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DOE/METC/C-94/7124

Greater Green River Basin Well-Site Selection

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Conference Title:

Fuels Technology Contractors Review Meeting

Conference Location:

Morgantown, West Virginia

Conference Dates:

November 16-18, 1993

Conference Sponsor:

Morgantown Energy Technology Center

MASTER

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INTRODUCTION

Recent estimates of the natural gas resources of Cretaceous low-permeability reservoirs of the Greater Green River basin indicate that as much as 5,000 trillion cubic feet (Tcf) of gas may be in place (Law and others 1989). Of this total, Law and others (1989) attributed approximately 80 percent to the Upper Cretaceous Mesaverde Group and Lewis Shale. Unfortunately, present economic conditions render the drilling of many vertical wells unprofitable. Consequently, a three-well demonstration program, jointly sponsored by the U.S. DOE/METC and the Gas Research Institute, was designed to test the profitability of this resource using state-of-the-art directional drilling and completion techniques. DOE/METC studied the geologic and engineering characteristics of "tight" gas reservoirs in the eastern portion of the Greater Green River basin in order to identify specific locations that displayed the greatest potential for a successful field demonstration.

The demonstration is planned to include vertical, high-angle, and horizontal wells drilled from closely spaced locations. The vertical well will be used to characterize the reservoirs. The high-angle wellbore is intended to test a thick section of lenticular reservoirs. In contrast, the horizontal well will target a relatively thin, yet laterally continuous, "tight" gas reservoir with limited internal heterogeneities. For production, both wells will depend heavily on the occurrence of natural fractures.

The appraised area includes townships 12-26N and ranges 93-105W. This area encompasses the Rocks Springs Uplift, Wamsutter Arch, and the Washakie and Red Desert (or Great Divide) basins of southwestern Wyoming. The work was divided into three phases. Phase 1 consisted of a regional geologic reconnaissance of 14 gas-producing areas encompassing 98 separate gas fields. In Phase 2, the top four areas were analyzed in greater detail, and the area containing the most favorable conditions was selected for the identification of specific test sites. In Phase 3, target horizons were selected for each project area, and specific placement locations were selected and prioritized.

PHASE 1: SELECTING THE TOP FOUR AREAS

Phase 1 consisted of a reconnaissance of the geology and production characteristics of 14 areas of closely spaced and geologically similar gas fields in the eastern half of the Greater Green River basin. The area studied included townships 12-26N and ranges 93-105W (Figure 1). Each area was evaluated for current rates of gas, oil, and water production, estimated ultimate recovery (EUR), unit status, typical well spacings, core availability, and discovery date. Phase 1 work occurred in FY 1992, and a synopsis of that work was presented at a DOE/GRI Green River Basin Workshop in Denver, Colorado.

Figure 1. Location of the Study Area; major geologic features of the Greater Green River basin are noted.

Selection criteria

Phase 1 screening was based on six criteria: (1) production from the Mesaverde Group or Lewis Shale (because of the large resource base of those units); (2) drilling depths less than 12,500 feet (in order to maintain reasonable costs for the project); (3) field economics described as marginal or sub-commercial (a subjective criterion based on current levels of drilling and production - intended to ensure that the project would be useful to industry); (4) well spacing of 640 acres (necessary in order to provide sufficient undrained reservoir within field

limits); (5) availability of quality log, core, and production data (to allow for the mapping and correlation necessary to minimize geologic risk); and (6) unitized production (necessary to simplify the project logistics).

Phase 1 results

The geologic characteristics of the 14 areas appraised in Phase 1 are presented in Table 1. The names represent the dominant field in each area. The areas selected for further geological evaluation in Phase 2 are Desert Springs, Wamsutter, Wild Rose, and Hay Reservoir (Figure 2).

Table 1. Characteristics of the 14 Areas Screened in Phase 1

Area	Reservoir*	Unitized	Spacing (acres)	Data Available	Depth (feet)
Antelope	Al, Fr, Lw	Yes	160-640	Fair	7,000
Baxter Basin	Dk, Fr	Yes	320-640	Poor	3,500
Canyon Creek	Mv	--	--	--	--
Deadman Wash	Bl, Fr	Yes	640	Fair	7,000
Desert Springs	Al	Yes	640	Fair	6,000
Dripping Rock	Al, Lw	Yes	640	Limited	13,000
Freighter Gap	Fr	Yes	640	Good	14,000
Hay Reservoir	Lw	Yes	640	Good	10,000
Jacknife Springs	None	--	--	Limited	--
Nitchie Gulch	Dk, Fr	Yes	320	Fair	8,000
Powder Springs	None	Yes	640	Limited	--
Salt Wells	Fr, Rk	Yes	320-640	Poor	5,000
Wamsutter	Al	Yes	640	Good	11,500
Wild Rose	Al	Yes	640	Fair	9,500

* Al = Almond, Bl = Blair, Dk = Dakota, Fr = Frontier, Lw = Lewis, Mv = Mesaverde

PHASE 2: SELECTING THE TARGET FIELD FOR DETAILED STUDY

The objective of Phase 2 was to conduct broad-based geologic investigations of the four areas selected in Phase 1. Investigation focused on the nature of the reservoirs, data quality, and risk of reservoir depletion. The goal was to select the one area that would provide the best potential test sites. The results of these analyses are summarized below.

Desert Springs area (T19-22N: R97-99W)

The Desert Springs area includes several highly-productive oil and gas fields that lie at depths of less than 6,000 feet on the eastern flank of the Rock Springs Uplift. The biggest producing fields were discovered in the 1940s and 1950s and include Table Rock -- 461 billion cubic feet of gas (bcfg) cumulative through 1991, Desert Springs -- 267 bcfg, Patrick Draw -- 152 bcfg, and Arch -- 84 bcfg.

Figure 2. Location of the Four Areas Selected for Detailed Study

However, with the exception of Desert Springs Field, the reservoirs are drilled on extremely close spacing and produce large amounts of oil. Gas production at Desert Springs is primarily from shoreline sandstones of the upper Almond Formation.

Two upper Almond reservoirs attain thicknesses of 30 feet. Although determination of reservoir quality is difficult because of limited porosity data, available log and production data suggest that reservoir quality may be too good to allow the area to be an appropriate example of a "tight" gas reservoir. In addition, Desert Springs is not a good candidate area because of

the probable widespread reservoir depletion and a lack of high-angle well opportunities.

Hay Reservoir area (T23-26N: R96-99W)

The Hay Reservoir area is located on the northeastward-dipping southern flank of the Red Desert (Great Divide) basin. Within the area, Hay Reservoir Field, 57 bcfg cumulative through 1991, is the only candidate location for the field demonstration. Several recent wells drilled on 320-acre spacing in the Hay Reservoir area have encountered near original reservoir pressure, indicating that vertical wells have not been able to effectively drain the reservoir at the prevailing 640-acre spacing.

Well demonstration targets at Hay Reservoir field are limited to eight separate sandstone reservoirs scattered throughout a pay interval that is 400 feet thick. Only one of these reservoirs is widespread and consistently greater than 20 feet in thickness. Furthermore, acid stimulation and hydraulic fracturing are commonly necessary to maintain a completion. The only potential high-angle project would be an attempt to drill where several Lewis sandstones are vertically-stacked. Furthermore, the Mesaverde Group, which is the preferred target because of its enormous estimated resource base, is not productive at Hay Reservoir. Consequently, Hay Reservoir area is not recommended as a possible location for the proposed field demonstration.

Wild Rose area (T16-19N: 94-96W)

The Wild Rose area contains a number of small gas fields that occur upon the crest and southern flank of the Wamsutter Arch. Gas production in the area is dominated by the Standard Draw (127 bcfg cumulative through 1991), Wild Rose (89 bcfg), and Barrel Springs (27 bcfg) fields. The various fields of the Wild Rose area produce from low-permeability Mesaverde Group reservoirs at moderate depths.

Logging suites from the Wild Rose area are highly variable, making net porosity and cross-over maps less accurate than desired. Although the assessed risk of reservoir depletion is low, none of the productive Almond or Ericson reservoirs displays the necessary continuity or thickness to be a suitable horizontal well target. Individual reservoirs generally do not exceed 20 feet in thickness and are highly lenticular.

Wamsutter area (T21-24N: R94-96W)

The Wamsutter area includes the Wamsutter (84 bcfg cumulative through 1991), Siberia Ridge (17 bcfg), and other smaller fields that occur along the northward-dipping north flank of

the Wamsutter Arch. The area produces primarily from north-south trending marginal-marine sandstones of the upper Almond Formation.

The 98 productive wells in the Wamsutter area are located at a 640-acre spacing. Many of the wells, especially those in the Siberia Ridge field, are of exceptional quality. Average pay thickness is greater than 30 feet. The main field reservoir has the lateral continuity and thickness necessary to be the horizontal-well target. The reservoirs in the lower Almond and Ericson formations are highly-lenticular and gas-charged, and provide multiple potential targets through a thick pay zone. The drilling depth is marginal, up to 14,500 feet to the base of the fluvial sequence at the northern end. However, to the south, over 2,000 feet of non-marine section, containing up to 40 percent sandstone, exists above the 12,500 feet drilling depth. Most Ericson reservoirs display low porosity and permeability, making them ideal subjects for the high-angle-well field demonstration.

Phase 2 results

Of the four areas reviewed in Phase 2, the Wamsutter area displays the best conditions for selecting specific horizontal and high-angle well sites. The results of Phase 2 are summarized in Table 2.

PHASE 3: SELECTING SPECIFIC WELL TARGETS AND LOCATIONS

The objective of Phase 3 was to investigate the geology of the Wamsutter area to delineate specific potential locations for the horizontal and high-angle field demonstration wells. During the course of this investigation, differences in the geology and the nature of the potential targets related to decreasing drilling depths resulted

Table 2. Results of Phase 2 Screening

Area (Location)	Depth	Reservoir	Data Quality	Typical "Tight" Field	Horizontal Well Targets	Slant Well Targets	Risk of Depletion
Desert Springs (T19-22N : R97-99W)	○	○	●	●	●	●	●
Hay Reservoir (T23-26N : R96-99W)	○	◐	○	○	○	●	○
Wamsutter (North) (T21-24N : R94-96W)	◐	○	○	○	○	●	◐
Wamsutter (South) (T19-20N : R94-96W)	○	○	◐	○	●	○	○
Wild Rose (T16-18N : R94-96W)	○	○	◐	○	○	◐	○

= Good
(Low Risk of Depletion)

= Fair
(Medium Risk of Depletion)

= Poor
(High Risk of Depletion)

in the separation of the Wamsutter area into northern and southern parts.

The criteria used for selecting the horizontal well target from among the various reservoirs in the field are (1) thickness of at least 30 feet, (2) limited internal heterogeneities expected, (3) proven or likely gas productivity, and (4) blanket geometry. The specific site at which to drill the well was chosen by identifying areas with optimal reservoir quality that have not been drained by surrounding wells.

The high-angle well target was chosen based on the following criteria: (1) a thick sequence of vertically-stacked reservoirs,

(2) proven or expected gas productivity, and (3) highly lenticular geometry. Since reservoir depletion was not an issue for the high-angle targets, the main factors in choosing the specific sites were (1) proximity to good horizontal well locations, and (2) maximization of sand-to-shale ratio in the sequence.

Horizontal well

Within the Wamsutter area, only the reservoirs within the upper Almond Formation fit the general criteria for a horizontal well target. Mapping of total thickness and density-neutron crossover was completed for each of six sandstones. Four main upper Almond sandstones

occur, designated from top to bottom as MA-1, MA-2, MA-3, and MA-4 (Figure 3). To the south and east, the upper four units shale out, leaving the MA-4 sandstone as the uppermost Almond sandstone throughout most of the Wamsutter area. Isopach maps of various sandstones reveal that depositional strike was roughly to the north-northeast. As recognized by numerous previous workers, the mapped trend, the outcrop character, and the nature of surrounding lithologies indicate that the upper Almond sandstones were deposited in marginal-marine settings such as shallow near-shore shelves, beaches, and barrier islands (Weimer, 1965; McCubbin and Brady, 1969; Van Horn, 1979).

MA-1: The MA-1 sandstone is a thin, texturally fining-upwards, marine sandstone that occurs in only the northernmost sections of Wamsutter area (Siberia Ridge Field). Maximum thickness in the Wamsutter area is only 20 feet. The unit is not productive in the Wamsutter area.

MA-2: The MA-2 sandstone is a thick, clean, texturally coarsening-upwards, marginal-marine sandstone. The sandstone has been penetrated by 18 wells in the Wamsutter area; however, it was perforated for production in only one well, where it was commingled with several other Almond zones. Although porosity in the unit is typically 8 to 10 percent, gas indications on the neutron-density log are rare.

MA-3: The MA-3 sandstone is clean, texturally coarsening-upwards unit like the overlying MA-2. The unit is seen in 20 wells. Maximum thickness of the sandstone in the Wamsutter area is 25 feet. "Tight" streaks are common in the center of the unit. Porosity is commonly 8 to 10 percent. Commingled production has occurred in two wells, both of which were sandfraced and acidized. Neither well was an economic success (.103 and .135 bcfg cumulative).

Figure 3. Type Log for the Northern Portion of the Wamsutter Area

MA-4: The MA-4 sandstone is the lowermost clean, blocky sandstone that occurs in the Almond Formation in the Wamsutter area. The

sandstone is especially well-developed in T22N R94W, where it forms the main pay sandstone for the field. Sandstone thickness ranges from 25 to 35 feet. Porosity ranges from 10 to 14 percent. From 10 to 20 feet of neutron-density crossover is typical.

Based on data summarized above, the most favorable horizontal well locations occur in the thick MA-4 lobe located in T22N R94W. This area contains the thickest, most continuous reservoir in the area. In addition, the productivity of the unit is well established. To the south, reservoir thickness decreases and risk of reservoir depletion increases; to the north, there is a significant increase in depth and deterioration in data quality. Within T22N R94W, the best locations were found in sections 8, 17, 14, and 11.

Industry may be currently developing plans on its own to develop the Almond reservoirs at Wamsutter with a horizontal well. Of course, this event would greatly reduce the need for a U.S. DOE demonstration program in the Almond. Consequently, alternative target horizons were considered. Analysis of well logs and production data in the southern part of the Wamsutter area reveal that no single reservoir in the productive interval meets the stated criteria for a horizontal well. The only candidates occur 2,000 feet stratigraphically below the Almond main field pay at the base of the Mesaverde Group. These units, although not proven reservoirs, are generally regarded as good prospects. A successful test of these units by U.S. DOE would provide significant benefits to industry. The concept of targeting these reservoirs was first brought to the attention of U.S. DOE by the USGS.

Five major basal Mesaverde sandstones exist and are designated LM-4, LM-5, LM-7, LM-9, and LM-10 (Figure 4). The upper two units can be observed in four wells; the lower

Figure 4. Type Log for the South Wamsutter Area

two units are penetrated by only three wells. The units, especially the lower three, are likely to be marginal marine sandstones with blanket geometry and limited internal heterogeneity. However, the data are insufficient to allow these predictions to be tested through mapping. None of the units were perforated or tested in the four wells.

LM-4: The LM-4 interval contains one lobe that can be traced between the several deep well logs. The unit contains over 20 feet of pay with a water saturation of approximately 35 percent. However, the unit is most likely non-marine in origin, and can be expected to contain significant internal heterogeneity as well as overall lenticularity. Therefore, it is not recommended as an appropriate horizontal well target.

LM-5: This unit consists of a clean blocky sandstone separated by a persistent shale break into two lobes. The upper lobe varies in thickness from 8 to 26 feet. The lower lobe is 42, 45, and 50 feet thick in three wells; however, in the fourth, the unit is reduced to three thin sandstones totaling 14 feet. Porosity in the thicker units range from 11 to 13 percent. Two measured water saturations are 36 and 47 percent. The apparent lenticularity of the unit and its stratigraphic position render it difficult to determine whether the unit is marine or non-marine in origin.

LM-7: This sandstone is a clean, blocky unit. Thicknesses in the four wells are 28, 44, 45, and 47 feet. Porosity is 9 to 10 percent and there is no crossover on the neutron-density log. The induction log shows 20 ohm/m resistivity, corresponding to 60 percent Sw or more, depending on formation water resistivity.

LM-9: The LM-9 sandstone is a thick, slightly shaly unit with multiple shale breaks. Total sandstone thickness is greater than 70 feet in all three wells. The upper part of the unit is the cleanest and displays thicknesses of 34, 40, and 47 feet. The top of the unit occurs at 11,900 to 12,100 feet in depth. The porosity is low, roughly 8 percent. The induction log indicates a very high occurrence of water.

LM-10: The basal Mesaverde sandstone occurs at a depth of 12,100 to 12,300 feet. The unit is divided into two lobes. The shale content

of the sandstone is high. In two wells, the lower lobe is best developed (24 and 30 feet thick); in the other well, the lower lobe is thinner (15 feet) and shaly. The upper unit is clean and thick (34 feet) in only one of the three wells. Porosity in the lower lobe approaches 10 percent. However, water saturation is 75 percent in the Frewen Deep Unit No. 4 well.

Of these five candidate lower Mesaverde sandstones, the most promising is the LM-5. This particular unit appears to be the most gas-prone and is largely shale-free. However, the depositional origin of the unit is unclear. Given the limited data available on the lower Mesaverde targets, it is advisable to reduce geologic risk by locating the test as close as possible to the control points. Therefore, the best sections from which to drill the horizontal well at Wild Rose would be sections 6, 7, 18, or 19 of T19N R94W or sections 12, 13, or 24 of T19N R95W.

High-angle well

The high-angle well at the original North Wamsutter location (T22N R94W) would target reservoirs in the Lower Almond and Ericson formations. This interval is up to 1,000 feet in thickness and contains up to 350 feet of sandstone. Below the Ericson is over 1,000 feet of lower Mesaverde Group, which is also a potential horizontal well target. However, this interval lies below the 12,500 feet drilling depth at the planned location. The sandstones are thin and discontinuous at the top of the interval; however, the lower Ericson is marked by several massive sandstones that combine to form a 250- to 300-foot thick unit. Porosity in the units is usually less than 10 percent. As much as 100 feet of this total sandstone thickness may show gas indications on the neutron-density log; however, the amount of crossover is commonly only 60 to 70 feet. The best fluvial section at Wamsutter is located in the southern half of

T21N R94W and the northern halves of T20N R94W and T22N R95W. No effort has been made to determine the proper azimuth for the well. The well should be designed so as to intersect the largest number of fractures (i.e., perpendicular to the trend of major fractures). However, no fracture data has been collected at this time.

The entire 2,000 feet of non-marine section, stretching from the base of the upper Almond to near the base of the Mesaverde Group, can be tested by a slant well at the alternative South Wamsutter location. The top of the target section occurs at approximately a 9,500-foot measured depth. As much as 250 feet of gas pay can be expected. However, a 1,000-foot thick, reservoir-barren zone directly below the Ericson divides the targets into two separate zones. As with the Wamsutter location, no data on fractures has been collected, so no recommendation as to the orientation of the well is given.

DISCUSSION

Two potential test locations have been described. The North Wamsutter is located in T22N R94W, based on the lowest-risk horizontal well target. The location provides the best chance for a good gas well while minimizing the risk of a thinned, missing, or depleted reservoir. However, there are two main drawbacks to this location. First, industry is planning to drill horizontal wells into the Almond in this area. If this occurs, the need for U.S. DOE to expend its resources on a similar project is reduced. Second, the area is not an optimal location for drilling a high-angle well: half the prospective target lies below the 12,500 feet drilling depth, and the units that can be drilled are relatively sandstone-poor compared to surrounding areas.

Consequently, an alternative program in the South Wamsutter area was investigated. This location takes advantage of the decreasing

structural elevation of the reservoirs. Although the Almond and Ericson formations do not provide suitable targets for the horizontal well, alternative targets occur in the marine sandstones at the base of the Mesaverde Group. Because these units have not been produced, there is no risk of encountering a depleted reservoir. In addition, the lack of available data on these units indicates that a successful demonstration by the U.S. DOE would have a major impact on the industry. However, with this increased "potential" comes a significantly increased risk because of the uncertain reservoir quality, geometry, and producibility. An additional advantage to the South Wamsutter location is the ability to drill the entire 2,000-foot thick non-marine sequence with the high-angle well. Reservoir characteristics of the North and South Wamsutter areas are provided in Tables 3 and 4.

No specific recommendation for locating the field demonstration project can be given at this time. Instead, the following three alternatives are presented. These alternatives will continue to be investigated.

Option 1: Drill at North Wamsutter:

The least risk of total project failure occurs if the project is located in T22N R94W at Wamsutter. The horizontal well target is a proven productive reservoir with sufficient porosity and permeability to be an economic success even if fracture porosity is non-existent. The high-angle well can be drilled into the lower Almond and Ericson formations to a depth of 12,500 feet, or the entire non-marine section can be drilled if the decision to go to 13,500 feet is made. The nature of the lower Mesaverde in this area is not well understood. It is known, however, that the Ericson in this area contains less sandstone than elsewhere.

Option 2: Drill at South Wamsutter: Of the current options being considered, the greatest

Table 3. Characteristics of Reservoirs in the North Wamsutter Area

Unit	Depth (Feet)	Pay (Feet)	ϕ (Percent)	Sw (Percent)
Main Almond-1	11,500	0	--	--
Main Almond-2	11,525	0	--	--
Main Almond-3	11,550	0	--	--
Main Almond-3a	11,560	0	--	--
Main Almond-4	11,600	9-23	10-15	45-65
Lower Almond-1	11,650	0-3	8	40-60
Lower Almond-2	11,750	4-11	9-11	20-35
Ericson-1	11,850	0-14	9-12	20-40
Ericson-2	11,950	0-13	8	15-25
Ericson-3	12,025	10-26	7-9	12-25
Ericson-4	12,125	19-24	6	10
Ericson-5	12,350	42	9	20
Ericson-6	12,500	0	--	--

potential benefit to industry would be achieved by a successful field demonstration along the boundary of T19N R94W and T19N R95W in the Wild Rose area. The high-angle well would test the entire 2,000 feet of the Ericson and Allen Ridge non-marine sequence at moderate depths. The horizontal well and the vertical characterization well would test the underlying marine reservoirs at the base of the Mesaverde Group. Total drilling depth for the project would be approximately 11,900 feet. Both intervals are estimated by the USGS to contain large volumes of gas that are currently not being exploited. However, the potential that both targets could be non-economic even with directional drilling is very real. Furthermore, the general lack of wells that have fully

penetrated the sequence renders the geologic interpretation less assured than is desirable. Finally, as with Option 1, the presence of fractures will play a key role in the success of the project; yet little is currently known about the existence or orientation of fractures.

Option 3: Separate the two wells geographically: In this scenario, the high-angle well would be drilled first through the Ericson, Allen Ridge, and Rock Springs formations in the Wild Rose area. If the high-angle well shows potential in the basal Mesaverde sandstones, then locate the horizontal well there. However, if the sands appear too "tight," and if the slant hole shows no hint of extensive fracturing, then shift the project 25 miles to the north and

Table 4. Characteristics of Reservoirs in the South Wamsutter Area

Unit	Depth (Feet)	Pay (Feet)	ϕ (Percent)	Sw (Percent)
Main Almond	9,750	0-3	10	45
Lower Almond	9,850	8-10	12-13	40
Ericson-2	10,050	10-12	12-15	23-40
Ericson-3	10,200	48-61	9-14	27-41
Ericson-4	10,300	68-79	9-14	25-51
Ericson-5	10,400	25-27	10-12	50-59
Lower Mesaverde-1	10,500	0	9	66-71
Lower Mesaverde-2	10,900	0	7-9	60-97
Lower Mesaverde-3	11,200	0-14	7-11	43-68
Lower Mesaverde-4	11,450	22-67	12-13	34-37
Lower Mesaverde-5	11,650	16-30	11-13	30-61
Lower Mesaverde-6	11,750	0-7	10-11	54-70
Lower Mesaverde-7	11,850	0	9	85-97
Lower Mesaverde-8	11,950	0	10	97
Lower Mesaverde-9	12,050	0	9	90
Lower Mesaverde-10	12,200	0	6-9	75-100

horizontally drill the Almond MA-4 sandstone in the heart of the Wamsutter area.

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