The Unconventional Gas Resource Base

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Background. Our understanding of the unconventional gas resource base has improved significantly in the past decade. With data from drilling over 100,000 wells and developing 120 Tcf of reserves in the past 10 years, we now have a more solid foundation for the resource potential of tight gas sands, coalbed methane and gas shales. Still, there is much we do not know, such as - - *where are the productive limits of the emerging gas plays; what is the optimum well spacing; and, how will advances in well drilling and completion technologies change the productivity of wells?* As such, our estimates of the recoverable portion of the large in-place unconventional gas resource will likely change many times during the next decade.

In this second article of this six-part series on unconventional gas, we examine the size and nature of the resource base including why and how the estimates of recoverable resources will likely change and evolve.

Our Latest Resource Base Estimate. In our view, the recoverable resource base for unconventional gas is large, estimated at 580 Tcf, with 379 Tcf for tight gas sands, 73 Tcf for coalbed methane and 128 Tcf for gas shales. Table 1 shows our unconventional gas resource base estimates (for technically recoverable resources) at three points in time - - 1996, 2002 and 2006. Table 2 provides additional regional detail for the year 2006 resource estimate. The largest segment of the unconventional gas resource is the tight gas sand play in the Rocky Mountain basins, followed by the gas shales and tight gas sands of the Appalachian Basin. The fastest growth in unconventional gas resources has been in East and Central Texas, with the emergence of the Barnett gas shales and the Cotton Valley/Bossier tight gas sands.

When looking at the resource base numbers, it is important to remember that these estimates are merely a “snapshot in time”. The continuing emergence of new unconventional gas plays, the ability to more intensively develop an already discovered play, and advances in extraction technology can and will affect the ultimate size of the recoverable resource. The statement - - we do not yet know the true size and nature of the unconventional gas resource base - - is as true today as when it was nine years ago (Kuuskraa and Schmoker, 1998).

The Resource Pyramid. One useful way to view the size and nature of the unconventional gas resource base is as a resource triangle or pyramid (Masters, 1984; Kuuskraa and Schmoker, 1998), Figure 1. At the top of the pyramid are the high quality unconventional gas plays (and portions of plays), many which are already extensively developed. These higher quality plays have provided 160 Tcf of past production and hold 105 Tcf of proved reserves. In the middle of the pyramid are the economic (260 Tcf) and marginally economic (140 Tcf) portions of the undeveloped unconventional gas resource base. Toward the bottom of the pyramid are the lower quality, uneconomic plays (and portions of active plays, such as the basin margin), totaling 180 Tcf. At the base and inside the pyramid, still out of view, are the new, still to be assessed and discovered unconventional gas plays.

The unconventional gas plays within the resource pyramid are dynamic - - they can move vertically with progress in technology and knowledge, from an initial low quality, high cost foothold to a position of higher quality. One example of this is how the application of horizontal wells and multi-stage hydraulic fracturing have enabled gas shales plays to become “the new hot thing.” Exploration and new resource appraisals can enable the still unassessed unconventional gas plays inside the pyramid to emerge.

Perspective on Resource Base Estimates. Assessing the size and quality of recoverable unconventional gas is challenging for several reasons.

- ***New Assessment Methodologies***. First, given the continuous nature of the unconventional gas deposits, one cannot use the traditional resource assessment methodologies developed for conventional gas - - field size distribution, finding rates and discovery process. (Later in this article we will discuss our preferred assessment methodology for unconventional gas.)

- ***Massive Volumes of Data***. Second, the assessment process requires vast quantities of geologic, engineering and well performance data plus numerous "expert judgment" calls. (For example, we periodically review the performance of several hundred thousand unconventional gas wells to establish up to date trends in well productivity.)

- ***Rapid Changes in Outlook***. Third, the individual unconventional gas plays are prone to rapid and large changes in performance. Successful introduction of new geologic knowledge and advances in well drilling and completion practices can significantly improve the outlook for a play. (A prime example is how the application of horizontal drilling, restimulation and closer well spacing converted the Barnett Shale from a 3 Tcf (USGS, 1996) marginal gas resource to a major 26 Tcf (USGS, 2004) to 49 Tcf (an Advanced Resources' internal assessment) gas play. The Advanced Resources estimate for the Barnett Shale differs from the USGS assessment in that it contains significant expectations for gas recovery from the extension (non-core) areas of this play through use of horizontal wells. At the same time, as an unconventional gas play becomes increasingly mature, its well productivities and success rates will begin to decline, unless technology progress is able to outpace resource depletion, as discussed in the first article in this series.

Resource Assessment Methodology. Because unconventional gas resources are so dynamic, the plays need to be assessed frequently, every two to three years, not once a decade. Our preferred resource assessment methodology for continuous gas play consists of five key steps:

1. ***Gas In-Place/Play Area.*** In addition to establishing the play outline (using various measures such as thermal maturity or minimum net pay), we recommend mapping the gas in-place contours to define the ultimate resource target and establish the quality portion of the gas play.
2. ***Well Drainage and Spacing.*** Use production data, reservoir properties and a tight formation type-curve model (such as METEOR) to establish analytically rigorous well drainage. In addition, examine oil and gas commission spacing rules appropriate for each play.
3. ***Trends in Well Performance and Success Rates.*** Assemble a comprehensive, accurate and up-to-date data base of well performance - - reserves/well and success rate - - for key time periods to understand resource maturity and the impacts of advances in technology.
4. ***Trends in Technology Progress***. Document how progress in technology, (e.g., pay selection, well completion practices) is improving or may improve future well performance. Selected field case studies plus in-depth technical performance data can provide valuable insights on the performance and benefits of improved technology.
5. ***Higher Quality/Accessible Play Partitions.*** Use the empirical well performance data base plus basin modeling, stress mapping and other methods to define the higher productivity (e.g., permeability) portions of the plays. In addition, examine federal and state regulatory stipulations to establish the portion of the basin that may or may not be accessed in the foreseeable future.

The first assessment step - - Basin/Play Area - - can be established from geologic maps, but requires judgment as to where to draw the “quality” gas play outline. The next two assessment steps - - Well Drainage/Spacing and Trends in Well Performance/Success Rates - - can be empirically established from drilling and production data. Trends in Technology Progress, the fourth assessment steps, requires assembling considerable technical information and rigorous case studies. The greatest uncertainty and expert judgment is in assessment steps five - - *what portion of the* *unconventional gas play will have access and be of sufficient quality to be developed in the foreseeable future?*

Comparison of Resource Estimates. Table 3 compares three estimates of the recoverable portion of the unconventional gas resource base (Advanced Resources, 2006; NPC, 2003; USGS, 2006).

- *Advanced Resources International (ARI)* assembles annual updates on unconventional drilling, production and reserves and periodically updates their resource assessments*. The unconventional gas resource estimate of 580 Tcf by Advanced Resources is, at times, considered "aggressive" in that it incorporates expectations of technology progress and intensive resource development. We note, however, that our estimate of 10 Tcf for the Barnett Shale in 1998 was also considered aggressive at the time (Kuuskraa, et al, 1998).

- *National Petroleum Council (NPC)* used a combination of Gas Research Institute and USGS data, industry reviews and outside contractor support to provide estimates of unconventional gas resources. The latest NPC study, completed in 2003 (with resource base data through 1998), used an estimated accessible lower-48 unconventional gas resource base of 206 Tcf.

- *U.S. Geological Survey* has re-assessed 22 priority basins and has plans to re-assess 10 more basins since its last comprehensive assessment in 1996. The current USGS estimated for lower-48 continuous gas resources is 304 Tcf. The USGS assessment methodology combines the use of total petroleum systems and the "cell based" resource estimation methodology, involving play area, well density, well productivity, success rate and play

* *U.S. DOE/Energy Information Administration* uses a combination of USGS and Advanced Resources resource base data and contracts with Advanced Resources for estimates for updates to tight gas reserves, drilling and production. These input data are incorporated into the UGRSS module of their OGSM system.

access. It is useful to note that the continuous gas resources in many large basins (Anadarko, Big Horn, East Texas) are yet to be included in the USGS unconventional gas resource assessment.

Why Do Resource Estimates for Unconventional Gas Differ? Given the differences in methodologies, data and assumptions being used, it is not surprising that estimates of the remaining unconventional gas resource base differ. What is surprising is that the differences, both overall and for any given play, are so large.

Still, why should one care? We believe that accurate assessments are important in assisting industry better target its efforts and in assisting policy makers make better decisions. For example:

- It matters greatly whether the remaining accessible unconventional gas resource base is 580 Tcf (Advanced Resources, end of 2005) or 206 Tcf (NPC, end of 1998). Our play by play tabulation shows that in the past seven years (1999-2005) industry has developed 100 Tcf of the undiscovered unconventional gas resource. If the accessible resource base is 206 Tcf (as set forth in the NPC 2003 study), then only 106 Tcf remains undeveloped as of the end of 2005, with implications that the unconventional resource base is close to being depleted. With declines in conventional gas production (both onshore and offshore), a severely depleting unconventional gas resource base would call for massive gas imports, particularly LNG, if a gas supply crisis is to be averted. However, if the remaining unconventional gas resource base is 580 Tcf (as set forth in the recent Advanced Resources assessment), then there is potential for at least maintaining today's domestic natural gas production, with advances in technology providing potential for improving this outlook.

- Similarly, it matters whether a particular unconventional gas play has only 3 Tcf or over 40 Tcf of remaining undeveloped resource. For example, as shown in Table 4, two resource estimates exist for the Williams Fork (Mesaverde) lenticular tight gas play in the Piceance Basin - - 3.1 Tcf (USGS, data through 1999) and 42.5 Tcf (Advanced Resources, data through 2005). With 2,250 wells drilled and 2.85 Tcf of resource developed since 1999 (Table 5), the Williams Fork (Mesaverde) tight gas play would be essentially over in the USGS case or just starting in the Advanced Resources case.

We will use the above cited Williams Fork/Mesaverde tight gas play in the S. Piceance Basin as a "case study" to illustrate how modest differences in assumptions can lead to widely different estimates, Table 4.

1. ***Basin Area.*** The USGS and Advanced Resources both use essentially the same area for the basin, approximately 2,000 square miles. Advanced Resources divides the basin into two distinct segments - - the North and the South. For the southern portion of the basin, Advanced Resources prepared a gas in-place contour map and used the 50 Bcf per section contour to define the "quality" portion of this gas play, Figure 2.

2. ***Well Spacing***. USGS used an average of 80 acre-spacing per well, Advanced Resources used 20 acres per well based on recent Colorado Oil and Gas Commission (COGA) rules allowing such well spacing. Advanced Resources also conducted type-curve matching of production data to establish well drainage, confirming the validity of using 20 acres per well spacing. Figure 3 shows a type-curve calculation of a 15 acre well drainage for the representative RMV 58-20 well. In addition, Advanced Resources evaluated the intensive resource development in Rulison Field, Section 20 (T6S R94W). This high visibility pilot of infill development shows that over 110 Bcf may be recoverable from one section of this tight gas sand play with even closer, ten acre well spacing, Figure 4.

3. & 4.*<u>Success Rates and Well Performance (Recovery Per Well).</u>* Both the USGS and ARI use high success rates, because of the dominance of infill wells in S. Piceance. USGS uses 0.9 Bcf as the estimated ultimate recovery (EUR) per well*; Advanced Resources uses an EUR of 1.3 Bcf per well for the S. Piceance Basin area (1.85 Bcf per well for the N. Piceance Basin area). The higher anticipated recoveries in the Advanced Resources assessment are due to improved technology being used in new wells and the application of recompletions in older wells. The USGS well data base is as of 1999 and contains 822 wells; the ARI well data base is as of 2005 and contains 2,920 wells. Table 5 illustrates the "time slices" methodology used by Advanced Resources for establishing success rates and recovery per well for this tight gas play. This table shows:

- All wells drilled and completed by key time periods, to isolate basin maturity (depletion) and technology progress.
- Trends for well performance, the distribution of current well performance and trends in well success rates.

5. "Quality/Accessibility Factor". A major assessment uncertainty is - - *What portion of this play can and will be developed in the near future?* USGS assumed that only a relatively small portion of the available drill sites will be developed in 30 years, and applied a 28% "Quality-Accessibility Factor". Advanced Resources, after mapping the high gas in place portion of the S. Piceance Basin and examining the Federal leasing stipulations for this basin, used an 87% "Quality-Accessibility Factor".

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* *The USGS acknowledges that "the EUR's presented in this report (Uinta-Piceance Province) represent current completions only, and do not include the anticipated production potential for behind pipe gas that is not yet being produced. When this is added, the EUR's should be considerably higher. . . ",* citing an Advanced Resources study of the Piceance Basin (Advanced Resources, 1997).

The above "case study" of two rigorously performed resource assessments provide insights on the challenges faced in making resource assessment for unconventional gas and why these resource assessments may differ. Clearly, assembling and rigorously using up-to-date well performance data are important. As important is using appropriate well spacings and expectations for resource access and development for these large, "continuous-type" resources.

Unconventional Gas Assessments Require Frequent Updates. Improvements in technology and knowledge can rapidly change the outlook for unconventional gas plays. To see these changes at work, frequent assessments are required, particularly for resources where technology progress is helping unlock a gas play. A prime example of this is the Mesaverde/Williams Fork play in the Piceance Basin where multi-zone stimulation and new understanding of reservoir geometry has justified several rounds of down-spacing, resulting in a substantial increase in the recoverable resource base. The knowledge gained from such assessments will be vital for guiding investments by industry and for formulating sound energy and natural gas policy.

Figure 1. The Unconventional Gas Resource Pyramid

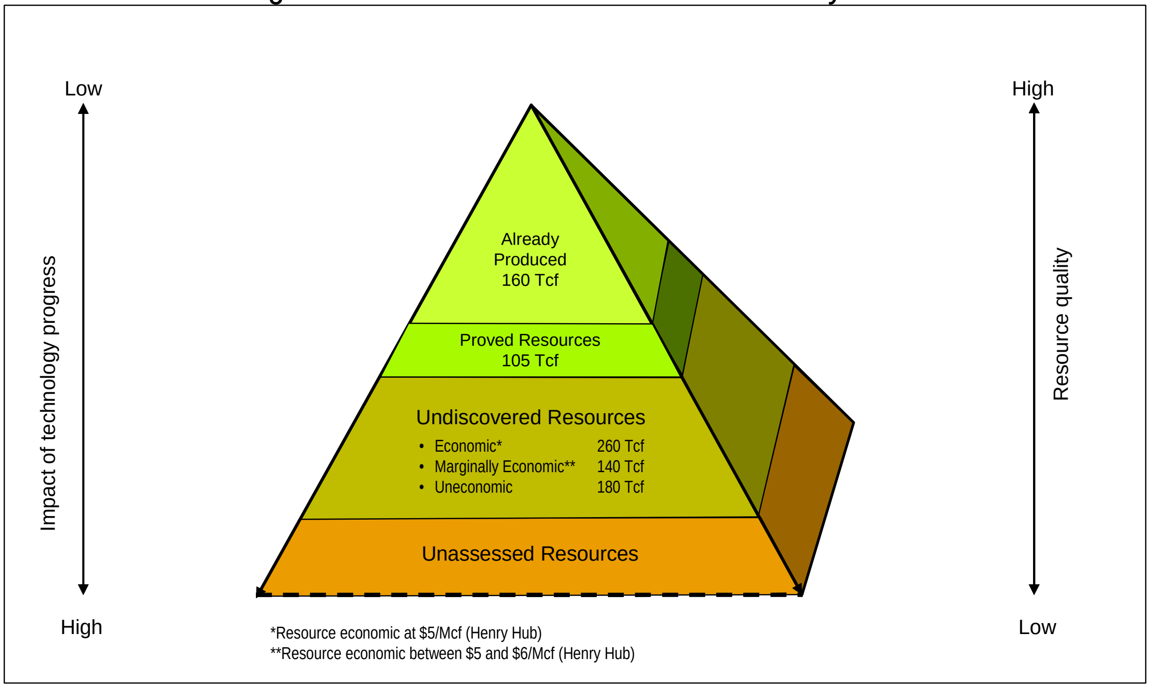

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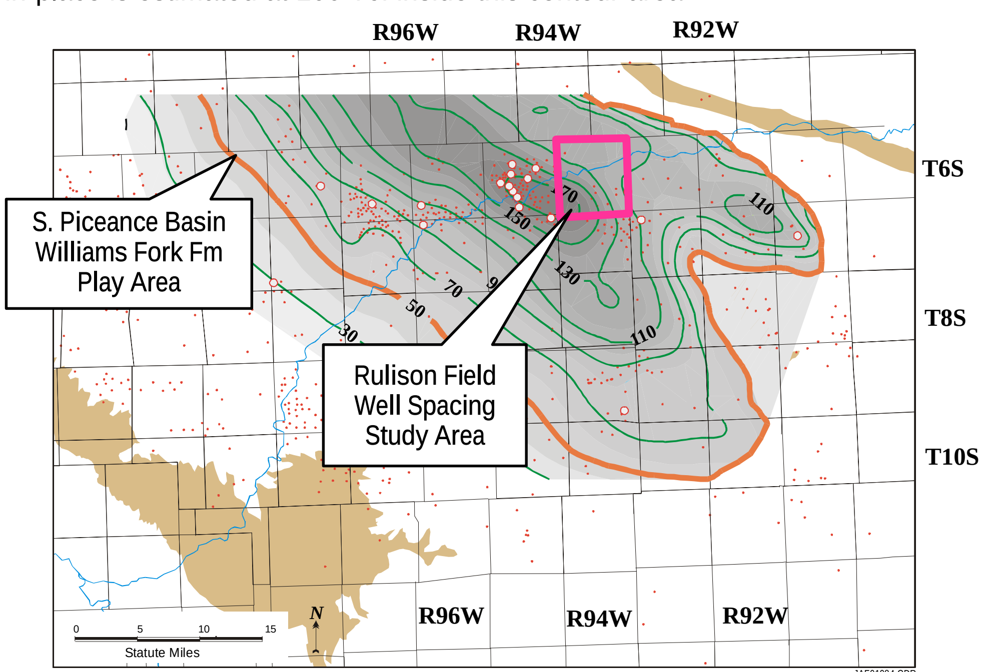
Figure 2. S. Piceance Basin: Gas In Place and Basin/Play Area

Twenty eight townships (1,008 square miles) exist within the 50+ Bcf per section gas in-place contour for Williams Fork/Mesaverde gas play. The gas in-place is estimated at 100 Tcf inside this contour area.



Gas In-Place (Bcf per Section), Williams Fork/Mesaverde, Southern Piceance Basin.

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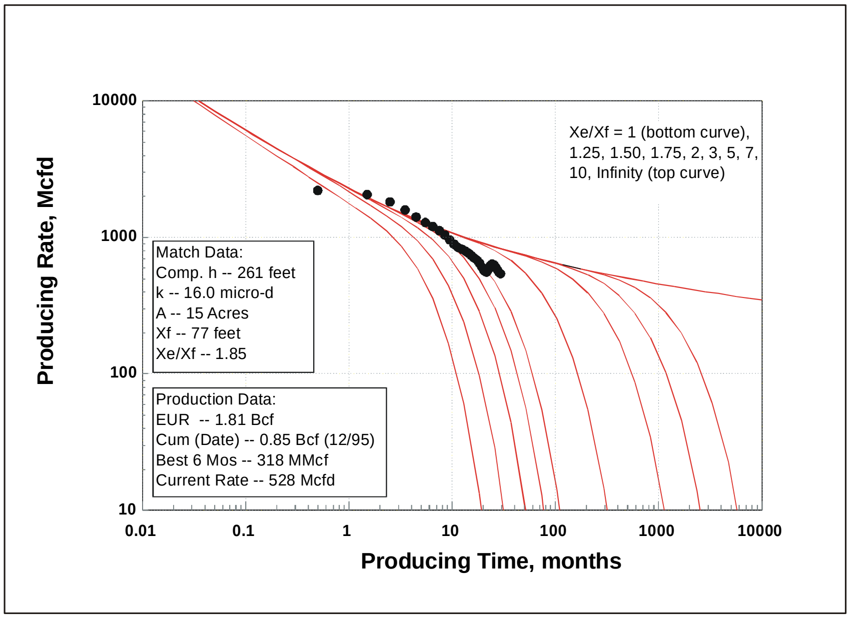
Figure 3. Examining Well Drainage and Spacing



RMV 58-20 Log-Log Type Curve Plot.

Estimates of well drainage (and ultimate well spacing) can be developed from type-curve matching of early time production data once key reservoir properties are established.

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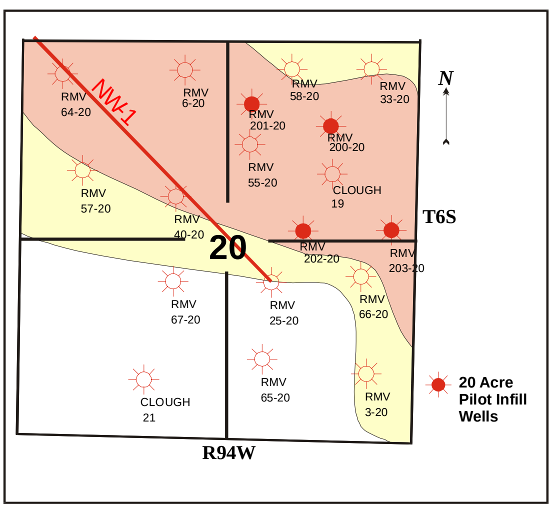
Figure 4. Rulison Field: Intensive Resource Development

Intensive Field Development Pilot, Sec. 20, Rulison Field*



For wells drilled through 1997.

Expected Results from Intensive Field Development (Sec. 20, Rulison)*

Date	Wells and Spacing	EUR/ Well (Bcf)	EUR/ Section (Bcf)
Initial	4 wells @ 160 A/W	2.1	9
1995	4 wells @ 80 A/W	2.0	8
1996-1998	8 Wells @ 40 A/W	2.0	16
1997-2000	16 wells @ 20 A/W	1.7	27
Latest	32 Wells @ 10 A/W	1.6	50
TOTAL (64 Wells)		1.7	110

For wells drilled through 2006.

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Table 1. A Decade of Unconventional Gas Resources Estimates (Technically Recoverable, Tcf)*

	1996	2002	2006**
Tight Gas Sands	259	348	379
Coalbed Methane	55	83	73
Gas Shales	52	78	128
TOTAL	366	509	580

* U.S. Lower-48 only
**With data through 2005

Table 2. Unconventional Gas Resource Estimates (Technically Recoverable, Tcf)

	Basins/Areas	Tight Gas Sands (Tcf)	Coalbed Methane (Tcf)	Gas Shales (Tcf)	TOTAL* (Tcf)
1	Rocky Mountain Basins	223	57	3	283
2	East/Central Texas	32	-	49	81
3	Appalachia	67	5	15	87
4	Other	57	11	61	119
	TOTAL	379	73	128	580

*With data through 2005; U.S. Lower-48 only.

Table 3. Comparison of Unconventional Gas Resource Estimates (U.S. Lower-48, Tcf)

	Advanced Resources* (2006)		National Petroleum Council (2003)**	U.S. Geological Survey (2006)***
	Proved Reserves	Undeveloped Resources		
Tight Gas Sands	73	379	131	177
Coalbed Methane	20	73	46	67
Gas Shales	12	128	29	60
TOTAL	105	580	206	304

*With data through 2005
** For accessible undeveloped resources, current technology, with data through 1998
*** Estimates for undeveloped continuous resources, with data from 1995-2006.

Table 4. Comparison of USGS and Advanced Resources Estimates for the Mesaverde (Williams Fork) Tight Gas Sand Play, Piceance Basin, Colorado

	U.S. Geologic Survey (2003)*	Advanced Resources (2006)**	
		S. Basin	N. Basin
Play Area (square miles)	1,989	1,008	1,008
Well Spacing (acres/well)	80	20	80
Wells Drilled	822	2,920	199
Success Rate (%)	80%	95%	87%
EUR/Well (Bcf)	0.9	1.3	1.85
Quality/Accessibility Factors (%)	28%	87%	87%
Recoverable Resource (Tcf)	3.1	31.5	11.0

*With data through 1999
**With data through 2005

Table 5. S. Piceance Basin, Williams Fork/Mesaverde Well Performance and Success Rates

A. Well Performance (by time period)

	Total Wells	Successful Wells	EUR (Bcf)	EUR/Well (Bcf)	Success Rate (%)
Pre-1990	98	67	70	1.04	68%
1990-1995	219	207	266	1.29	95%
1996-1999	353	335	406	1.21	95%
2000-2005	2,250	2,191	2,850	1.30	97%

B. Well Performance Distribution (recent wells)

2000-2005 (% of wells)	Successful Wells	Actual Well Distribution	Smoothed Well Distribution
		(Bcf/Well)	(Bcf/Well)
10%	231	2.95	2.60
20%	438	1.81	1.95
30%	657	1.24	1.30
40%	865	0.65	0.65
Total	2,191		

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