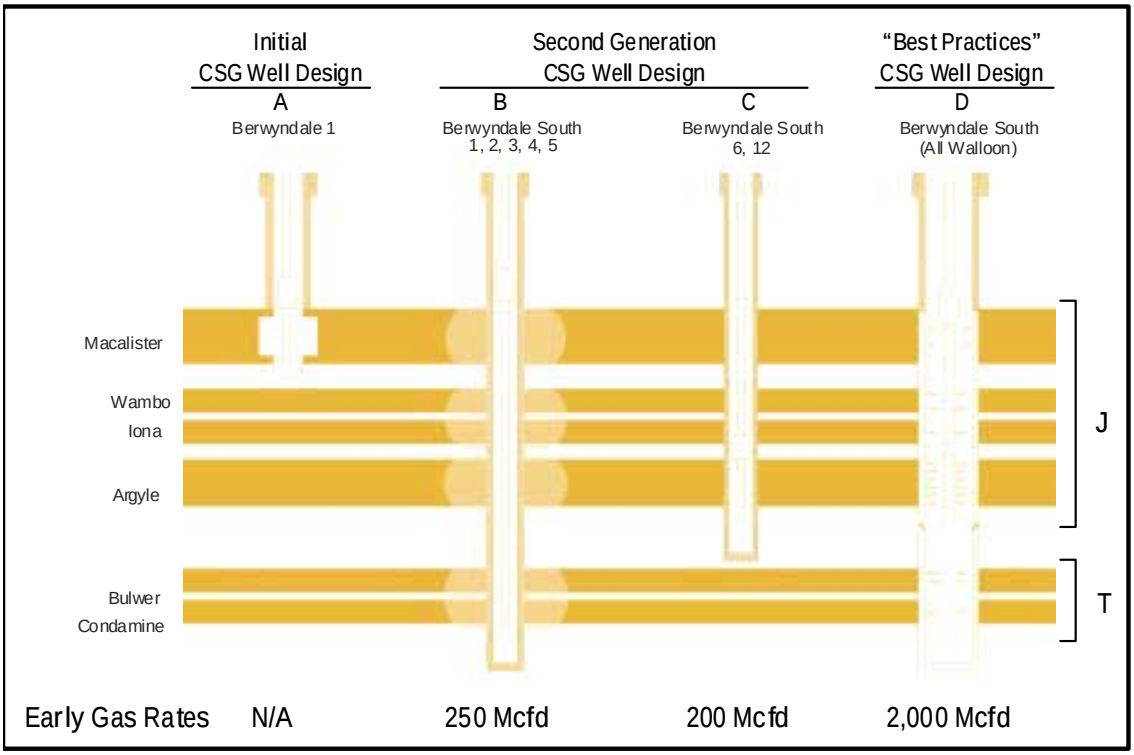


Figure 3-26. Jurassic/Walloon CSG: Well Completion Case Study

- The initial generation of CBM wells used completion methods borrowed from practices used in high coal rank basins (cased, cemented, perforated and stimulated wells).

- The “best practice” well completions practices that “unlocked” this CBM play are: (1) drill, case and cement the well at the top of the Juandah coals; (2) drill through and under-ream all significant coal seams (including the deeper Taroom coals); (3) place a pre-perforated 7” casing across the open-hole coal section; and (4) install high capacity downhole pumps for rapid dewatering.

3.3.3 Summary

Operators have yet to achieve fully effective multi-seam CBM completions in the Powder River Basin. Though, in most of these examples, the additional coal seams completed by a multi-seam well contribute to CBM production, they appear to consistently underperform what would be expected based on their theoretical potential.

As shown by the Australia case study, these problems can be overcome with rigorous research and a series of multi-seam completion technology field tests. Successful application of MSC Technology would enable the full coalbed methane resource residing in the Powder River Basin to be added to the nation’s natural gas reserves with fewer wells and less environmental disturbance.

SECTION 4. BENEFITS OF MULTI-SEAM COMPLETION TECHNOLOGY IN THE POWDER RIVER BASIN

4.1 Summary

The benefits of developing and successfully applying Multi-Seam Completion (MSC) Technology in the Powder River Basin are numerous. First is the increased access this technology would provide to the significant 20 Tcf of CBM resource residing in thin coal seams. Second is the improved economics that MSC Technology would bring to the Powder River Basin CBM play. Third is the increased royalty and severance tax revenues that would accrue to Montana, Wyoming and Federal budgets. Fourth, is the reduction in environmental impacts that would result from producing this CBM resource with fewer wells.

4.2 Increased Access to the Coabed Methane Resource in the PRB

Successful application of MSC Technology would increase the accessible CBM gas in-place in the Powder River Basin to 78 Tcf, from 58 Tcf of gas in-place under Single-Seam Completion (SSC) Technology, Figure 4-1 and Table 4-1. The application of MSC Technology is particularly relevant to the coalbed methane resource in the Montana portion of the Powder River Basin, an area dominated by thin, marginal coals. With MSC Technology, the accessible CBM resource in-place in Montana (in Basin Partitions #9, #10 and #13) is 4.9 Tcf, compared to 1.9 Tcf with SSC Technology.

Importantly, MSC Technology would raise the technically recoverable CBM resource in this basin to 52 Tcf, up from 37 Tcf under traditional Single-Seam Completion Technology, Figure 4-2 and Table 4-1.

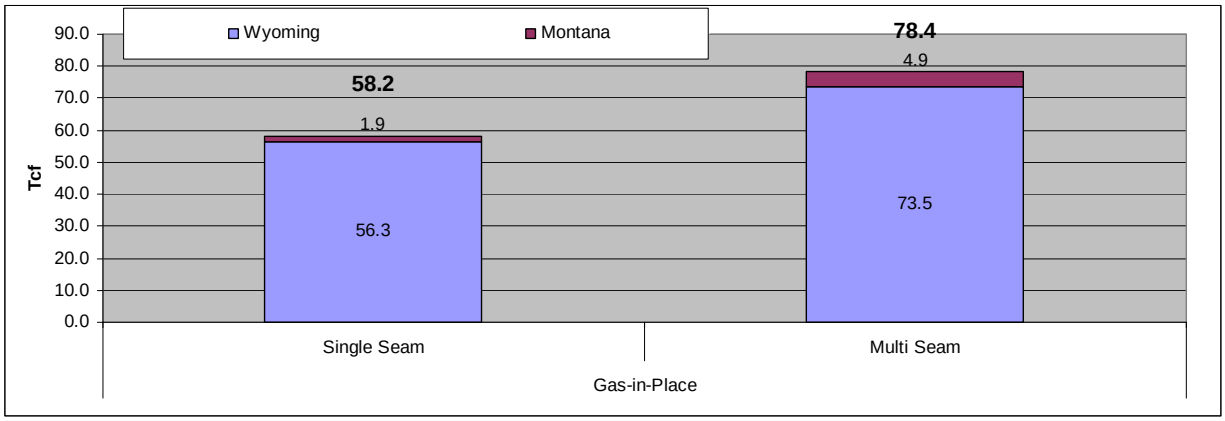


Figure 4-1. Comparison of the CBM Gas-In-Place in the Powder River Basin under SSC and MSC Technologies

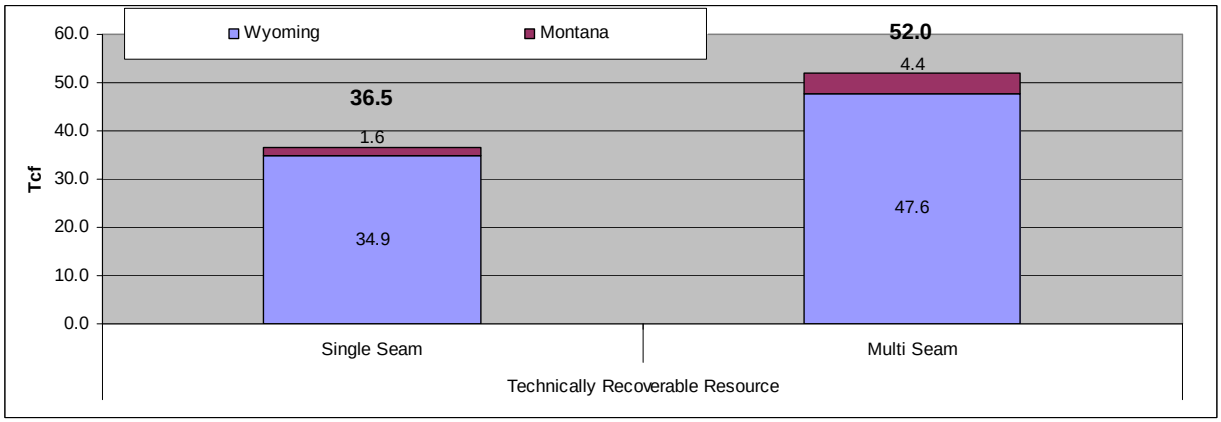


Figure 4-2. Comparison of the Technically Recoverable Resource Base in the Powder River Basin under SSC and MSC Technologies

Table 4-1. Coal and Coalbed Methane Resources of the Powder River Basin, by Basin Partition

State	Partition	GIP (Bcf)			Gas Technically Recoverable (Bcf)		
		Single Seam	Multiseam	Increase	Single Seam	Multiseam	Increase
Wyoming	1	1,612	2,242	631	1,287	1,778	491
	2	2,965	3,772	807	1,497	2,142	645
	3	5,146	6,597	1,452	1,735	2,829	1,094
	4	3,755	4,483	729	2,358	2,902	544
	5	22,499	26,873	4,374	13,423	16,747	3,324
	6	8,715	11,400	2,685	6,393	8,250	1,857
	7	3,230	6,210	2,980	2,521	4,783	2,262
	8	6,296	9,098	2,803	4,580	6,657	2,077
	11	1,693	2,461	768	988	1,431	444
	12	370	370	-	120	120	-
	Total	**56,279**	**73,507**	**17,228**	**34,902**	**47,640**	**12,738**
Montana	9	115	1,479	1,364	89	1,325	1,235
	10	524	1,136	613	447	1,017	569
	13	1,302	2,285	982	1,096	2,041	945
	Total	**1,941**	**4,900**	**2,959**	**1,633**	**4,382**	**2,749**
Basin Total		**58,220**	**78,407**	**20,187**	**36,535**	**52,022**	**15,487**

4.3 Larger Economically Recoverable Resource

Multi-Seam Completion Technology would also improve the economics of producing coalbed methane in the Powder River Basin. Using a $8.00/MMBtu (Henry Hub spot) price for natural gas, 41 Tcf of coalbed methane is economically recoverable from the Powder River Basin in Wyoming with MSC Technology, compared to 23 Tcf economically recoverable with SSC Technology. This increase is due to the ability of MSC Technology to recover CBM from currently bypassed thin coal seams as well as link a series of otherwise marginally productive coals into a single highly effective package.

Table 4-2 presents the economically recoverable CBM resource for Wyoming and Montana and Table 4-3 presents the number of CBM wells expected to be drilled, by partition, assuming an $8/MMBtu Henry Hub gas price. An important point to note is that MSC Technology would add 16 Tcf of economically recoverable CBM resource but with only 9,650 (12 %) more CBM wells.

Table 4-2. Economically Recoverable CBM Resource by Partition

State	Partition	Economically Recoverable (Bcf)		
		Single Seam	Multiseam	Increase
Wyoming	1	1,277	1,878	601
	2	819	1,525	707
	3	1,177	1,843	666
	4	1,587	2,027	440
	5	8,602	13,831	5,229
	6	4,250	6,572	2,322
	7	906	4,442	3,536
	8	3,055	5,111	2,056
	11	251	818	567
	12	66	66	-
	Total	**21,990**	**38,113**	**16,123**
Montana	9	89	878	790
	10	317	991	674
	13	835	1,608	773
	Total	**1,241**	**3,477**	**2,236**
Basin Total		**23,231**	**41,590**	**18,359**

Table 4-3. Wells Drilled by Partition

State	Partition	Wells Drilled		
		Single Seam	Multiseam	Increase
Wyoming	1	4,007	3,679	(328)
	2	3,381	4,113	732
	3	4,334	5,311	977
	4	6,997	5,624	(1,373)
	5	25,003	18,993	(6,010)
	6	9,303	9,022	(281)
	7	3,122	9,298	6,176
	8	13,318	13,184	(134)
	11	1,251	2,501	1,250
	12	158	158	-
	Total	**70,874**	**71,883**	**1,009**
Montana	9	576	4,896	4,320
	10	2,304	4,896	2,592
	13	5,472	7,200	1,728
	Total	**8,352**	**16,992**	**8,640**
Basin Total		**79,226**	**88,875**	**9,649**

4.4 Increased State and Federal Revenues

The larger economically recoverable CBM resource, available with Multi-Seam Technology, provides significantly higher state, federal and private revenues from royalty payments, ad valorem taxes and severance taxes. In addition, developing this natural gas resource will inject billions of dollars of additional economic activity into Wyoming and Montana, increasing jobs and public infrastructure.

Royalty payments would provide $43.1 billion of revenues, with $22.2 billion from federally owned lands, $3.4 billion from state-owned lands, and $16.7 billion from CBM leases on private lands. Montana and Wyoming would receive half of the royalty income from leases on federal lands, raising their royalty income to $14.5 billion from CBM development in the Powder River Basin. Ad valorem and severance taxes on CBM revenues would add another $30.1 billion of state and local revenues.

Finally, CBM development would provide a much needed stimulus to state and local economies. Over the life of the Powder River Basin CBM play, an estimated $16 billion of capital expenditures would be injected in the basin providing jobs, infrastructure and other revenue. Table 4-4 summarizes the revenue benefits that would result from successful development and application of MSC Technology in the Powder River Basin for Wyoming and Montana.

Table 4-4. State and Federal Revenues From CBM Development in the Powder River Basin

Mineral Ownership	Royalty Revenues (Millions)			Ad Valorem and Severance Tax Revenues (Millions)		
	WY	MT	Total	WY	MT	Total
Federal	$20,924	$1,909	$22,833	$17,196	$1,217	$18,413
State	$3,208	$264	$3,472	$1,973	$140	$2,113
Private	$15,367	$1,402	$16,769	$9,021	$639	$9,659
Total	$39,499	$3,575	$43,074	$28,190	$1,996	$30,185

4.5 Economic Sensitivity

The study examined the benefits of Multi-Seam Well Completion Technology at three price scenarios, $8/MMBtu, as well as $6/MMBtu and $10/MMBtu. Additionally the study examined two MSC Technology performance scenarios. Scenario 1 assumes that MSC wells produce the full theoretically recoverable gas in each seam completed. Scenario 2 assumes MSC wells only produce 80% of this theoretically recoverable resource.

Price Sensitivity.[*] With either MSC or SSC Technology, the volume of economically recoverable CBM from the PRB is, as expected, sensitive to natural gas prices (Henry Hub, spot), Figures 4-3 and 4-4:

- At Base Case gas prices of $8/MMBtu, the economically recoverable CBM resource is 42 Tcf (23 Tcf with SSC Technology).
- At a gas price of $6/MMBtu, the economically recoverable CBM resource with MSC Technology is 38 Tcf (18 Tcf with SSC Technology).

[*] All results assume surface impoundment of produced CBM water.

- At a gas price of $10/MMBtu, the economically recoverable CBM resource is 42.5 (24.6 with SSC Technology).

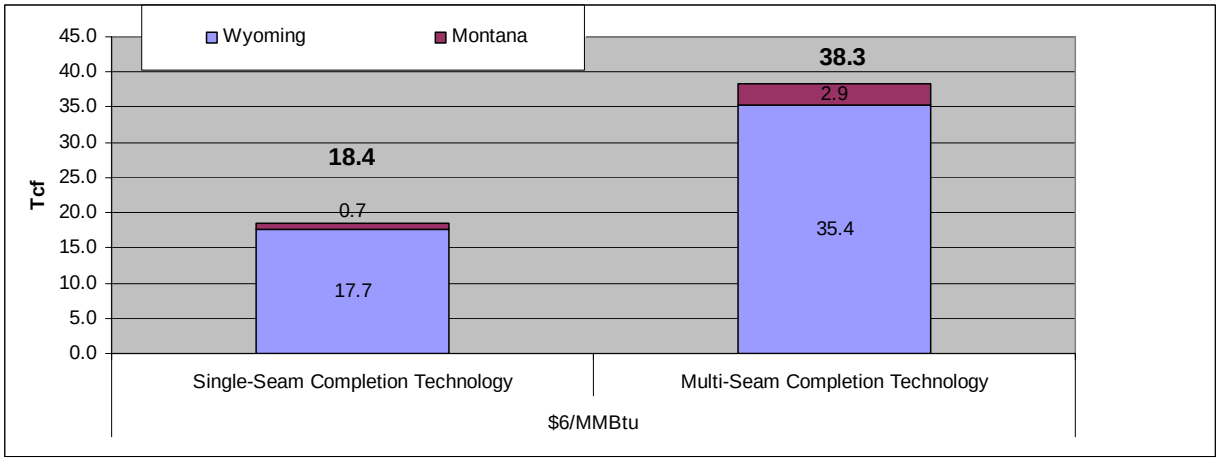


Figure 4-3. MSC Economically Recoverable Resource Under a $6/MMBtu Wellhead Gas Price

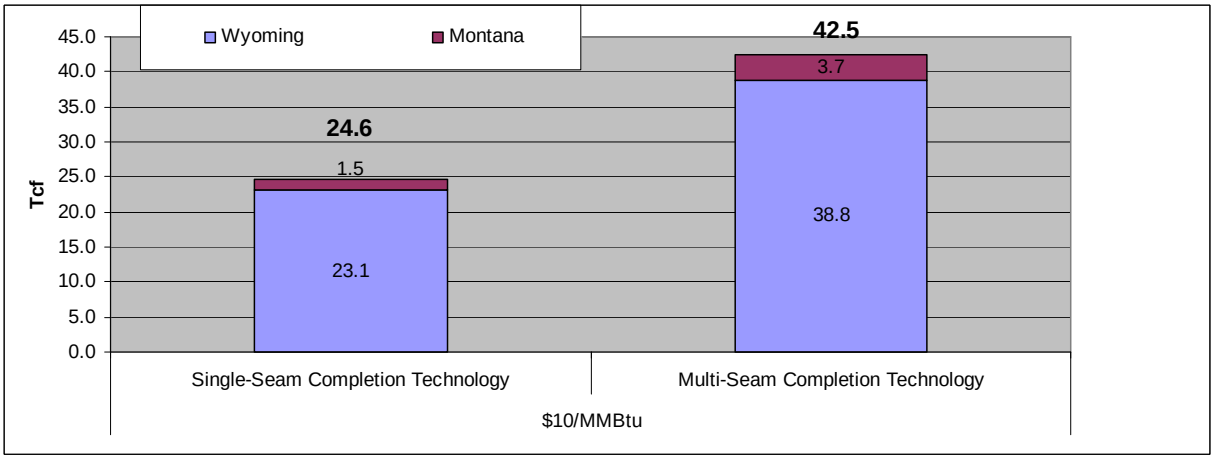


Figure 4-4. MSC Economically Recoverable Resource Under a $10/MMBtu Wellhead Gas Price

Recovery Scenarios. The volume of economically recoverable CBM for the PRB also depends on the performance of MSC Technology, Figure 4-5.

- Under Scenario #1, where MSC Technology performs at its theoretical optimum, the economically recoverable CBM resource is 41.6 Tcf assuming $8 MMBtu (Henry Hub, spot).

- Under Scenario #2, where MSC Technology performs at 80% of its theoretical potential, the economically recoverable CBM resource is 31.4 Tcf. However, even at this lower level of performance, MSC Technology would provide much more economics CBM recovery than would SSC Technology.

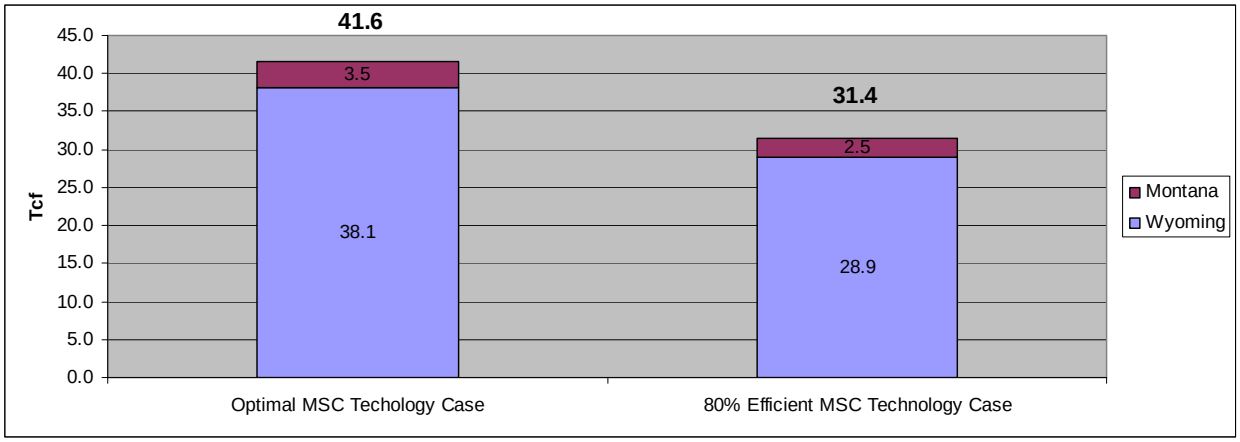


Figure 4-5. Powder River Basin MSC Economically Recoverable Resource under 80% Recovery Efficiency Assumption at $8/MMBtu Henry Hub Spot Price.

Two important insights can be gained from this economic sensitivity analysis. First, with the larger volumes of CBM contacted with MSC Technology, these CBM wells have a large enough revenue stream to remain economic even at lower natural gas prices. Second, a less than optimum technology performance scenario could reduce the economically recoverable CBM in the Powder River Basin by nearly 10 Tcf, placing high value on rigorously pursuing MSC technology.

4.6 Water Treatment Options

Handling the large volume of produced water from CBM wells will likely require producers to employ a more advanced method of water treatment than surface disposal. Using the water treatment costs outlined in Section 2, above, we calculated how the utilization of various water treatment technologies would affect the amount of economically recoverable resource in the basin. The results are presented in Table 4-5.

Table 4-5. PRB Economically Recoverable Resource from MSC Technology Under Varying Water Treatment Scenarios

				Active Treatment	
Water Treatment Option	**Surface Discharge**	**Impoundment**	**Shallow Reinjection**	**Trucking**	**Deep Injection**
Wyoming	38,113	37,545	37,504	34,890	36,493
Montana	3,477	3,420	3,387	2,957	3,314
Total	41,590	40,966	40,891	37,847	39,807

Under the most expensive water treatment option, Active Treatment with trucking of residual wastes, the economically recoverable CBM resource in the PRB declines only by 4 Tcf, from 41.6 to 37.8 Tcf. This analysis also suggests that the additional revenue accrued from the application of MSC Technology throughout the basin will provide producers a compensating option to higher cost water treatment , helping counter the significant reductions in economically recoverable CBM that would result from use of higher cost water management options throughout the basin.

SECTION 5. CONCLUSION

This study provides a major update to the previous work prepared by Advanced Resources International in 2003 on the potential value of using MSC Technology in the Powder River CBM play. The primary differences between this report and the previous studies are: (1) we rigorously updated coal seam thickness and depth data throughout the basin with an emphasis on adding thin coal seams; (2) we added over 30 new "type-wells" to provide greater accuracy in well recovery analysis; (3) we developed and incorporated an updated methane adsorption isotherm specific to PRB coals; and, (4) we updated costs and used gas prices more reflective of today's market conditions.

The study shows that MSC Technology can appreciably improve the outlook for CBM development in the Powder River Basin, by improving reserves-per-well and reducing environmental impact. However, other actions are still required to reach optimum development of this major domestic coalbed methane resource. These actions include improving market access for the produced methane, lowering gathering costs, establishing more optimum well spacing, and developing lower cost water management options. These topics set the stage for further research and technology development.